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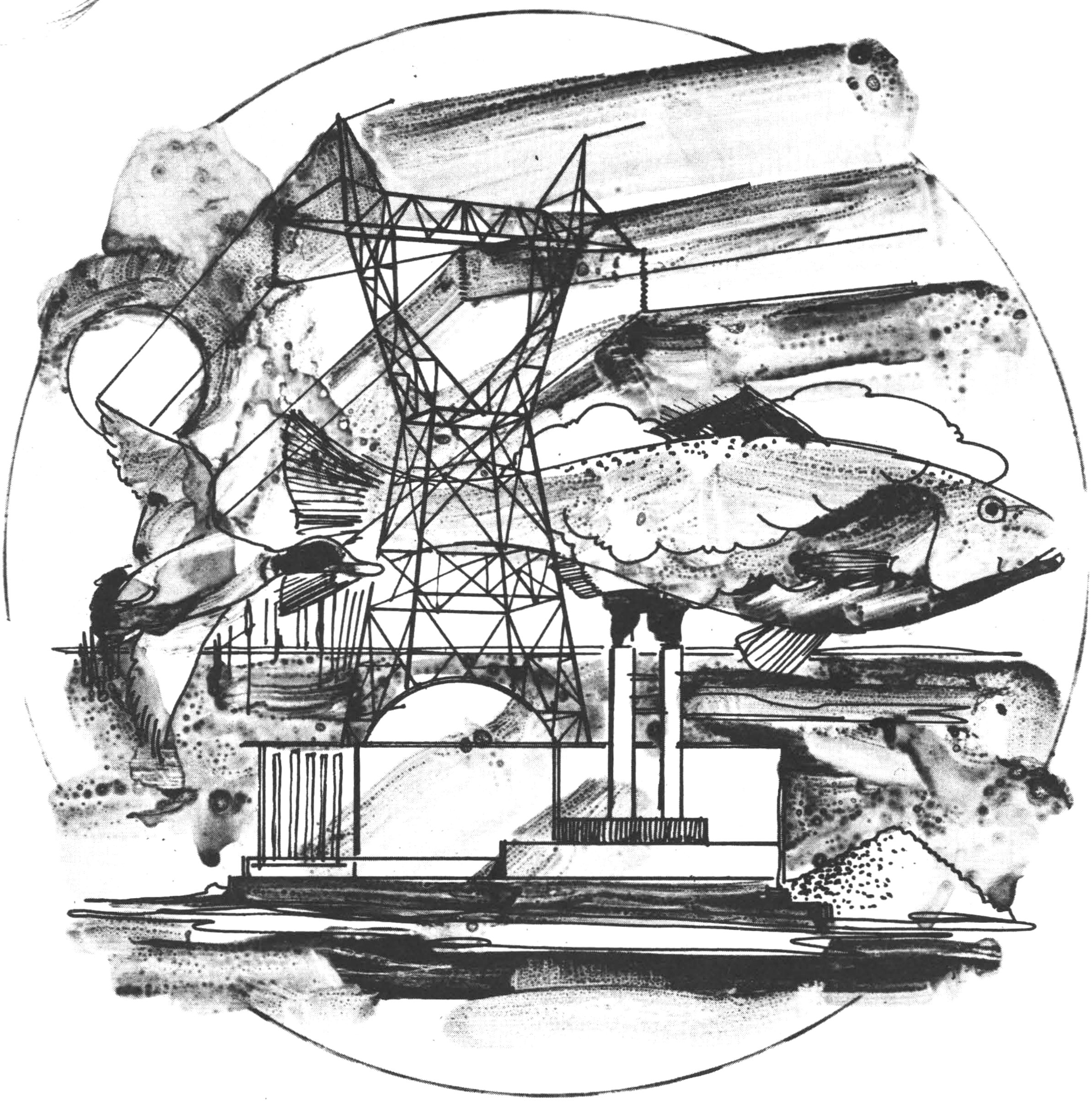
An Empirical Transport Model for Evaluating Entrainment of Aquatic Organisms by Power Plants



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AN EMPIRICAL TRANSPORT MODEL FOR EVALUATING ENTRAINMENT OF AQUATIC ORGANISMS BY POWER PLANTS

by

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EXECUTIVE SUMMARY

One of the more important potential aquatic impacts of steam electric power plants is the mortality of organisms that are contained in the water that is drawn through the plant for condenser cooling purposes. Organisms that are small enough to pass through the plant's intake screening system are said to be entrained, and many of these organisms may be killed by exposure to mechanical, chemical, or thermal stresses during plant passage. Of particular concern are the early life stages of populations of fish and shellfish that inhabit the adjacent water body or use the area as a spawning or nursery habitat.

A first step in assessing the impact of entrainment mortality is to estimate the conditional entrainment mortality rate, which is the fraction of the population which would be killed due to entrainment in the absence of any other source of mortality. Mathematical models for evaluating the conditional entrainment mortality rate have been proposed by numerous authors. Although some of these models simulate the movement of organisms through the use of hydrodynamic equations, few of the models specify movement patterns based directly on field data. This report describes a generalized mathematical model that incorporates empirically derived organism distribution and movement characteristic to estimate the conditional entrainment mortality rate. The generalized model is formulated as follows:

$$m_T = 1 - \frac{\sum_{s=1}^{S} N_0 R_s \left\{ \prod_{j=0}^{J} \left[\sum_{k=1}^{K} D_{s+j,jk} e^{-(M_{s+j,jk}+E_{s+j,jk})t} \right] \right\}}{\sum_{s=1}^{S} N_0 R_s \left\{ \prod_{j=0}^{J} \left[\sum_{k=1}^{K} D_{s+j,jk} e^{-(M_{s+j,jk})t} \right] \right\}}$$

where: m_T = total conditional entrainment mortality rate,

N_0 = total number of eggs spawned,

s = week of spawning period,

S = total number of weeks in spawning period,

R_s = proportion of eggs spawned during week s,

j = age 0, 1, 2, . . ., J,

J = oldest entrainable age,

k = region 1, 2, 3, . . ., K,

K = total number of regions within the water body,

$D_{s+j,jk}$ = proportion of total standing crop of age j individuals during week s+j in region k,

$M_{s+j,jk}$ = instantaneous natural mortality rate constant of age j individuals during week s+j in region k (units: per day),

$E_{s+j,jk}$ = instantaneous entrainment mortality rate constant of age j individuals during week s+j in region k (units: per day), and

t = duration (in days) of week s+j.

In this formulation, the numerator of the term on the right side of the equation is the total probability of survival for the population when exposed to both natural and entrainment mortality; the denominator is the probability of survival from natural causes only. Both rates of mortality are time-, space-, and age-specific. The model can be simplified by making various assumptions. For example, if natural mortality is assumed to be a function only of age, then the generalized equation can be simplified to:

$$m_T = 1 - \sum_{s=1}^{S} R_s \left\{ \prod_{j=0}^{J} \left[\sum_{k=1}^{K} D_{s+j,jk} e^{-(E_{s+j,jk})t} \right] \right\}$$

Note that with the simplifying assumption, estimates of age, spatial, and temporal variations in natural mortality are not required for estimation of the conditional entrainment mortality rate.

Obtaining the input data needed for the model involves the following: specifying geographic regions within the water body to define the distribution and movement of organisms while they are vulnerable to entrainment; obtaining estimates of physical factors (water volume and power plant intake flow in each region); determining entrainment susceptibility in each region for the various life stages present as a function of calendar time; determining the length of time that organisms will be vulnerable to entrainment; and calculating the distribution of life stages among the regions of the water body as a function of calendar time.

The effect of organism movement patterns is incorporated by the variable D in the model. Given sufficient data, the actual spatial and temporal distributions of the various ages of the organisms, as determined through field sampling, can be used to define D. The value of this approach is that it relies on observed movement patterns rather than complex simulations of incompletely understood mechanisms of organism distribution, which are often unable to adequately replicate distributions observed in the field. A disadvantage of this approach is that it requires an extensive and detailed set of observations throughout the period of occurrence of the entrainable life stages of the population in question.

If sufficient observational detail is lacking to define the values of D as a function of both organism age and calendar time, then field data can be processed to provide a seasonally-averaged distribution as a function of organism age or life stage. The adequacy of this and other simplifications can be studied by sensitivity analyses which allow the user to ascertain the relative importance and probable direction of error that might be introduced by the simplification processes.

The two most important limitations of the application of the model are related to the acquisition and processing of field data. The first lies in the inability of current technology to separate the processes of mortality and movement of entrainable organisms. If natural mortality varies spatially, then changes in observed distributions of organisms are caused by both movement and differential mortality among regions of the water body. This complication may or may not be important, depending on the magnitude of the spatial variation in mortality. This limitation applies to all models that have been proposed to estimate entrainment impacts. As such, the user should carefully evaluate the probable impact of the entrainment mortality on the observed distributions, since projections of conditional mortality rates are likely to be overestimated for preoperational studies and underestimated for post operational studies. These tendencies may exist because of a localized depletion of organisms due to entrainment mortality.

The second limitation is that the model uses distribution data collected under specific conditions. Such conditions may vary from year to year. As a consequence, several years of data are needed to establish the probable variation that would occur in the input variables and hence provide a range of conditional entrainment mortality rate estimates.

These limitations preclude the use of this or other models to "measure" the actual conditional entrainment mortality rate. Such an ability is beyond the present state-of-the-art. However, this model can be used where sufficient data are available as a tool for directly estimating the entrainment mortality rate without the uncertainties imposed by complex simulations of incompletely understood mechanisms of organism movements.

This report presents the mathematical development of the generalized model, termed the Empirical Transport Model (ETM), along with several alternative formulations that could be used depending on the level of detail in data obtained from field studies. The model is applied to a hypothetical population inhabiting an estuary where several power plants are proposed to be sited. The model application involves processing hypothetical field data to establish the values of the input variables, as well as a sensitivity analysis of the conditional entrainment mortality rate estimate to variations in the input variables.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

Den	density, expressed as number of organisms per unit volume
SC	standing crop
TCM	thousand cubic meters (1,000 m^3)

SYMBOLS

$C_{j\ell}$	fraction of age j individuals in life stage ℓ
D_{ijk}	proportion of the total standing crop of age j individuals- during week i in region k
$D_{ij\ell}$	proportion of total standing crop of life stage ℓ individuals
$D_{s+j,jk}$	proportion of the total standing crop of age j individuals during week s+j in region k
$D_{s+j,k\ell}$	proportion of total standing crop of life stage ℓ individuals during week s+j in region k
D_{jk}	average proportion of the total standing crop of age j individuals in region k during the entrainment period
$D_{k\ell}$	average proportion of total standing crop of life stage ℓ individuals in region k during the entrainment period
E_i	instantaneous entrainment mortality rate constant during week i (units: per day)
E_{ij}	instantaneous entrainment mortality rate constant of age j individuals during week i (units: per day)
E_{ijk}	instantaneous entrainment mortality rate constant of age j individuals during week i in region k (units: per day)
$E_{ik\ell}$	instantaneous entrainment mortality rate constant of life stage ℓ individuals during week i in region k (units: per day)
E_{jk}	average instantaneous entrainment mortality rate constant of age j individuals in region k (units: per day)
$E_{k\ell}$	average instantaneous entrainment mortality rate constant for life stage ℓ individuals in region k (units: per day)
$E_{s+j,jk}$	instantaneous entrainment mortality rate constant of age j individuals during week s+j in region k (units: per day)
$E_{s+j,k\ell}$	instantaneous entrainment mortality rate constant of life stage ℓ individuals during week s+j in region k (units: per day)

SYMBOLS (cont.)

e	base of natural logarithms, equals 2.71828...
F_{ijk}	entrainment vulnerability of age j fish during week i in region k
f_{ijk}	fraction of age j fish killed due to plant passage during week i in region k
I	duration of the entrainment period
i	week 1,2,3,...,I
J	oldest entrainable age, equals duration of the entrainment interval
j	age 0,1,2,...,J
K	total number of regions within the water body
k	region 1,2,3,...,K
L	total number of entrainable life stages
ℓ	life stage 1,2,3,...,L
M_i	instantaneous natural mortality rate constant during week i (units: per day)
m_i	conditional entrainment mortality rate during week i
M_{ij}	instantaneous natural mortality rate constant of age j individuals during week i (units: per day)
M_{ijk}	instantaneous natural mortality rate constant of age j individuals during week i in region k (units: per day)
$M_{s+j,jk}$	instantaneous natural mortality rate constant of age j individuals during week s+j in region k (units: per day)
M_J	total natural mortality rate during the entrainment interval
M_j	natural mortality rate of age j individuals
m_T	total conditional entrainment mortality rate
m_{Tp}	total conditional entrainment mortality rate imposed by power plant p
N_E	total number of individuals alive at the end of the entrainment period with the absence of natural mortality during the entrainment period
N_I	number of individuals alive at the end of the entrainment interval
N_i	number of individuals alive at the beginning of week i

SYMBOLS (cont.)

N

N_{i+1}	number of individuals alive at the beginning of week i+1
N_{i+1}^{*}	number of individuals alive at the beginning of week i+1 in the absence of entrainment mortality during week i
$N_{i,0}$	number of eggs spawned in week i
N_{ij}	number of age j individuals alive at the beginning of week i
$N_{i+1,j+1}$	number of age j+1 individuals alive at the beginning of week i+1
N_0	total number of eggs spawned
p	power plant index
P_{ik}	volume of water withdrawn by power plants in region k during week i
R_s	proportion of total eggs spawned during week s
S	total number of weeks in spawning period
s	week of spawning period
SC_{ij}	total standing crop of age j individuals during week i
SC_{ijk}	standing crop in region k of age j individuals during week i
t	duration (in days) of week i or week s+j
V_{ik}	average water volume of region k during week i
W_{ijk}	ratio of the average power plant intake concentration to average regional concentration of age j fish during week i in region k

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INTRODUCTION

A first step in assessing the impact of entrainment mortality imposed on fish or shellfish populations is estimating the conditional entrainment mortality rate. Mathematical models for evaluating entrainment of aquatic organisms have been proposed by numerous authors, including Christensen et al. (1975), Hess et al. (1975), Horst (1975), Portner (1975), UEC (1975), Eraslan et al. (1976), Lawler (1976), Goodyear (1977), and Polgar (1977). Although some of these models simulate ichthyoplankton movement patterns through the use of hydrodynamic equations, few of the models specify movement patterns based directly on field data. Models that do specify movement patterns have been developed and applied in the context of a specific power plant location. This paper presents a generalized mathematical model, incorporating empirically-derived organism distribution and movement characteristics, for estimating the conditional entrainment mortality rate.

Provided sufficient information is available, the model, termed the Empirical Transport Model (ETM), may be applied to fish or shellfish populations inhabiting water bodies containing existing or proposed power plants. A hypothetical example is presented to illustrate how the ETM may be applied to estimate the conditional entrainment mortality of a fish population. Entrainment mortality of fish populations in estuaries will be discussed in this paper, although the concepts presented may also be applied to populations of other aquatic organisms.

TERMINOLOGY

Several terms used in this paper require precise definitions. These terms relate age to calendar time for entrainable life stages of a fish population. Identification of this relationship is necessary due to the usual presence of more than one entrainable life stage in concurrent field samples.

The calendar time period during which entrainable life stages are present in the water body is termed the *entrainment period.* The entrainment period is approximately equal to the duration of the spawning period plus the length of time an individual organism takes to grow through the entrainable life stages. The duration of this latter length of time is termed the *entrainment interval.*

A *time step* is an arbitrary division of the entrainment period. For purposes of this paper, the time step is measured in weeks, although any calendar measurement may be used. A *cohort* is a group of individuals of the same age (in weeks), i.e., they were spawned during the same time step. A cohort may spend more then one time step in a given life stage contained in the entrainment interval, depending on the duration of the life stage. Furthermore, more than one cohort may be present in the water body during a given time step, depending on the duration of the spawning period. If all spawning occurs during one time step, then only one cohort will be present in the water body during each subsequent time step. A schematic diagram of the relationships among the above-mentioned terms is shown in Figure 1. The following section relates these terms mathematically.

MATHEMATICAL BASIS OF THE EMPIRICAL TRANSPORT MODEL

The number of entrainable individuals surviving a week (time step) during the entrainment period can be expressed as follows:

$$N_{i+1} = N_i e^{-(M_i+E_i)t} \tag{1}$$

where i = week 1,2,3,...,I,

I = duration of the entrainment period,

N_i = number of individuals alive at the beginning of week i,

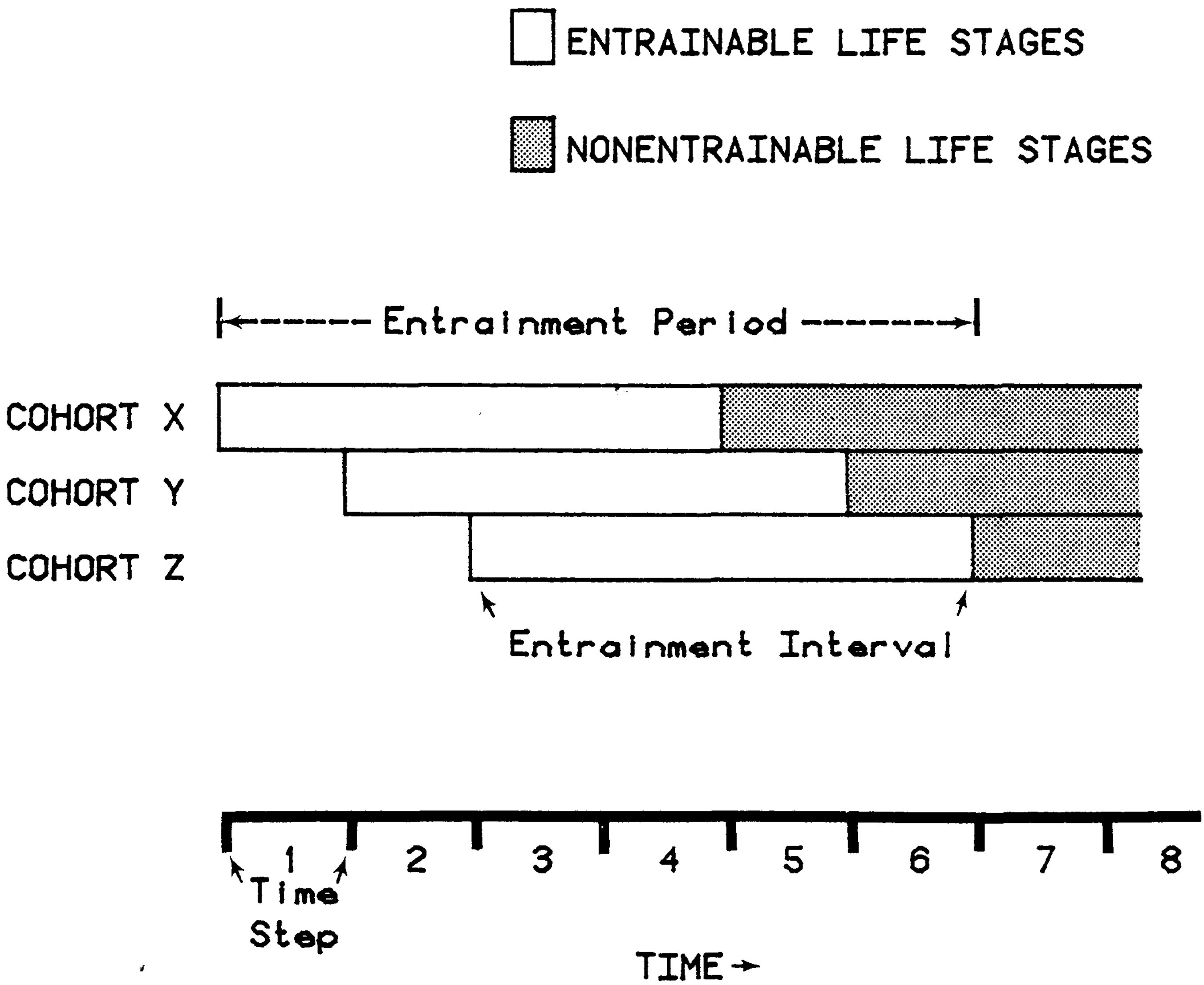

Figure 1. Relationship among the terms "entrainment period," "entrainment interval," "time step," and "cohort" as used in this paper.

N_{i+1} = number of individuals alive at the beginning of week i+1,

M_i = instantaneous natural mortality rate constant during week i (units: per day),

E_i = instantaneous entrainment mortality rate constant during week i (units: per day), and

t = duration (in days) of week i.

The conditional entrainment mortality rate during week i may be derived from equation 1 as 1.0 minus the ratio of the number surviving week i in the presence of entrainment mortality to the number surviving week i in the absence of entrainment mortality:

$$m_i = 1 - \frac{N_{i+1}}{N^*_{i+1}} = 1 - \left[\frac{N_i e^{-(M_i+E_i)t}}{N_i e^{-(M_i)t}}\right] = 1 - e^{-(E_i)t} \tag{2}$$

where N^*_{i+1} = number of individuals alive at beginning of week i+1 in the absence of entrainment mortality during week i, and

m_i = conditional entrainment mortality rate during week i.

If vulnerability to sources of mortality changes with age of the individual, equation 1 can be modified as follows to allow for age-specific mortality rates:

$$N_{i+1,j+1} = N_{ij} e^{-(M_{ij}+E_{ij})t} \tag{3}$$

where j = age (in weeks) 0,1,2,...,J,

J = oldest entrainable age,

N_{ij} = number of age j individuals alive at the beginning of week i,

$N_{i+1,j+1}$ = number of age j+1 individuals alive at the beginning of week i+1,

M_{ij} = instantaneous natural mortality rate constant of age j individuals during week i (units: per day), and

E_{ij} = instantaneous entrainment mortality rate constant of age j individuals during week i (units: per day).

The oldest entrainable age, J, is also a measure of the entrainment interval. This interval may be estimated in any of several ways; for example, (1) the time period during which any entrainable life stage occurs, minus the time period during which the first entrainable life stage occurs, plus the time period during which only the first entrainable life stage occurs; (2) the time period between the first appearance of eggs and the first appearance of nonentrainable juveniles; (3) the time period between the last appearance of eggs and the first period within which entrainable organisms have disappeared permanently from the system; (4) the time period between peak standing crops of the first entrainable and first nonentrainable life stages (although this may be biased); or (5) from available literature sources.

Vulnerability to sources of mortality may also be affected by the distribution of entrainable individuals within the water body. The distribution of age j fish during week i may be defined as the proportion of the total water-body-wide standing crop of age j fish during week i occuring in each water body region k. Equation 3 can be modified to account for differential mortality rates of entrainable individuals within K regions of the water body as follows:

$$N_{i+1,j+1} = N_{ij} \left[\sum_{k=1}^{K} D_{ijk} e^{-(M_{ijk}+E_{ijk})t} \right] \tag{4}$$

where k = region 1,2,3,...,K,

K = total number of regions within the water body,

D_{ijk} = proportion of the total standing crop of age j individuals during week i occurring in region k; thus

$$\sum_{k=1}^{K} D_{ijk} = 1 \tag{4A}$$

$$D_{ijk} = \frac{SC_{ijk}}{SC_{ij}} \tag{4B}$$

where SC_{ijk} = standing crop in region k of age j individuals during week i,

SC_{ij} = total standing crop of age j individuals during week i,

M_{ijk} = instantaneous natural mortality rate constant of age j individuals during week i in region k (units: per day), and

E_{ijk} = instantaneous entrainment mortality rate constant of age j individuals during week i in region k (units: per day).

The instantaneous entrainment mortality rate, E_{ijk}, is a function of the amount of water withdrawn by power plants in region k, as well as a function of the susceptibility of age j individuals to withdrawal and of subsequent mortality due to plant passage. This function can be expressed mathematically as follows:

$$E_{ijk} = \frac{P_{ik}F_{ijk}}{V_{ik}} \tag{4C}$$

where P_{ik} = volume of water withdrawn by power plants in region k per day during week i,

V_{ik} = average water volume of region k during week i, and

F_{ijk} = entrainment vulnerability of age j fish during week i in region k.

The entrainment vulnerability factor, F_{ijk}, is the product of the fraction of organisms killed due to plant passage and the ratio of average power plant intake concentration to average regional concentration:

$$F_{ijk} = f_{ijk}W_{ijk} \tag{4D}$$

where f_{ijk} = fraction of age j fish killed due to plant passage during week i in region k, and

W_{ijk} = ratio of the average power plant intake concentration to average regional concentration of age j fish during week i in region k.

A W-ratio of unity ($W_{ijk}=1$) implies that power plants located in the region are withdrawing the average regional concentration of individuals. This ratio must account for possible day-night differences in susceptibility of the individuals to withdrawal, as well as active intake avoidance and plant effluent recirculation. Note that the ratio is defined as zero for $j>J$.

The factor f in equation 4D needs to account for both direct and indirect mortality due to plant passage. Direct mortality is estimated using information concerning the proportion of live organisms in the intake vs discharge (Barnthouse et al. 1977). Indirect mortality due to plant passage may be manifested in such ways as increased vulnerability to predation and disease, inability to feed, or failure to reproduce upon attainment of sexual maturity.

Regions used in equation 4 should have a general homogeneity of habitat type and an adequate intensity and distribution of sampling. Equation 4 implicitly assumes the average cross-sectional density of individuals in a cohort is constant along the longitudinal axis during a given week. The volume of a region (V_{ik} in equation 4C) can be estimated from topographic maps using planimetry. Depending on the location of a power plant intake within a region, it may be appropriate to allocate a portion of the water withdrawn by the power plant (P_{ik} in equation 4C) to an adjacent region(s). In a tidal river or estuary, where the water itself actually moves in both directions along the longitudinal axis, the allocation of a power plant's withdrawal among several regions could be assumed to be directly related to the proportion of the tidal cycle period when water "belonging" to a region is in front of the plant. The total withdrawal flow of a power plant may therefore be distributed among more than one region according to these proportions.

To calculate the total number of individuals surviving to the first nonentrainable age (age J+1), equation 4 can be reformulated in the following manner:

$$N_I = \sum_{s=1}^{S} N_0 R_s \left\{ \prod_{j=0}^{J} \left[\sum_{k=1}^{K} D_{s+j,jk} e^{-(M_{s+j,jk}+E_{s+j,jk})t} \right] \right\} \qquad (5)$$

where N_0 = total number of eggs spawned,

N_I = number of individuals surviving to the first nonentrainable age,

$D_{s+j,jk}$ = proportion of the total standing crop of age j individuals during week s+j in region k,

$M_{s+j,jk}$ = instantaneous natural mortality rate constant of age j individuals during week s+j in region k (units: per day),

$E_{s+j,jk}$ = instantaneous entrainment mortality rate constant of age j individuals during week s+j in region k (units: per day),

s = week of spawning period,

S = total number of weeks in spawning period,

R_s = proportion of total eggs spawned during week s; thus

$$\sum_{s=1}^{S} R_s = 1 \qquad \text{and} \qquad R_s = \frac{N_{s,o}}{N_o} \qquad (5A)$$

where $N_{s,0}$ = number of eggs spawned in week s.

Note that the "i" subscript in equation 4, which accounts for calendar time during the entrainment period, is replaced by an "s+j" subscript in equation 5. This substitution is more descriptive of the relationship among the week of the spawning period, age, and calendar time; i = s+j.

If the instantaneous natural mortality rate, $M_{s+j,jk}$, is assumed equal for all regions and assumed not to be density-dependent, the total conditional entrainment mortality rate for the entrainment period can be derived from equation 5 in a manner similar to equation 2:

$$m_T = 1 - \frac{N_E}{N_0} = 1 - \sum_{s=1}^{S} R_s \left\{ \prod_{j=0}^{J} \left[\sum_{k=1}^{K} D_{s+j,jk} e^{-(E_{s+j,jk})t} \right] \right\} \qquad (6)$$

where N_E = total number of individuals alive at the end of the entrainment interval with the absence of natural mortality during the entrainment period, and

m_T = total conditional entrainment mortality rate.

Equation 6 is the mathematical basis of the ETM. Operation of the ETM, based on equation 6, is shown in Figure 2.

Obtaining the input data needed for the ETM, as listed in Figure 2, involves specifying geographic regions within the water body to define cohort distribution and movement characteristics during the entrainment period; obtaining estimates of physical factors (total water volume and power plant withdrawal flow rate in each region); calculating the distribution of cohorts among regions during each time step of the entrainment period; determining entrainment susceptibility in each region for each cohort in each time step and region; and determining an appropriate time step for the entrainment period. An appropriate time step should reflect the degree of detail available in the data and necessary to indicate changes in cohort distribution during the entrainment period. The ETM is most precise when the data depicting distributions are collected during a relatively short time span from all areas of the water body where the cohorts are present. In addition, it is assumed that sample abundance estimates are relative (although not necessarily absolute) indices of actual abundances and that the indices are comparable among all regions, i.e., sampling gear efficiency is equal among regions.

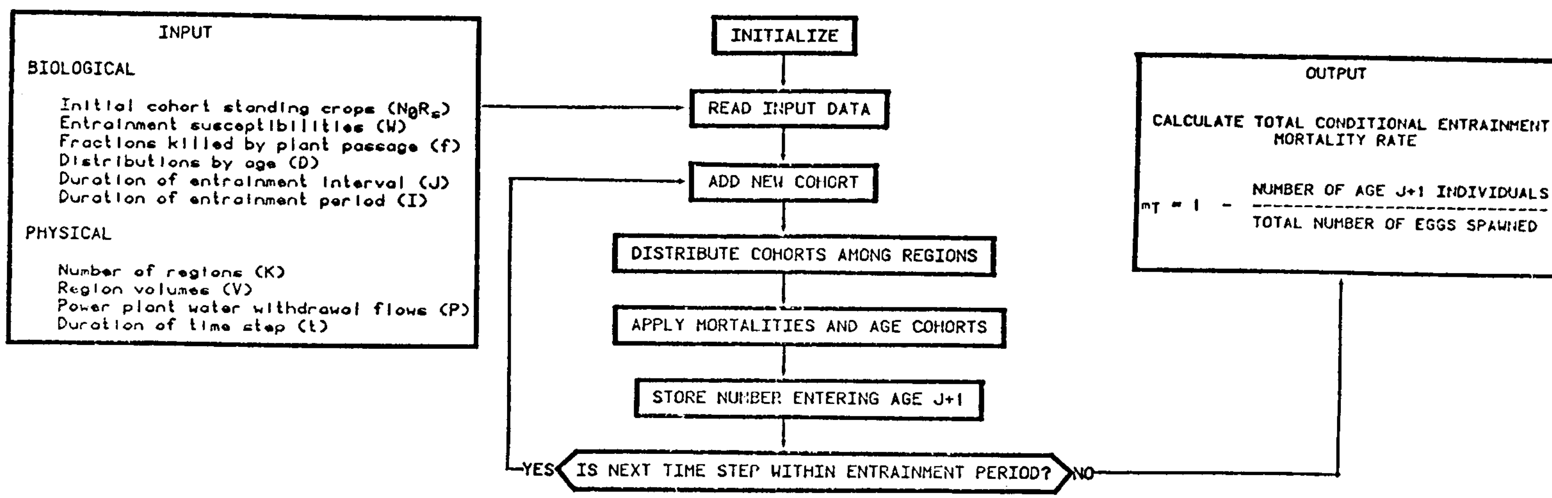

Figure 2. Schematic diagram of the Empirical Transport Model (ETM) based on equation 6. See text for explanation of symbols.

Three versions of equation 6 may be applied to field data to calculate the conditional entrainment mortality rate. The first version, or "Type I" ETM, requires spatial distribution and entrainment vulnerability data by age for each week of the entrainment season. This version is represented by equation 6.

A second version, or "Type II" ETM, can be used when time-dependent spatial distribution data are not available for each age j fish. This condition prevails when distribution data are categorized by life stage rather than age. The observed spatial distributions over the entire entrainment period can be averaged for each life stage, weighted by relative abundance. The resultant distribution represents what might be typical for the younger, more numerous members of each life stage. Using interpolation, organisms may, as they age, be "moved" from the distribution representing younger members of one life stage to the distribution representing younger members of the next life stage. The resultant parameter values can be used to calculate the conditional entrainment mortality rate by modifying equation 6 as follows:

$$m_T = 1 - \sum_{s=1}^{S} R_s \left\{ \prod_{j=0}^{J} \left[\sum_{k=1}^{K} D_{jk} e^{-(E_{s+j,jk})t} \right] \right\} \tag{7}$$

where D_{jk} = average proportion of the total standing crop of age j individuals in region k during the entrainment period.

A third version, or "Type III" ETM, collapses equation 6 temporally, such that all spawning occurs during the initial time step. This single cohort model approach can be used under the assumption that the spatial distribution and entrainment vulnerability of an age j fish does not vary with calendar time. The "Type III" ETM is expressed mathematically as follows:

$$m_T = 1 - \prod_{j=0}^{J} \left[\sum_{k=1}^{K} D_{jk} e^{-(E_{jk})t} \right] \tag{8}$$

where E_{jk} = average instantaneous entrainment mortality rate constant of age j individuals in region k during the entrainment period (units: per day).

Values for the parameters D_{jk} and E_{jk} are derived in the manner described for D_{jk} values in the "Type II" ETM.

Durations of entrainable life stages may be longer or shorter than the duration of a model time step. For these cases the input data, expressed as life stage values, may be adjusted to conform with ETM time steps. For the strict "Type I" ETM, no adjustment is necessary, since all parameters are specified on the basis of age. A situation may arise, however, where data specifying the D and E parameters were available on a life stage basis rather than an age basis, and a "Type II" ETM was somehow deemed inappropriate. In this situation, equation 6 could be modified as follows:

$$m_T = 1 - \sum_{s=1}^{S} R_s \left(\prod_{j=0}^{J} \left\{ \prod_{\ell=1}^{L} \left[\sum_{k=1}^{K} D_{s+j,k\ell} e^{-(E_{s+j,k\ell})C_{j\ell}t} \right] \right\} \right) \tag{9}$$

where ℓ = life stage 1,2,3,...,L,

L = total number of entrainable life stages,

$C_{j\ell}$ = fraction of age j individuals in life stage ℓ,

$D_{s+j,k\ell}$ = proportion of total standing crop of life stage ℓ individuals during week s+j in region k, and

$E_{s+j,k\ell}$ = instantaneous entrainment mortality rate constant of life stage ℓ individuals during week s+j in region k (units: per day).

For example, if eggs require 4 days to hatch and larvae last 13 days, $C_{1,1}$ would equal 4/7, $C_{1,2}$ would equal 3/7, and $C_{1,3}$, $C_{1,4}$, etc., would all equal zero; $C_{2,1}$ would equal zero, $C_{2,2}$ would equal 1, and $C_{2,3}$, $C_{2,4}$, etc., would all equal zero; and so on.

For the "Type II" ETM, the same principle applies. The notation would be as follows:

$$m_T = 1 - \sum_{i=1}^{S} R_s \left(\prod_{j=0}^{J} \left\{ \prod_{\ell=1}^{L} \left[\sum_{k=1}^{K} D_{k\ell} e^{-(E_{s+j,k\ell})C_{j\ell}t} \right] \right\} \right) \tag{10}$$

where $D_{k\ell}$ = average proportion of total standing crop of life stage ℓ individuals in region k during the entrainment period.

Here, the D values have been converted to region- and age-specific values from region- and life stage-specific values by using interpolation.

Finally, the temporally collapsed "Type III" ETM is expressed as:

$$m_T = 1 - \prod_{j=0}^{J} \left\{ \prod_{\ell=1}^{L} \left[\sum_{k=1}^{K} D_{k\ell} e^{-(E_{k\ell})C_{j\ell}t} \right] \right\} \tag{11}$$

where $E_{k\ell}$ = average instantaneous entrainment mortality rate constant for life stage ℓ individuals in region k (units: per day).

Since all spawning occurs during one week in this version of the ETM, the R_s term, as well as the "s+j" subscripts, are dropped in equation 11.

APPLICATION OF THE ETM TO A HYPOTHETICAL SET OF DATA

Hypothetical data representing a possible estuarine situation are presented in this section to illustrate how the ETM (equation 7) may be applied to estimate the conditional entrainment mortality rate of a fish population. Techniques for translating field data to ETM input parameter values, as well as associated assumptions and limitations, are also presented.

PHYSICAL DATA

A hypothetical estuary 100 km long is under consideration for the future siting of five steam-electric power plants. Plant A will be sited 40 km from the mouth of the estuary (kilometer point 40) and will withdraw an average of 3,000 thousand cubic meters per day (3,000 TCM/day) of water from the estuary for condenser cooling purposes. Plant B will be sited at kilometer point 45 and will also withdraw water at a rate of 3,000 TCM/day. Plants C and D will be sited on opposite banks of the estuary at kilometer point 65, and will withdraw water at rates of 3,000 and 6,000 TCM/day, respectively. Operators of Plant D have promised to reduce the water withdrawal rate by 50 percent 5 weeks after the beginning of the entrainment period for the fish population of concern in this example. Plant E will withdraw water at a rate of 3,000 TCM/day and will be sited at kilometer point 75.

The hypothetical estuary was divided into 10 geographic regions, each 10 km in length, for the purposes of this study. Figure 3 shows the locations of the regions and the proposed sites for the five power plants. The volume of each region and associated power plant withdrawal flow rates are listed in Table 1. Plant A, which will be located on the boundary separating regions 4 and 5, will withdraw half of its cooling water from each region. All other plants will withdraw water from a single region. It is assumed that the region water volumes will remain constant throughout the entrainment period.

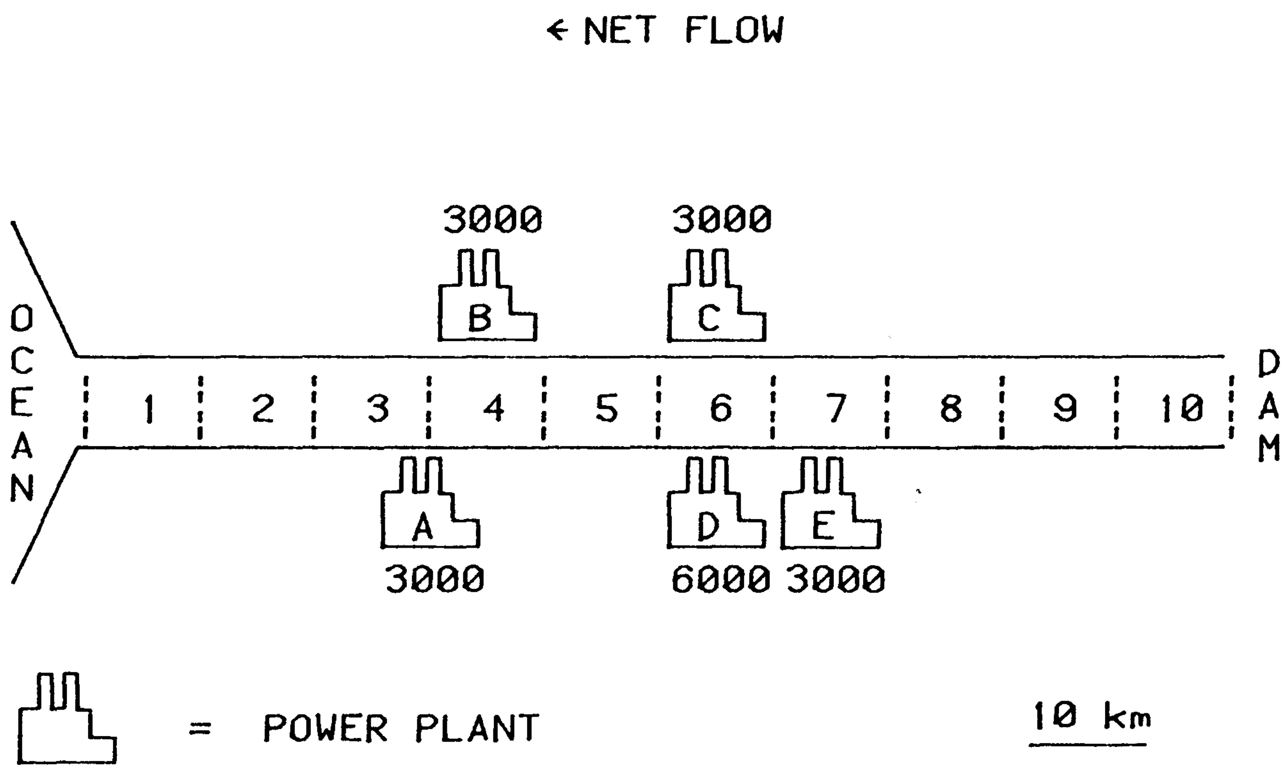

Figure 3. Hypothetical estuary showing locations of five proposed power plants (A-E) and their cooling water withdrawal flow rates, expressed as $1000 m^3$/day (TCM/day). Physical characteristics are listed in Table 1.

Table 1. Water volumes and power plant water withdrawal flow rates in thousands of cubic meters per day (TCM/day) for each region of a hypothetical estuary. Each region is 10 km in length.

Region	Volume ($1{,}000 m^3$)	Plant withdrawal flow rates (TCM/day)					Total plant withdrawal (TCM/day)
		A	B	C	D	E	
1	400,000	0	0	0	0	0	0
2	380,000	0	0	0	0	0	0
3	360,000	1,500	0	0	0	0	1,500
4	340,000	1,500	3,000	0	0	0	4,500
5	320,000	0	0	0	0	0	0
6	300,000	0	0	3,000	6,000[a]	0	0
7	280,000	0	0	0	0	3,000	3,000
8	260,000	0	0	0	0	0	0
9	240,000	0	0	0	0	0	0
10	220,000	0	0	0	0	0	0

[a]reduced to 3,000 TCM/day after 5 weeks of the entrainment period.

BIOLOGICAL DATA

Sampling was conducted on a weekly basis throughout the time of year when potentially entrainable life stages of the fish population were present in the estuary. The specific sampling design employed is beyond the scope of this paper. Two weekly sampling programs were conducted: (1) a general survey of the entire estuary intended to estimate the average life stage densities in each region; and (2) within each region containing proposed power plant sites, a transect survey in the vicinity of each proposed power plant intake location, using the same sampling gear, to determine probable relative intake concentrations of each entrainable life stage. The results of these surveys are presented in Appendix A and summarized in Tables 2 and 3. Table 2 presents the estimated total standing crop by week for each entrainable life stage, summed over regions, and Table 3 presents the estimated total standing crop in each region for each entrainable life stage, summed over the entrainment period. Region standing crops were derived by multiplying the average life stage density by the respective region volume (listed in Table 1). Table 4 summarizes the transect survey data listed in Appendix B.

Studies on the fish species used in this example were conducted at an existing power plant in a nearby estuary to determine mortality due to plant passage. The results of those studies, expressed as the proportion of each entrainable life stage surviving in intake and discharge samples, are listed in Table 5. It is assumed that the mortality rates derived from those studies are directly applicable to the fish population inhabiting the hypothetical estuary.

ETM INPUT PARAMETER VALUES

Input parameter values for a "Type II" ETM (equation 7) can be derived from information presented in Tables 1-5. Symbols used in the following discussion are as defined in the previous section.

Table 2. Estimated total standing crop ($\times 10^{-6}$), by week, of early life stages of a fish population inhabiting a hypothetical estuary. Based on data presented in Appendix A.

Sample week	Eggs	Larvae	Entrainable juveniles	Nonentrainable juveniles
1	150	0	0	0
2	200	30	0	0
3	300	52	0	0
4	200	76	7.2	0
5	150	64	15.5	0
6	0	46	22.1	5.2
7	0	12	21.1	11.6
8	0	0	14.9	16.6
9	0	0	5.7	16.3

Table 3. Estimated total standing crop ($x10^{-6}$), by region, of early life stages of a fish population inhabiting a hypothetical estuary, summed over sample weeks. Based on data presented in Appendix A.

Life stage	Region 1	2	3	4	5	6	7	8	9	10	Total
Egg	0	0	50.0	150.0	200.0	300.0	200.0	150.0	0	0	1,000.0
Larva	0	28.0	42.0	70.0	70.0	42.0	21.6	7.0	0	0	280.0
Entrainable juvenile	0	17.3	25.9	17.3	17.3	8.6	0	0	0	0	86.4
Nonentrainable juvenile	0	14.9	14.9	9.9	9.9	0	0	0	0	0	49.7

Table 4. Estimated average entrainable life stage densities (No. per 10^4 m^3) in areas of proposed power plant intakes compared to average densities for the respective regions. Based on data presented in Appendices A and B.

Life stage	Estimate	Region 3	Region 4	Region 6	Region 7
Egg	Intake	138.90	441.20	666.70[a]	535.70
	Region	277.80	882.40	1,666.70	892.90
	Ratio	0.50	0.50	0.40	0.60
Larva	Intake	11.67	20.59	18.67[a]	9.99
	Region	19.45	34.32	23.34	12.49
	Ratio	0.60	0.60	0.80	0.80
Entrainable juvenile	Intake	10.80	7.62	3.36[a]	0
	Region	12.00	8.47	4.80	0
	Ratio	0.90	0.90	0.70	-

[a]Average of Plants C and D intake densities.

Table 5. Results of entrainment mortality studies conducted on the fish species at an operating power plant in a nearby estuary. Number of alive eggs determined by hatching success. Numbers of live larvae and juveniles represent 96-hr survival after sampling.

Life stage	Intake			Discharge			f^a
	Alive	Dead	Total	Alive	Dead	Total	
Egg	1,825	205	2,030	551	992	1,543	0.60
Larva	580	145	725	164	518	682	0.70
Entrainable juvenile	344	86	430	66	349	415	0.80

$$^{a}f = 1 - \frac{\text{(Proportion alive in discharge samples)}}{\text{(Proportion alive in intake samples)}}$$

Time Step, Entrainment Period, and Entrainment Interval

The weekly sampling schedule implies that an appropriate time step (t in equation 7) is 7 days. The ETM requires that time steps be of equal duration throughout the entrainment period, which is defined as the time period entrainable life stages are present in the water body. Based on information provided in Table 2, the entrainment period for the fish population inhabiting the hypothetical estuary was 9 weeks. Therefore, the ETM has nine time steps (I=9).

Data summarized in Table 2 indicate that eggs were present in field samples during the first 5 weeks of the entrainment period. Based on a 5-week spawning period and 9-week entrainment period, the entrainment interval is 5 weeks (J=5).

Egg Deposition Rate

The egg deposition rate, which is equal to the proportion of total eggs spawned during a given week (R_s), can be derived from information presented in Table 2 using equation 5B. ETM egg deposition rate input parameter values are listed in Table 6. The value of R_s equals 0 for weeks subsequent to the spawning period.

Life Stage Durations

In most situations, field data will not be specific enough to determine movement patterns and entrainment vulnerability for each cohort for every time step during the entrainment period. The ability to do so would require classifying individuals collected in field samples according to age (in weeks for this example). Individuals are usually classified by life stage, and each life stage may contain several ages. Since the ETM requires age-specific distribution and entrainment vulnerability values, conversion of life stages to ages is necessary to

Table 6. Estimated total standing crop of eggs sampled each week ($N_{s,0}$ in equation 5B) during the entrainment period of a fish population inhabiting a hypothetical estuary.

Week (s)	$N_{i,0}$ ($\times 10^{-6}$)	R_s[a]
1	150	0.15
2	200	0.20
3	300	0.30
4	200	0.20
5	150	0.15
N_0 =	1,000	

[a] $R_s = \frac{N_{s,0}}{N_0}$

derive these values. Such a conversion requires knowledge of life stage durations.

In laboratory studies using simulated ambient water temperatures present in the hypothetical estuary during the predicted entrainment period, entrainable life stages were raised from eggs taken from spawning adults of the fish population. The following life stage durations were determined:

Life Stage	Duration (weeks)
Egg	1
Larva	2
Entrainable Juvenile	2

Total duration of the entrainable life stages, therefore, was 5 weeks, which corresponds to the previous estimate of the entrainment interval (J). Furthermore, the time periods between peak standing crops of each life stage (Table 2) support life stage durations derived by the laboratory studies. These durations represent "average" values. Under natural conditions the development rate of an individual will be dependent upon a variety of physical and biological factors, including water temperature, chemical properties of the water, and food availability.

Distribution and Movement

As previously stated, distribution data for the fish population inhabiting the estuary is classified by life stage (Appendix A). Conversion of life stage distributions to distributions by age is necessary to derive the ETM proportional distribution input parameter values (D_{jk} in equation 7). The average proportional distribution of eggs among regions (Table 3) can be converted directly to the proportional distribution of age j=1 individuals, since the average duration of the egg stage is 1 week.

Derivation of proportional distributions for ages $j>1$ is complicated by two factors: life stage durations for larvae (2 weeks) and entrainable juveniles (2 weeks) are greater than the ETM time step (1 week), and life stage distribution data represented by field samples are probably weighted toward the younger, more numerous individuals in that life stage.

Based on these factors, proportional distribution input parameter values (D_{jk}) for ages $j>1$ were derived in the following manner from information presented in Table 3. The proportional distributions of age $j=2$ and age $j=3$ individuals are assumed to be equal to the average proportional distribution of larvae collected in field samples even though the field samples may be biased in favor of the younger individuals in that life stage. Proportional distributions for age $j=4$ and $j=5$ individuals in week i were assumed equal to the average proportional distribution of entrainable juveniles. Because average life stage distributions were used in these derivations, the proportional distributions by age were assumed equal for all cohorts, i.e., D_{jk} values are independent of the calendar week during which a cohort was spawned. As noted previously, this conforms to a "Type II" ETM. The resultant D_{jk} values used as ETM input are listed in Table 7.

Instantaneous Entrainment Mortality Rates

As indicated in equations 4C and 4D, several parameter values are necessary to derive the instantaneous entrainment mortality rates (E_{ijk} in equation 6). These values include region volumes (V_{ik} in equation 4C), total power plant water withdrawal rates for each region (P_{ik} in equation 4C), the probability of mortality due to plant passage (f_{ijk} in equation 4D), and the ratio of average power plant intake concentrations to average regional concentrations (W_{ijk} in equation 4D). The latter two parameters comprise the entrainment vulnerability factor (F_{ijk} in equation 4C).

Table 7. Estimated proportion of age j individuals in each region of a hypothetical estuary (D_{jk} in equation 7), based on data summarized in Table 3.

Age (j)	Region									
	1	2	3	4	5	6	7	8	9	10
1	0	0	0.050	0.150	0.350	0.250	0.125	0.075	0	0
2	0	0.100	0.150	0.250	0.250	0.150	0.075	0.025	0	0
3	0	0.100	0.150	0.250	0.250	0.150	0.075	0.025	0	0
4	0	0.200	0.300	0.200	0.200	0.100	0	0	0	0
5	0	0.200	0.300	0.200	0.200	0.100	0	0	0	0
6	0	0.300	0.300	0.200	0.200	0	0	0	0	0

Region volumes and total power plant withdrawal flow rates for each region can be obtained from information presented in Table 1. Entrainment vulnerability data are presented in Tables 4 and 5 for entrainable life stages; these data must be converted to age-specific values for incorporation into the ETM.

The technique for conversion of data in Tables 4 and 5 to age-specific entrainment vulnerability values is similar to the technique used in conversion of life stage distributions to age-specific distributions. Age j=1 intake/region concentration ratios (W_{ijk} in equation 4D) and mortality due to plant passage (f_{ijk} in equation 4D) are assumed equal to the values presented for eggs in Tables 4 and 5, respectively. Values presented for larvae are used for age j=2 individuals, and age j=3 values are the average of larval and entrainable juvenile estimates. Entrainable juvenile estimates are used for ages j=4 values. The mortality due to plant passage for j=5 individuals is assumed to be equal to the entrainable juvenile estimates, and the intake/region concentration ratio for j=5 fish equals the average of entrainable juvenile and non-entrainable juvenile estimates. The resultant entrainment vulnerability values used as ETM input are listed in Table 8.

RESULTS

Using the selected input values for equation (7), the total conditional entrainment mortality rate for the hypothetical fish population is 12.5 percent over the 9-week entrainment period. ETM output is shown graphically in Figure 4. Conditional entrainment mortality rates that will be imposed by individual plants are listed in Table 9. These rates are influenced by distribution of the entrainable life stages and power plant water withdrawal flow rates. For example, Plants B and E will withdraw the same amount of water per day, yet the mortality imposed by Plant B will be over four times greater than Plant E. The higher mortality rate associated with Plant B is due to its location in the

Table 8. Estimated entrainment vulnerability factors (F_{ijk} in equation 4C), based on estimates of mortality due to plant passage (f_{ijk} in equation 4D) from Table 5 and ratios of intake to region densities (W_{ijk} in equation 4D) from Table 4, for age j individuals of a fish population inhabiting a hypothetical estuary.

Age (j)	Region (k)	f_{ijk}	W_{ijk}	F_{ijk} [a]
1	3	0.60	0.50	0.30
	4	0.60	0.50	0.30
	6	0.60	0.40	0.24
	7	0.60	0.60	0.36
2	3	0.70	0.60	0.42
	4	0.70	0.60	0.42
	6	0.70	0.80	0.56
	7	0.70	0.80	0.56
3	3	0.70	0.60	0.42
	4	0.70	0.60	0.42
	6	0.70	0.80	0.56
	7	0.70	0.80	0.56
4	3	0.80	0.90	0.72
	4	0.80	0.90	0.72
	6	0.80	0.70	0.56
	7	0.80	-	-
5	3	0.80	0.90	0.72
	4	0.80	0.90	0.72
	6	0.80	0.70	0.56
	7	0.80	-	-

[a] $F_{ijk} = f_{ijk} W_{ijk}$

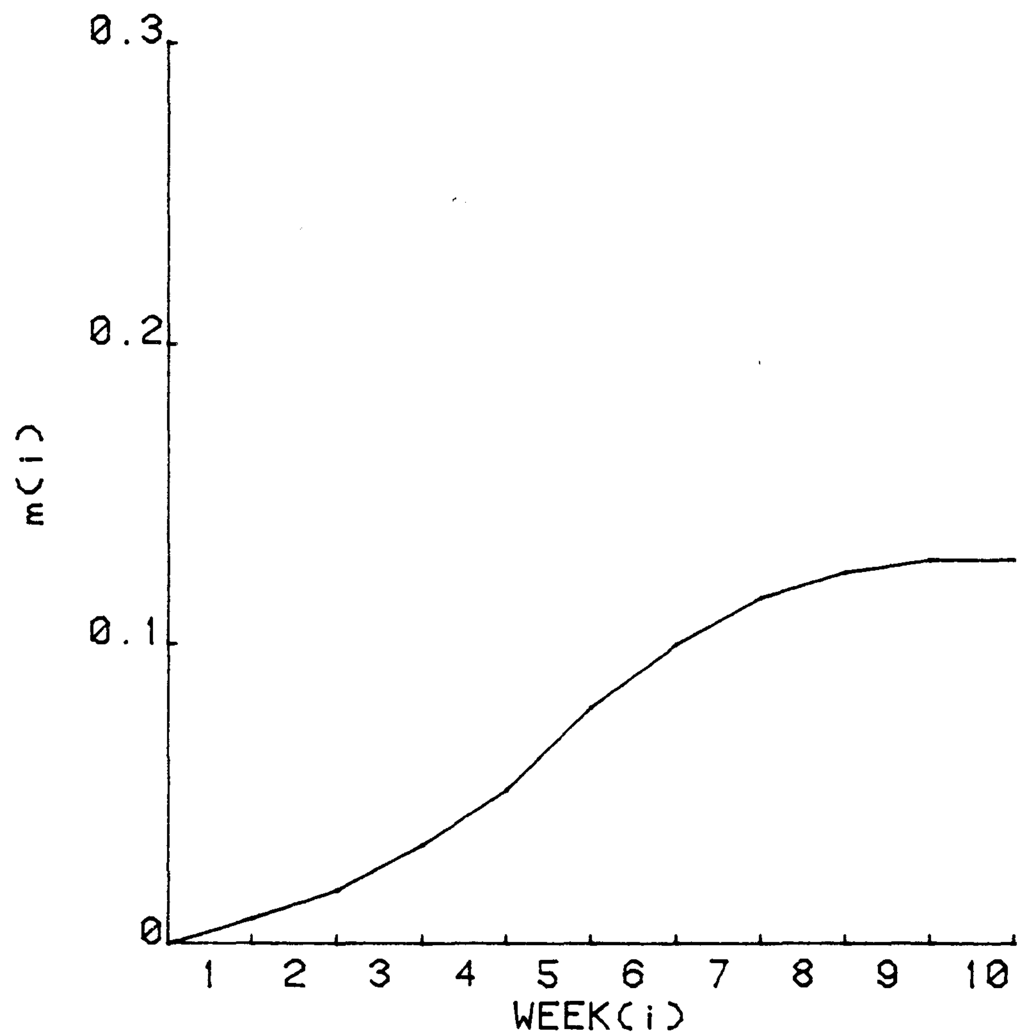

Figure 4. ETM estimates of the cumulative conditional entrainment mortality rate (m_i) during each week of the entrainment period of a fish population inhabiting a hypothetical estuary.

estuary, where a relatively higher standing crop of entrainable organisms occur over the 9-week entrainment period (Table 7). Plant D withdraws twice as much water per day as Plant C from region 6 during the first 5 weeks of the entrainment period, which explains the higher mortality imposed by Plant D.

The conditional mortality rate imposed by Plant D, if withdrawal flow will not be reduced by 50 percent in week 6, will be 0.7 percent higher (Table 9). This results in an increase in the total conditional entrainment mortality rate of 0.6 percent.

Incorporation of Natural Mortality

Standing crops of entrainable organisms during power plant operation can be simulated using equation 5, which incorporates natural mortality rates. To illustrate how this approach may be used, arbitrary age-specific natural mortality rates were chosen for the hypothetical fish population (Table 10). The natural mortality rates are assumed to be constant for each cohort and equal for all regions. The total number of eggs spawned (N_0 in equation 5) was set equal to 1×10^8.

The percent standing crop remaining during the 9-week entrainment period with vs without power plant operation is shown in Figure 5. The relative difference between the standing crop at the end of the ninth week with vs without power plants is 12.5 percent, as calculated in Table 9. The simulated actual standing crop during each week of the entrainment period is presented in Figure 6.

A schematic presentation of the standing crop of each entrainable life stage during the period that life stage appears in field samples is shown in Figure 7. The older life stages show more of a difference in weekly standing crops with vs without power plant operation. However, the more numerous younger life stages tend to obscure this relationship

Table 9. Estimated conditional entrainment mortality rates that will be imposed on a fish population inhabiting the hypothetical estuary, based on equation 7. Values in parentheses represent no reduction in Plant D withdrawal flow during the entrainment period.

Plant	Rate (m_{Tp})
A	0.033
B	0.032
C	0.023
D	0.037 (0.045)
E	0.009
Combined[a]	0.128 (0.135)

[a] $m_T = 1 - \prod_{p=1}^{5} (1-m_{Tp})$

Table 10. Age-specific natural mortality rates ($M_{s+j,jk}$ in equation 5) chosen for the entrainment interval of a fish population inhabiting a hypothetical estuary. Rates are assumed constant for each cohort and equal for all regions ($M_{s+j,jk} = M_j$).

Age (j)	Mortality (M_j)	
	per week	per day
1	0.8	0.22992
2	0.6	0.13090
3	0.4	0.07298
4	0.2	0.03188
5	0.1	0.01505

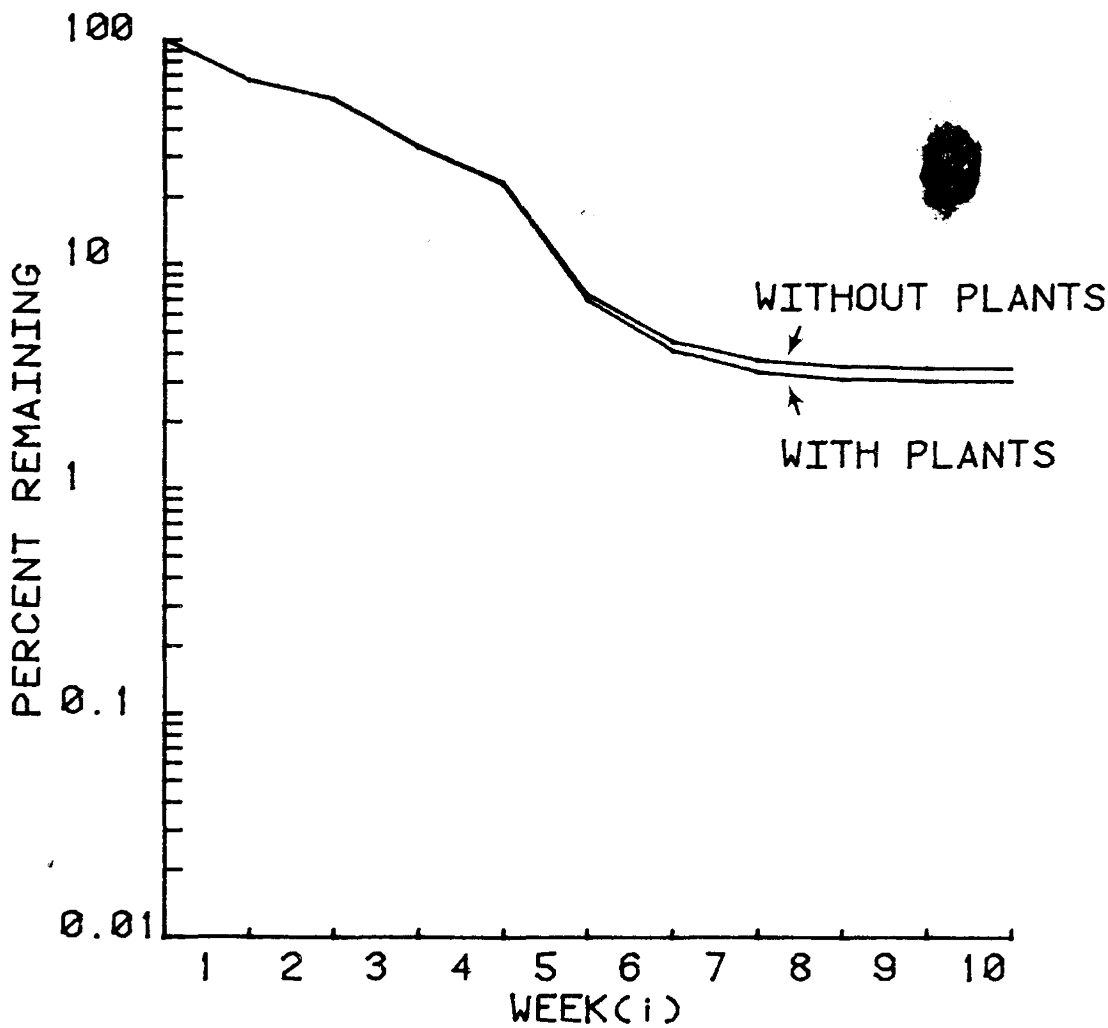

Figure 5. ETM estimates of the percent of the total egg production remaining after each week of the entrainment period, with and without power plants operating.

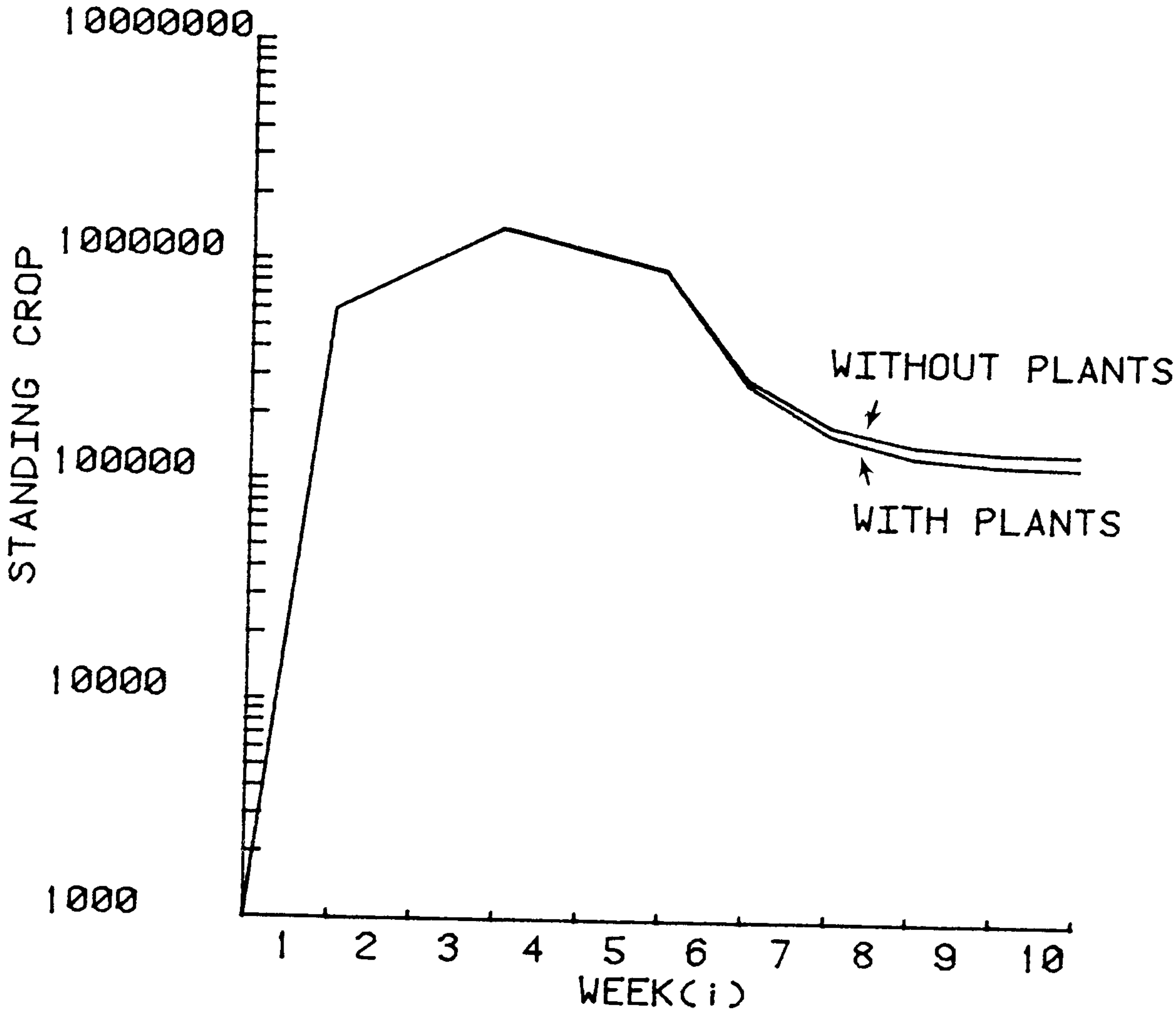

Figure 6. ETM estimates of the weekly standing crop of ichthyoplankton remaining after each week of the entrainment period, with and without power plants operating.

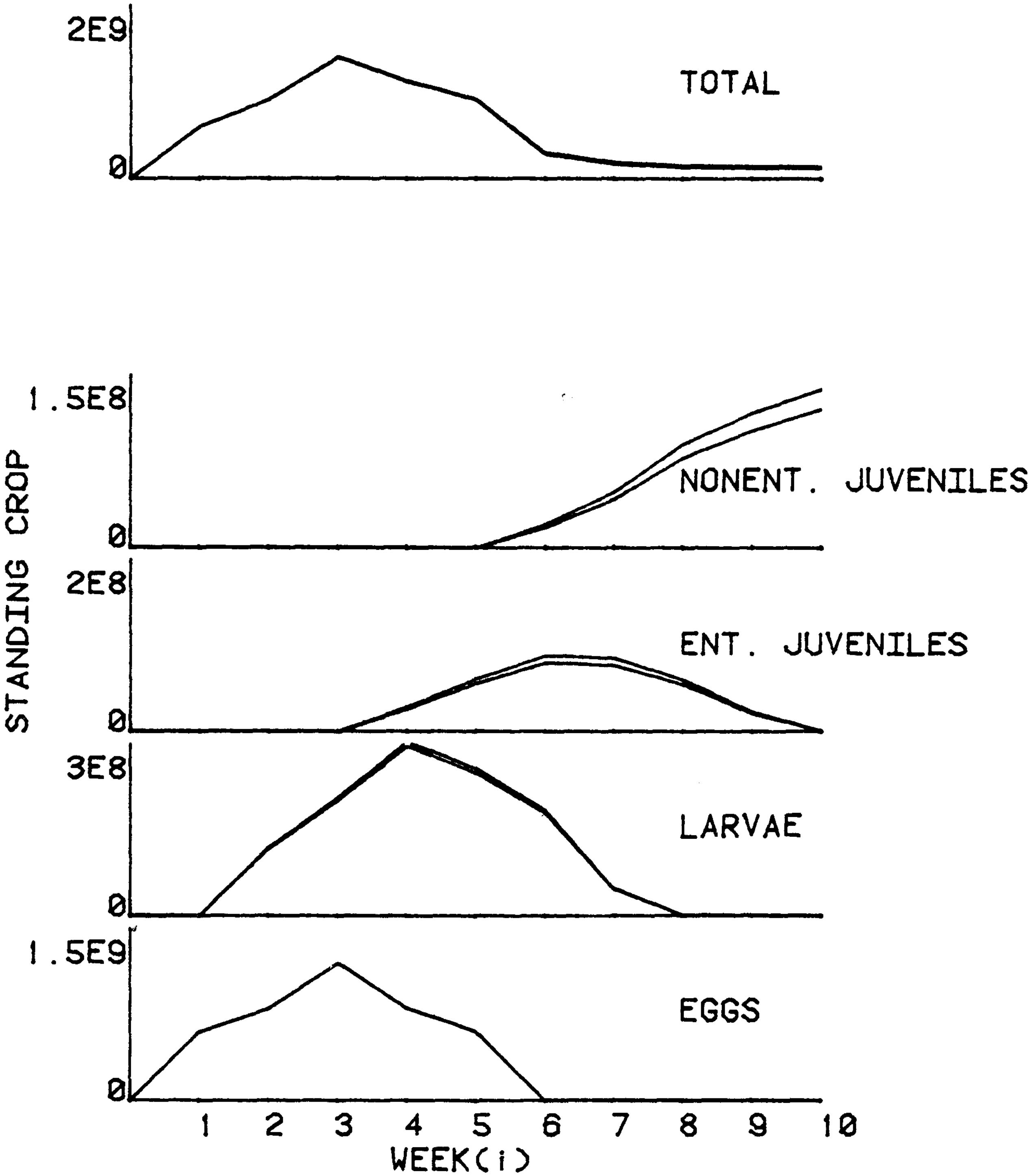

Figure 7. ETM estimates of the early life stage standing crops remaining after each week of the entrainment period. Upper line in each graph represents conditions with no power plants operating and the lower line reflects conditions with power plants operating. Graphs with one line indicate no detectable difference between the two conditions as presented on these graphs.

if life stage standing crops are combined each week, as is evidenced by the "total" plot in Figure 6. Power plant entrainment effects should be measured by the reduction in standing crop of recruits to the first non-entrainable life stage, rather than by the reduction in total standing crop measured during the entrainment period.

SENSITIVITY ANALYSES

Relatively small changes in an input parameter value may cause relatively substantial changes in mathematical model output values. When this occurs, the model is described as "sensitive" to that input parameter. This section presents sensitivity analyses of the physical and biological input parameters of the ETM (as listed in Figure 1). For each ETM input parameter analyzed, ETM runs were made on a range of values while all other input parameter values were held constant. Each value of the proportional distribution of cohorts among regions ($D_{s+j,jk}$ in equation 6) was set equal to (number of regions)$^{-1}$, and the entrainment vulnerability factor (F_{ijk} in equation 4D) was set equal to 1.0. Unless otherwise indicated, runs were based on a "Type III" ETM (equation 8), using a 5-week entrainment period (I=J).

PHYSICAL INPUT PARAMETERS

Number of Regions

The number of geographic regions within the hypothetical estuary (K in equation 8) was varied between 1 and 30. Power plant withdrawal flow from region 1 was set equal to 1 x 10^4 TCM/day. All other regions had no power plant withdrawal flows. Results, shown in Figure 8, indicate that the calculated conditional entrainment mortality rate gradually decreased as the number of regions increased, or (viewed in another way) as a larger proportion of each cohort was located in regions without power plant withdrawal. This result occurs because there is no exchange

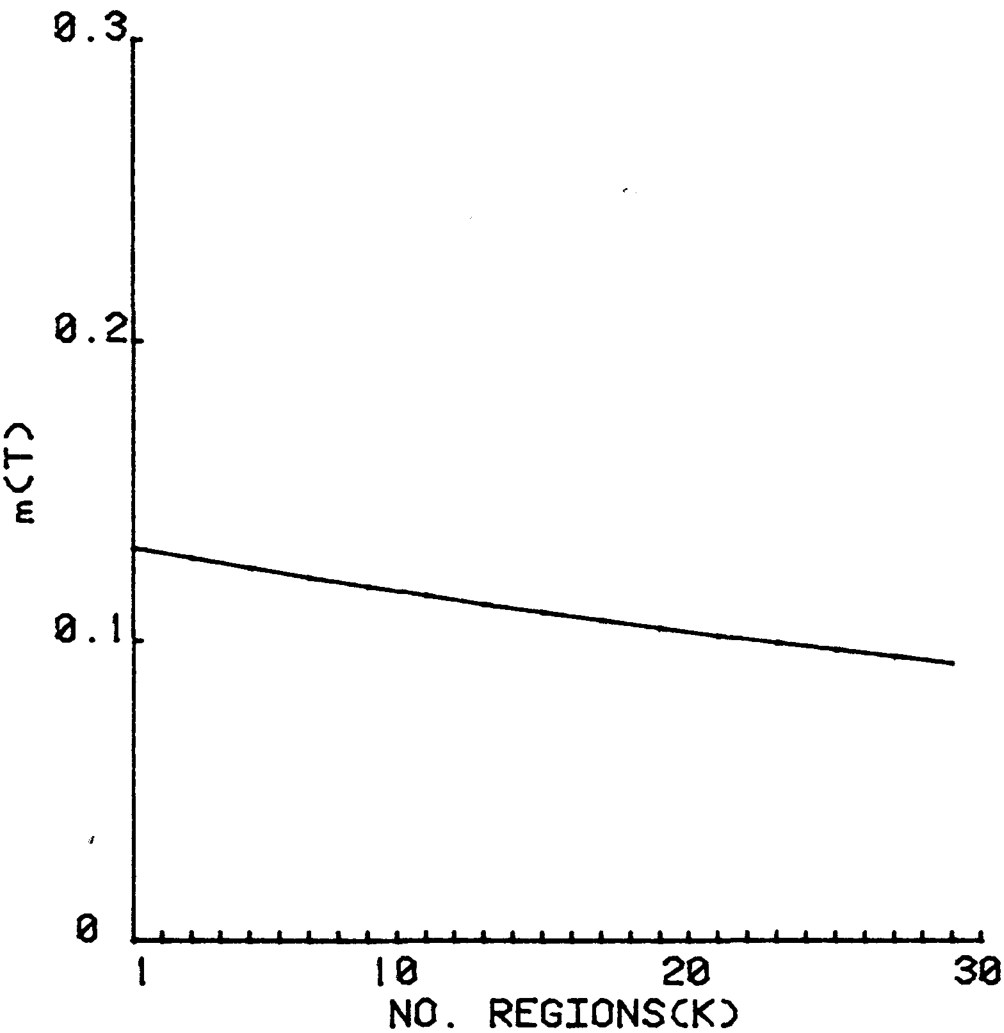

Figure 8. ETM conditional entrainment mortality rate (m_T) estimates with the total number of regions within the hypothetical estuary varied between 1 and 30.

of organisms regions within a model time step. Therefore, when region size is small, the population of entrainable organisms inhabiting the region from which the power plant withdraws water can become more depleted. When this happens, a smaller number are killed later in the time step.

Power Plant Withdrawal Flows

Withdrawal flows of the five power plants (P_{ik} in equation 4C) were varied between 0-5X the baseline rates. Resulting conditional entrainment mortality rate estimates are plotted in Figure 9. As power plant withdrawal flows increased, the conditional entrainment mortality rate increased, but with a continuously decreasing slope.

BIOLOGICAL INPUT PARAMETERS

Temporal Distribution of Spawning

The ETM was run with spawning period lengths of 1 to 5 weeks; an equal number of eggs were recruited each week of the spawning period. Different temporal distributions of egg recruitment (skewed early and skewed late) over a 5-week spawning period were also analyzed. Temporal distributions used in the analysis are presented in Table 11.

Variation in length of the spawning period caused no change in the total conditional entrainment mortality rate after 10 weeks when power plant flows remained constant throughout the entrainment period (Figure 10A). A 50 percent reduction in the water withdrawal flow of Plant D after 5 weeks of the entrainment period produced different final mortality estimates for each spawning period length. The final estimate decreased as spawning period length increased (Figure 10B), because more cohorts were exposed to the reduced withdrawal of Plant D as the spawning period length increased.

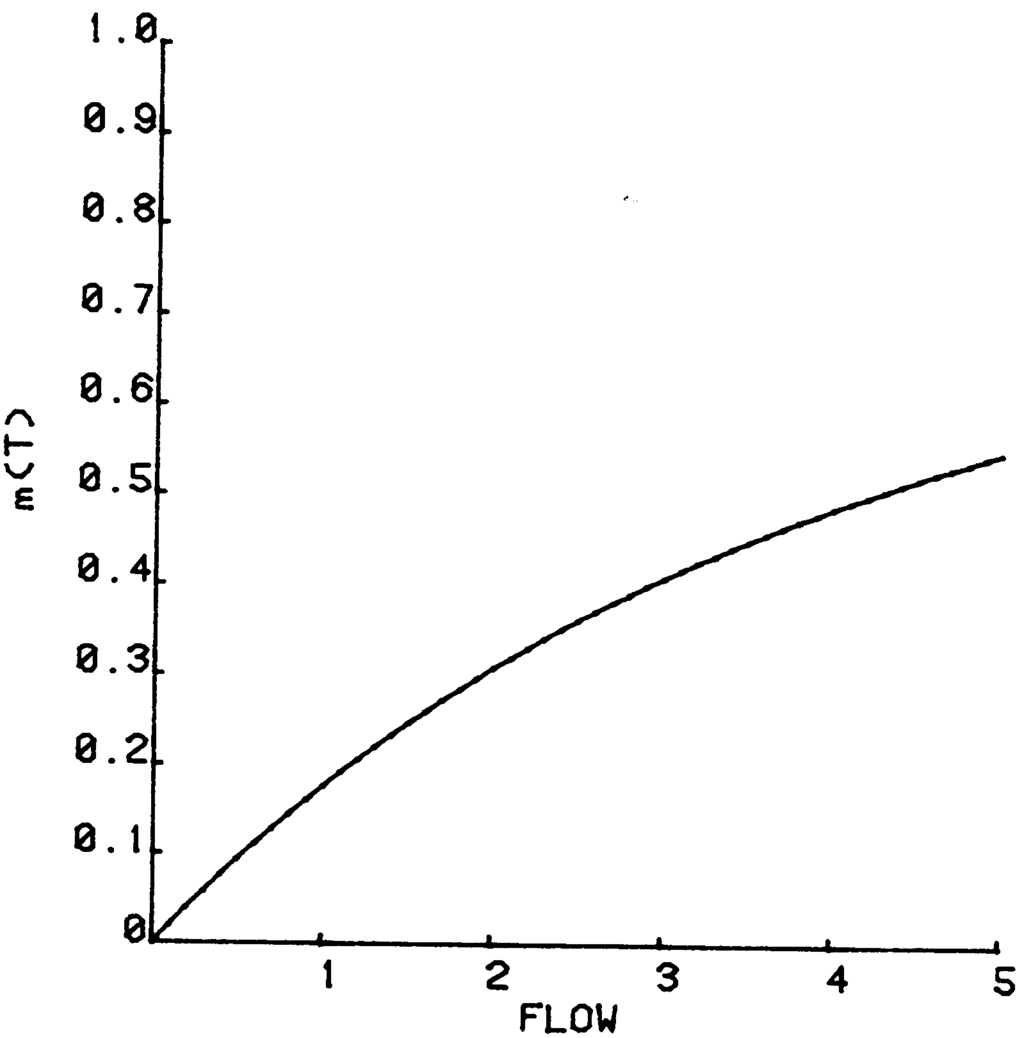

Figure 9. ETM conditional entrainment mortality rate (m_T) estimates with the power plant water withdrawal flows varying between 0-5X the baseline flow conditions listed in Table 1.

Table 11. Temporal distributions of egg recruitment used for sensitivity analysis of the ETM.

Distribution	Week(s) 1	2	3	4	5
Uniform	0.200	0.200	0.200	0.200	0.200
Skewed (early)	0.516	0.258	0.129	0.065	0.034
Skewed (late)	0.034	0.065	0.129	0.258	0.516

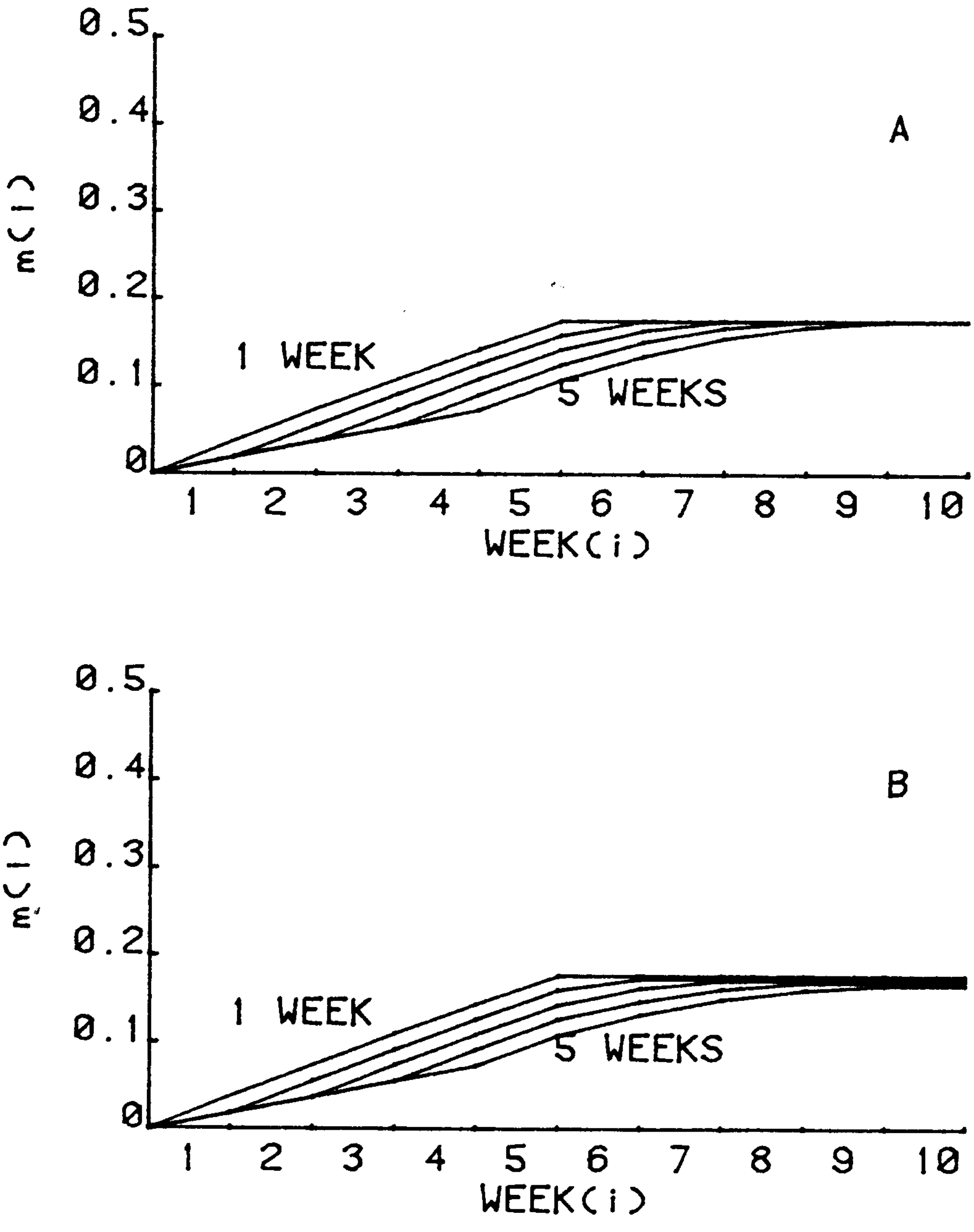

Figure 10. ETM conditional entrainment mortality rate (m_i) estimates with varying spawning period lengths of 1 to 5 weeks. A = constant power plant water withdrawal flows during the entrainment period; B = 50 percent reduction in Plant D water withdrawal flow after 5 weeks of the entrainment period. Temporal distribution of spawning is uniform.

As with length of the spawning period, different temporal distributions of egg recruitment resulted in the same conditional mortality rate estimate when power plant flows remained constant throughout the entrainment period (Figure 11A). Reduction of the withdrawal flow by Plant D after 5 weeks reduced the mortality rates in all runs where temporal distribution of spawning was varied. Temporal spawning distributions having a greater number of eggs recruited later in the spawning period had less of a reduction than the runs representing a greater number of eggs recruited earlier in the spawning period (Figure 11B). Thus, variation in power plant water withdrawal flows during the entrainment period affects the final conditional entrainment mortality estimate in a manner that depends on the length of the spawning period and temporal distribution of egg recruitment during the spawning period.

Distribution of Organisms among Regions

Three model runs were used to test sensitivity of the ETM to spatial distribution of the entrainable life stage (D_{jk} in equation 8). One run inverted the regional distribution of organisms presented in Table 7, i.e., region 10's organisms were placed in region 1, region 9's organisms were placed in region 2, and so on; power plants were not moved. The second run held all organisms for the 5 weeks in the regions where they occurred during the first week (no movement), and the third run (representing the reference conditions for this section on sensitivity analyses) incorporated a uniform spatial distribution of the life stages in the estuary during the entire entrainment period.

ETM output for the three model runs, compared to output using the original input parameter values listed in Table 7, is shown in Figure 12. The situation of no movement resulted in the highest conditional entrainment mortality estimate. This occurred because, in the hypothetical example, age 1 organisms were concentrated in the regions where power plants were located. Mortality estimates using the uniform and

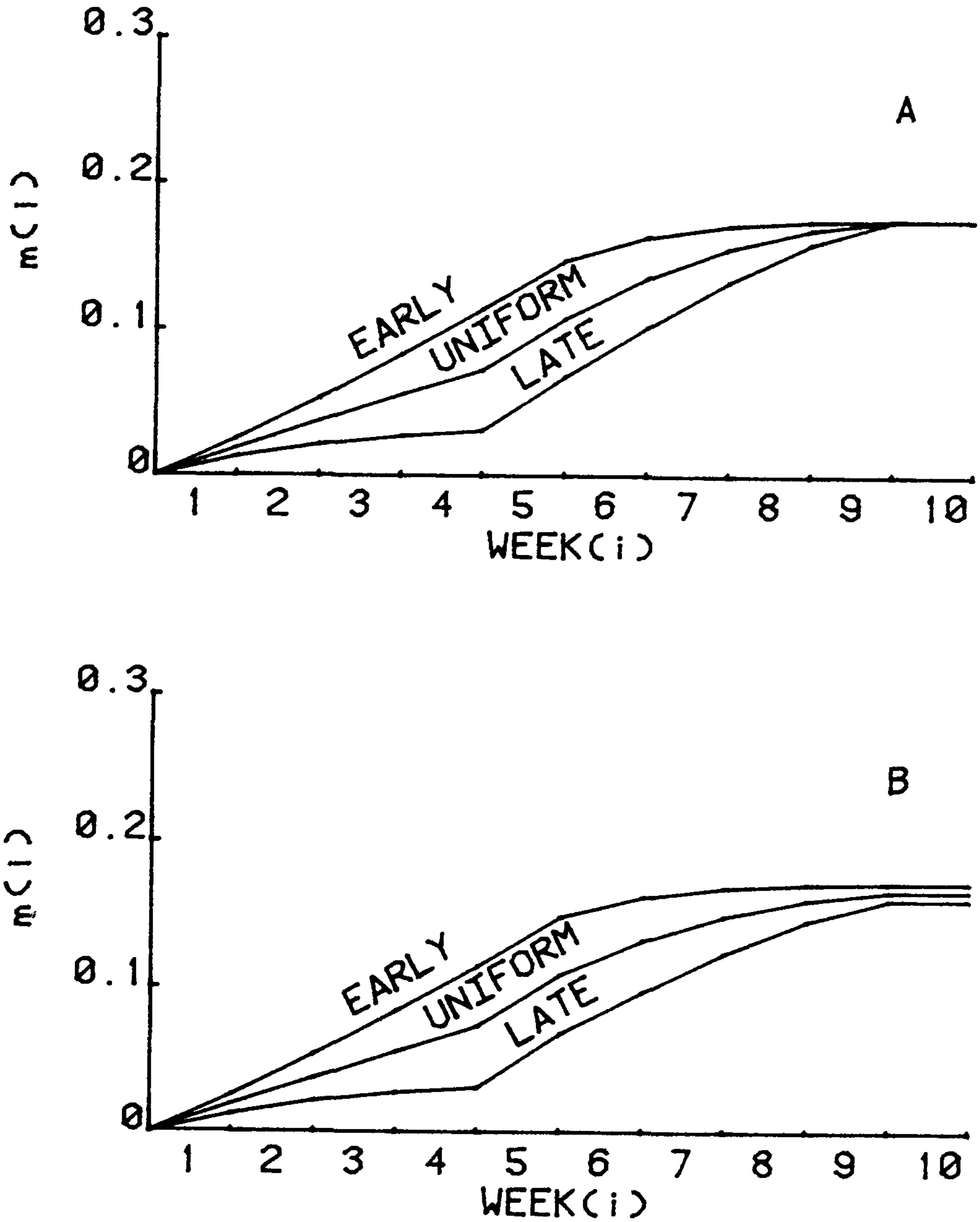

Figure 11. ETM conditional entrainment mortality rate (m_i) estimates with different temporal distributions of egg recruitment (Table 11) during the 5-week spawning period. A = constant power plant water withdrawal flows during the entrainment period; B = 50 percent reduction in Plant D water withdrawal flow after 5 weeks of the entrainment period.

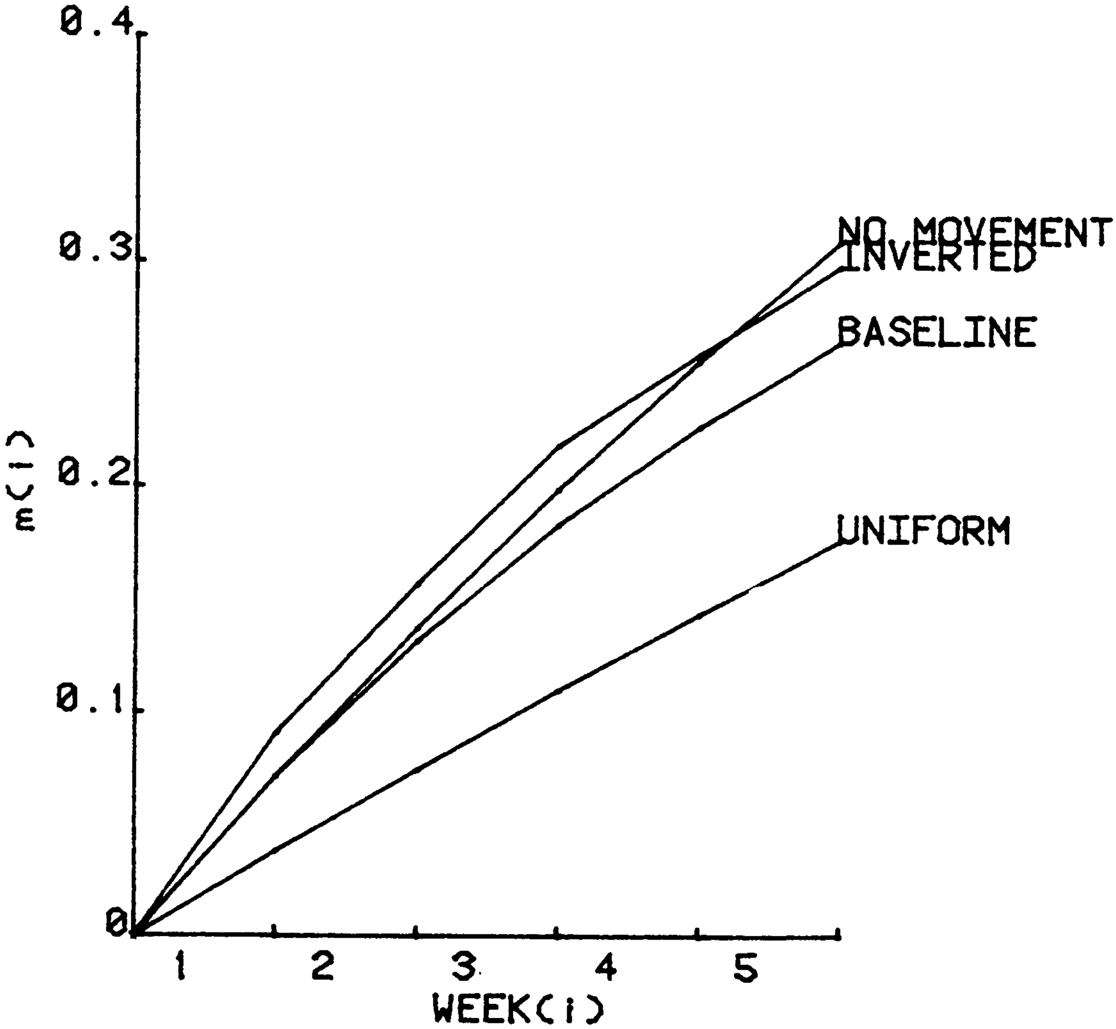

Figure 12. ETM conditional entrainment mortality rate (m_i) estimates with varying spatial distributions of the entrainable life stages.

inverted spatial distribution values were lower than the estimate using the baseline values.

Entrainment Vulnerability

The average power plant intake concentration, average regional concentration, and mortality due to plant passage are accounted for in the ETM by the entrainment vulnerability factor (F_{ijk} in equation 4D). The range of conditional entrainment mortality rates with the entrainment vulnerability factor held constant for all life stages at values between 0 and 10 at all plants is shown graphically in Figure 13. The conditional rate appears to approach 100 percent more or less asymptotically as the F value is increased, i.e., as the ratio of intake to region concentration is increased and/or as plant passage kills a larger fraction of organisms. As expected, this result is similar to the result obtained when power plant withdrawal flows were varied (Figure 8), since F and P are multiplied together in equation 4C to obtain the numerator of the instantaneous entrainment mortality rate.

Duration of the Entrainment Interval

The ETM was run using 5-(baseline), 10-, and 20-week entrainment intervals (J). Figure 14 presents the ETM output representing the three entrainment interval durations. The reductions were 18 percent (J = 5), 32 percent (J=10), and 54 percent (J=20), respectively, which reflect a direct relationship between entrainment interval duration and total conditional entrainment mortality.

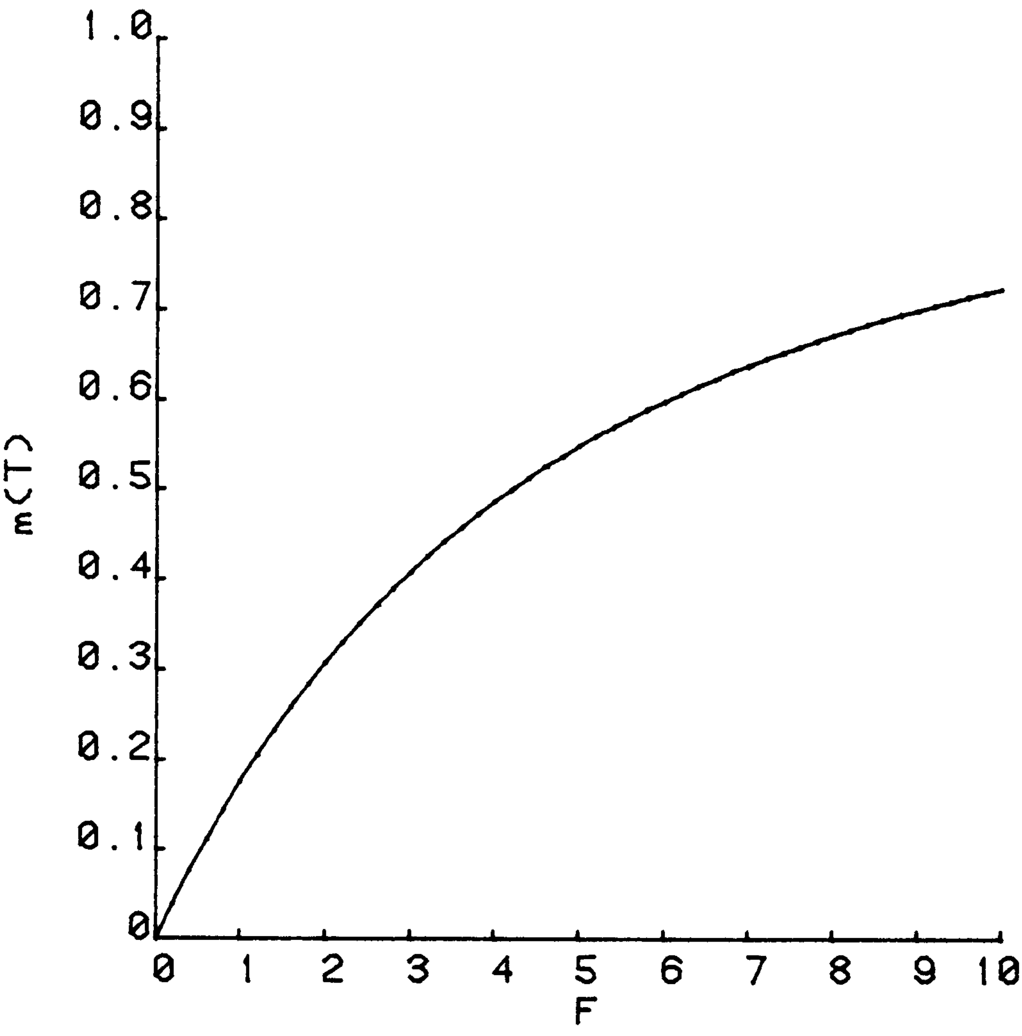

Figure 13. ETM conditional entrainment mortality rate (m_T) estimates with the entrainment vulnerability factor (F) held constant for all life stages and varying between 0 and 10.

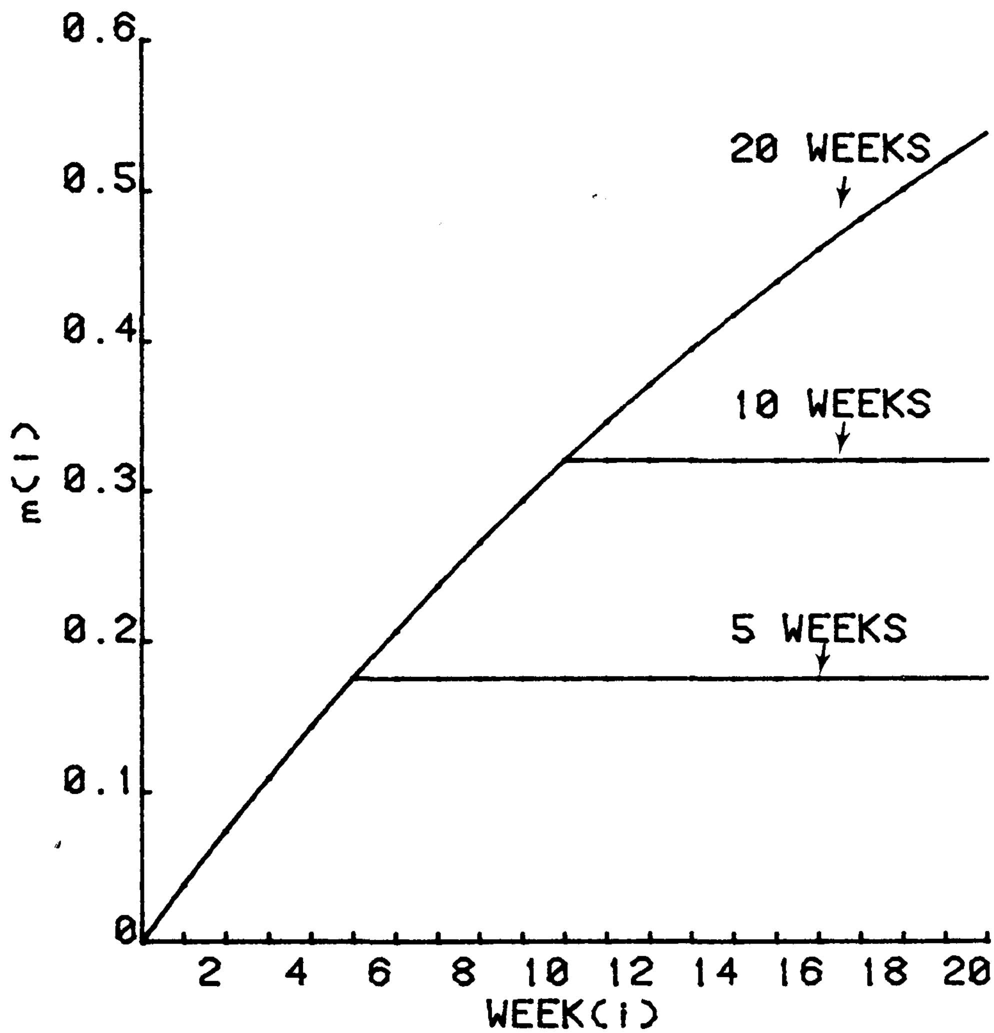

Figure 14. ETM conditional entrainment mortality rate (m_i) estimates with varying entrainment interval durations of 5 (baseline), 10, and 20 weeks.

DISCUSSION

The Empirical Transport Model (ETM) is applicable to any type of water body, provided ichthyoplankton distribution data and volume estimates are available. Use of the ETM to simulate reduction in early life stages of fish and shellfish due to power plant entrainment obviates the difficulties generally associated with development and application of hydrodynamic transport models. The ETM incorporates ichthyoplankton transport through utilization of actual distribution measurements. Ability of the ETM to accurately simulate field conditions depends primarily on the accuracy of the distribution measurements available for use in the model. Problems associated with gear bias, species and life stage identification, sample design, and data interpretation reduce overall confidence in the resultant ETM estimate, but no more than such problems reduce confidence in estimates from any other methodology.

The number of regions and time steps in the ETM can be adjusted to reflect the precision and amount of the available distribution data for entrainable life stages. If only one sample were taken during the entrainment period, it would be appropriate to use a completely mixed distribution and only one time step (although the result would not be particularly meaningful). As the number of sampling periods and number of samples per sampling period increases, the number of time steps and number of regions can be increased accordingly. The ETM's implicit assumption that all ichthyoplankton of a similar age within a region are equally vulnerable to entrainment by a power plant withdrawing water from that region should also influence choice of region size. In general, smaller time steps are increasingly appropriate as physical mixing and organism mobility increase in the system.

If the power plants are operating during the period of ichthyoplankton data acquisition, field measurements of the distributions of entrainable life stages may be influenced by reduction in numbers due to entrainment mortality in regions containing power plants. As a result, the ETM would underestimate the total conditional entrainment mortality rate. Under certain assumptions, the ETM may be run "backwards" to reproduce the numbers of organisms that would exist in each region with no power plant operation. The "restored" numbers can then be used to determine the proportional distribution of organisms among regions. Two assumptions must be made before the ETM is run "backwards" to restore these distributions: (1) natural mortality rates are constant among regions during each ETM time step; and (2) movement of entrainable organisms between the distribution of the first entrainable life stage and distribution of the first nonentrainable life stage is linear. These assumptions address the possibility that field measurements of entrainable life stage distributions, in addition to reflecting entrainment mortality, may also reflect region-dependent natural mortality rates and movement among regions.

In some situations, the members of the particular fish or shellfish population may be emigrating from the water body during the entrainment interval (termed "leakage"). If an estimate of the emigration rate can be made, the problem of leakage may be overcome by establishing an additional region (region K+1) into which these organisms move. If the emigration rate cannot be estimated, however, the ETM only provides a conditional entrainment mortality estimate for the standing crop of the entrainable life interval that remains in the water body. This estimate will be greater than the actual conditional entrainment mortality rate imposed on the target fish or shellfish population, unless all emigrating organisms die.

Calculation of conditional mortality rate due to entrainment is a necessary first-step in the determination of power plant impacts on fish or shellfish populations. Unless the conditional mortality rate due to entrainment is 0 or 100 percent, however, the conditional rate alone cannot be relied on as a final measure of power plant impact on a fish or shellfish population. This rate must be examined with respect to other existing sources of mortality that may exist in the stock. The consequences of sustained annual entrainment mortality on the overall population might be considered using a complementary methodology to the ETM, such as a life-cycle model (DeAngelis et al. 1978) or stock-recruitment formulation (Christensen et al. 1977). Output from the ETM can be used as input for these methodologies.

The ETM equation (equation 6) implicitly assumes natural mortality is independent of population density during the entrainment period. If density-dependent mechanisms such as cannibalism, starvation, or predation are operative concurrently with reduction in numbers due to entrainment mortality, this assumption will not be realistic. Density-dependent mortality could be incorporated into ETM estimates directly by allowing the natural mortality rate during a given time step to be a function of the population size at the beginning of that time step, or indirectly by multiplying the final conditional entrainment mortality rate estimate by a coefficient that accounts for compensatory capability of the population during the entrainment period (Christensen et al. 1977). The former technique would involve quantification of the density-dependent mortality rate on a time-step basis (which is generally beyond the present state-of-the-art) and the latter technique requires a prolonged time series of appropriate stock and recruitment data (which will seldom be available). Since both techniques are therefore extremely difficult to quantify even approximately, the level of confidence in the resulting estimates would almost always be very low. An alternative to using either of these techniques when density-dependent mechanisms are known or assumed to be operative during the entrainment period is to make a subjective judgement on the significance of the conditional entrainment mortality rate estimate from the ETM.

LITERATURE CITED

Barnthouse, L. W., J. B. Cannon, S. W. Christensen, A. H. Eraslan, J. L. Harris, K. H. Kim, M. E. LaVerne, H. A. McLain, B. D. Murphy, R. J. Raridon, T. H. Row, R. D. Sharp, and W. Van Winkle. 1977. A selective analysis of power-plant operation on the Hudson River with emphasis on the Bowline Point Generating Station. ORNL/TM-5877 (vols. 1 and 2). Oak Ridge National Laboratory, Oak Ridge, TN.

Christensen, S. W., D. L. DeAngelis, and A. G. Clark. 1977. Development of a stock-progeny model for assessing power plant effects on fish populations, pp. 196-226. in W. Van Winkle (ed.), Assessing the Effects of Power-Plant-Induced Mortality on Fish Populations. Pergamon Press, NY. 380 pp.

______, W. Van Winkle, and P. C. Cota. 1975. Effect of Summit Power Station on striped bass populations. Testimony before the Atomic Safety and Licensing Board in the matter of Summit Power Station, Units 1 and 2, USAEC Docket 50-450 and 50-451, March 1975.

DeAngelis, D. L., W. Van Winkle, S. W. Christensen, S. R. Blum, B. L. Kirk, B. W. Rust, and C. Ross. 1978. A generalized fish life-cycle population model and computer program. ORNL/TM-6125. Oak Ridge National Laboratory, Oak Ridge, TN. 157 pp.

Eraslan, A. H., W. Van Winkle, R. D. Sharp, S. W. Christensen, C. P. Goodyear, R. M. Rush, and W. Fulkerson. 1976. A computer simulation model for the striped bass young-of-the-year population in the Hudson River. ORNL/NUREG-8, Oak Ridge National Laboratory, Oak Ridge, TN. 208 pp.

Goodyear, C. P. 1977. Mathematical methods to evaluate entrainment of aquatic organisms by power plants. FWS/OBS-76/20.3. U.S. Fish and Wildlife Service. 17 pp.

Hess, K. W., M. P. Sissenwine, and S. B. Saila. 1975. Simulating the impact of the entrainment of winter flounder larvae, pp. 1-29. in S. B. Saila (ed.) Fisheries and Energy Production: A Symposium. Lexington Books, D. C. Heath and Company, Lexington, MA. 300 pp.

Horst, T. J. 1975. The assessment of impact due to entrainment of ichthyoplankton, pp. 107-118. in S. B. Saila (ed.), Fisheries and Energy Production: A Symposium. Lexington Books, D. C. Heath and Company, Lexington, MA. 300 pp.

Lawler, J. P. 1976. Physical measurements: Their significance in the prediction of entrainment effects, pp. 59-91. in L. D. Jensen (ed.), Third National Workshop on Entrainment and Impingement: Section 316(b)-Research and Compliance Considerations. Ecological Analysts, Inc., Melville, NY. 425 pp.

Polgar, T. T. 1977. Striped bass ichthyoplankton abundance, mortality, and production estimation for the Potomac River population, pp. 110-126. in W. Van Winkle (ed.), Assessing the Effects of Power-Plant-Induced Mortality on Fish Populations. Pergamon Press, NY. 380 pp.

Portner, E. M. 1975. Testimony on striped bass entrainment by Summit Power Station. Testimony before the Atomic Safety and Licensing Board in the matter of Summit Power Station, Units 1 and 2, USAEC Docket 50-450 and 50-451, 14 March 1975.

UEC (United Engineers & Constructors). 1975. Applicant's supplemental testimony (mathematical model) on entrainment of striped bass by Summit Power Station. Testimony before the Atomic Safety and Licensing Board in the matter of Summit Power Station, Units 1 and 2, USAEC Docket Nos. 50-450 and 50-451, 21 March 1975.

Appendix A. Estimated densities and standing crops of entrainable life stages of a fish population inhabiting a hypothetical estuary, based on simulated field samples. Den = average regional density (no. per 10^4 m^3); SC = region standing crop (No. x 10^{-6}), equals product of average density and region volume (from Table 1).

EGGS:

Sample Week	Estimate	Region 1	2	3	4	5	6	7	8	9	10	Total
1	Den	0	0	208.30	661.80	1,640.60	1,250.00	669.60	432.70	0	0	
	SC	0	0	7.50	22.50	52.50	37.50	18.75	11.25	0	0	150
2	Den	0	0	277.80	882.40	2,187.50	1,666.70	892.90	576.90	0	0	
	SC	0	0	10.00	30.00	70.00	50.00	25.00	15.00	0	0	200
3	Den	0	0	416.70	1,323.50	3,281.30	2,500.00	1,339.30	865.40	0	0	300
	SC	0	0	15.00	45.00	105.00	75.00	37.50	22.50	0	0	300
4	Den	0	0	277.80	882.40	2,187.50	1,666.70	892.90	576.90	0	0	
	SC	0	0	10.00	30.00	70.00	50.00	25.00	15.00	0	0	200
5	Den	0	0	208.30	661.80	1,640.60	1,250.00	669.60	432.70	0	0	
	SC	0	0	7.50	22.50	52.50	37.50	18.75	11.25	0	0	150
6	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
7	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
8	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
9	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
Total	SC	0	0	50.00	150.00	350.00	250.00	125.00	75.00	0	0	1,000

Appendix A. (cont.).

ENTRAINABLE JUVENILES:

Sample Week	Estimate	Region 1	2	3	4	5	6	7	8	9	10	Total
1	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
2	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
3	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
4	Den	0	3.79	6.00	4.24	4.50	2.40	0	0	0	0	
	SC	0	1.44	2.16	1.44	1.44	0.72	0	0	0	0	7.20
5	Den	0	8.08	12.81	9.03	9.59	5.13	0	0	0	0	
	SC	0	3.07	4.61	3.07	3.07	1.54	0	0	0	0	15.36
6	Den	0	11.63	18.39	13.00	13.81	7.37	0	0	0	0	
	SC	0	4.42	6.62	4.42	4.42	2.21	0	0	0	0	22.09
7	Den	0	11.05	17.61	12.41	13.19	7.03	0	0	0	0	
	SC	0	4.22	6.34	4.22	4.22	2.11	0	0	0	0	21.11
8	Den	0	7.84	12.39	8.76	9.31	4.97	0	0	0	0	
	SC	0	2.98	4.46	2.98	2.98	1.49	0	0	0	0	14.89
9	Den	0	3.03	4.81	3.38	3.59	1.90	0	0	0	0	
	SC	0	1.15	1.73	1.15	1.15	0.57	0	0	0	0	5.75
Total	SC	0	17.28	25.92	17.28	17.28	8.64	0	0	0	0	86.40

Appendix A. (cont.).

LARVAE:

Sample Week	Estimate	Region 1	2	3	4	5	6	7	8	9	10	Total
1	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
2	Den	0	7.89	12.50	22.10	23.40	15.00	8.04	2.89	0	0	
	SC	0	3.00	4.50	7.50	7.50	4.50	2.25	0.75	0	0	30
3	Den	0	13.70	21.70	38.20	40.60	26.00	13.90	5.00	0	0	
	SC	0	5.20	7.80	13.00	13.00	7.80	3.90	1.30	0	0	52
4	Den	0	20.00	31.70	55.90	59.40	38.00	20.40	7.31	0	0	
	SC	0	7.60	11.40	19.00	19.00	11.40	5.70	1.90	0	0	76
5	Den	0	16.80	26.70	47.10	50.00	32.00	17.10	6.15	0	0	
	SC	0	6.40	9.60	16.00	16.00	9.60	4.80	1.60	0	0	64
6	Den	0	12.10	19.10	33.80	35.90	23.00	12.30	4.42	0	0	
	SC	0	4.60	6.90	11.50	11.50	6.90	3.45	1.15	0	0	46
7	Den	0	3.16	5.00	8.82	9.38	6.00	3.21	1.15	0	0	
	SC	0	1.20	1.80	3.00	3.00	1.80	0.90	0.30	0	0	12
8	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
9	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
Total	SC	0	28.00	42.00	70.00	70.00	42.00	21.00	7.00	0	0	280

APPENDIX A. (Concluded)

NONENTRAINABLE JUVENILES:

Sample Week	Estimate	Region 1	2	3	4	5	6	7	8	9	10	Total
1	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
2	Den	0	0	0	0	0	0	0	0	0	0	0
	SC	0	0	0	0	0	0	0	0	0	0	0
3	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
4	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
5	Den	0	0	0	0	0	0	0	0	0	0	
	SC	0	0	0	0	0	0	0	0	0	0	0
6	Den	0	4.08	4.31	3.06	3.25	0	0	0	0	0	
	SC	0	1.55	1.55	1.04	1.04	0	0	0	0	0	5.18
7	Den	0	9.16	9.67	6.82	7.25	0	0	0	0	0	
	SC	0	3.48	3.48	2.32	2.32	0	0	0	0	0	11.60
8	Den	0	13.11	13.83	9.76	10.38	0	0	0	0	0	
	SC	0	4.98	4.98	3.32	3.32	0	0	0	0	0	16.60
9	Den	0	12.87	13.58	9.56	10.16	0	0	0	0	0	
	SC	0	4.89	4.89	3.25	3.25	0	0	0	0	0	16.28
Total	SC	0	14.90	14.90	9.93	9.93	0	0	0	0	0	49.66

Appendix B. Estimated average intake densities (no. per 10^4 m^3) of the entrainable life stages of a fish population inhabiting a hypothetical estuary, based on simulated field samples.

Sample week	Region	Eggs	Larvae	Entrainable juveniles
1	3	104.20	0	0
	4	330.90	0	0
	6[a]	550.00	0	0
	7	401.80	0	0
2	3	138.90	7.50	0
	4	441.20	13.26	0
	6[a]	666.70	12.00	0
	7	535.70	6.43	0
3	3	208.30	13.02	0
	4	661.80	22.92	0
	6[a]	1,000.00	20.80	0
	7	803.60	11.12	0
4	3	138.90	19.02	5.40
	4	441.20	33.54	3.82
	6[a]	666.70	30.40	1.68
	7	535.70	16.32	0
5	3	104.10	16.02	11.53
	4	330.90	28.26	8.13
	6[a]	500.00	25.60	3.59
	7	401.80	13.68	0
6	3	0	11.46	16.55
	4	0	20.28	11.70
	6[a]	0	18.40	5.16
	7	0	9.84	0
7	3	0	3.00	15.85
	4	0	5.29	11.17
	6[a]	0	4.80	4.92

Appendix B. (concluded)

Sample week	Region	Eggs	Larvae	Entrainable juveniles
8	3	0	0	11.15
	4	0	0	7.88
	6[a]	0	0	3.48
	7	0	0	0
9	3	0	0	4.33
	4	0	0	3.04
	6[a]	0	0	1.33
	7	0	0	0
Average	3	138.90	11.67	10.80
	4	441.20	20.59	7.62
	6[a]	666.70	18.67	3.36
	7	535.70	9.99	0

Appendix C. Generalized BASIC computer program for the Empirical Transport Model. A FORTRAN version of the program is available from S.W. Christensen, Oak Ridge National Laboratory, Oak Ridge, TN.

```
100 REM:      EMPIRICAL TRANSPORT MODEL - GENERALIZED CODE
110 REM:
120 REM:
130 REM:   THIS COMPUTER PROGRAM IS BASED ON EQUATION (7), OR A
140 REM:                    'TYPE II' ETM.
150 REM:
160 REM:                       GLOSSARY
170 REM:
180 REM:  A  = ARRAY OF POPULATION SIZE BY AGE AND REGION
190 REM:  C  = TOTAL NUMBER OF ENTRAINABLE ORGANISMS AT THE BEGINNING
200 REM:       OF A WEEK OF A GIVEN AGE
210 REM:  D  = DISTRIBUTION OF EACH AGE AMONG REGIONS. NOTE THAT FOR
220 REM:       EACH AGE, D MUST SUM TO 1.0
230 REM:  E  = INSTANTANEOUS ENTRAINMENT MORTALITY RATE (PER DAY)
240 REM:  F  = ENTRAINMENT VULNERABILITY FACTOR BY AGE IN EACH REGION
250 REM:  I  = TIME INDEX (IN WEEKS)
260 REM:  I9 = TOTAL DURATION OF THE ENTRAINMENT PERIOD (IN WEEKS)
270 REM:  J  = AGE INDEX (IN WEEKS)
280 REM:  J9 = DURATION OF ENTRAINMENT INTERVAL (IN WEEKS)
290 REM:  K  = REGION INDEX
300 REM:  K9 = TOTAL NUMBER OF REGIONS
310 REM:  L  = LIFE STAGE INDEX
320 REM:  L9 = TOTAL NUMBER OF ENTRAINABLE LIFE STAGES
330 REM:  K  = REGION INDEX
340 REM:  K9 = TOTAL NUMBER OF REGIONS
350 REM:  M  = TOTAL CONDITIONAL ENTRAINMENT MORTALITY RATE
360 REM:  N  = TOTAL NUMBER OF ORGANISMS SURVIVING ENTRAINMENT INTERVAL
370 REM:  O  = TOTAL NUMBER OF EGGS SPAWNED
380 REM:  P  = POWER PLANT INDEX
390 REM:  P8 = ARRAY OF POWER PLANT WITHDRAWAL FLOWS PER WEEK
```

Appendix C (cont.).

```
400 REM:  P9 = TOTAL NUMBER OF POWER PLANTS IN MODEL
410 REM:  R  = PROPORTION OF TOTAL EGGS SPAWNED THAT ARE SPAWNED IN
420 REM:       A GIVEN WEEK. NOTE THAT THE SUM OF R'S MUST EQUAL 1.0
430 REM:  S  = SURVIVAL RATE OF ORGANISMS BY AGE AND REGION
440 REM:  T  = DURATION OF TIME STEP (IN DAYS)
450 REM:  V  = VOLUME OF EACH REGION (TCM)
460 REM:  W  = FRACTION OF POWER PLANT WITHDRAWAL FLOW BY REGION, W'S
470 REM:       MUST SUM TO 1.0
480 REM:  X  = ARRAY OF LIFE STAGE TO AGE CONVERSION FACTORS
490 REM:  Z  = NATURAL MORTALITY RATE FOR EACH LIFE STAGE (PER DAY)
500 REM:
510 INIT
520 PAGE
530 I9=10
540 J9=6
550 K9=10
560 P9=5
570 L9=4
580 T=7
590 O=1.0E+8
600 REM:
610 REM: DIMENSION VARIABLES
620 DIM F(P9,L9),P8(I9,P9),D(K9,L9),Z(L9),X(J9,L9),F9(P9,L9)
630 DIM R(I9),V(K9),W(P9,K9),C(J9),E(K9,L9),W9(P9,L9)
640 R=0
650 REM:
660 REM: ENTER INPUT PARAMETER VALUES
670 GOSUB 1070
680 C=0
690 REM:
```

Appendix C (cont.).

```
700 REM: START REAL TIME
710 FOR I=1 TO I9
720 REM:
730 REM: RECRUIT NEW COHORT
740 C(1)=O*R(I)
750 REM:
760 REM: CALCULATE ENTRAINMENT MORTALITY RATE
770 GOSUB 2090
780 REM:
790 REM: KILL OFF THE ORGANISMS
800 FOR J=1 TO J9-1
810 S=0
820 FOR K=1 TO K9
830 FOR L=1 TO L9
840 S=S+C(J)*D(K,L)*(1-EXP(-((Z(L)+E(K,L))*T*X(J,L))))
850 NEXT L
860 NEXT K
870 C(J)=C(J)-S
880 NEXT J
890 REM:
900 REM: STORE NUMBER ENTERING FIRST NON-ENTRAINABLE AGE
910 C(J9)=C(J9)+C(J9-1)
920 REM:
930 REM: AGE ORGANISMS
940 FOR J=J9-1 TO 2 STEP -1
950 C(J)=C(J-1)
960 NEXT J
970 NEXT I
980 REM:
990 REM: CALCULATE TOTAL CONDITIONAL ENTRAINMENT MORTALITY RATE
```

Appendix C (cont.).

```
1000 M=1-SUM(C)/O
1010 PRINT "TOTAL ENTRAINMENT MORTALITY = ";M
1020 END
1030 REM
1040 REM
1050 REM
1060 REM: INPUT F-FACTORS BY PLANT AND LIFE STAGE
1070 FOR P=1 TO P9
1080 FOR L=1 TO L9
1090 READ F9(P,L)
1100 NEXT L
1110 NEXT P
1120 DATA 0.5,0.6,0.9,0
1130 DATA 0.5,0.6,0.9,0
1140 DATA 0.4,0.8,0.7,0
1150 DATA 0.4,0.8,0.7,0
1160 DATA 0.6,0.8,0,0
1170 FOR P=1 TO P9
1180 FOR L=1 TO L9
1190 READ W9(P,L)
1200 F(P,L)=F9(P,L)*W9(P,L)
1210 NEXT L
1220 NEXT P
1230 DATA 0.6,0.7,0.8,0
1240 DATA 0.6,0.7,0.8,0
1250 DATA 0.6,0.7,0.8,0
1260 DATA 0.6,0.7,0.8,0
1270 DATA 0.6,0.7,0.8,0
1280 REM:
1290 REM: INPUT PLANT FLOW RATES OVER ENTRAINMENT PERIOD
```

Appendix C (cont.).

```
1300 FOR I=1 TO I9
1310 FOR P=1 TO P9
1320 READ P8(I,P)
1330 NEXT P
1340 NEXT I
1350 DATA 3000,3000,3000,6000,3000
1360 DATA 3000,3000,3000,6000,3000
1370 DATA 3000,3000,3000,6000,3000
1380 DATA 3000,3000,3000,6000,3000
1390 DATA 3000,3000,3000,6000,3000
1400 DATA 3000,3000,3000,3000,3000
1410 DATA 3000,3000,3000,3000,3000
1420 DATA 3000,3000,3000,3000,3000
1430 DATA 3000,3000,3000,3000,3000
1440 DATA 3000,3000,3000,3000,3000
1450 REM:
1460 REM: INPUT DISTRIBUTIONS BY REGION AND LIFE STAGE
1470 FOR K=1 TO K9
1480 FOR L=1 TO L9
1490 READ D(K,L)
1500 NEXT L
1510 NEXT K
1520 DATA 0,0,0,0
1530 DATA 0,0.1,0.2,0.3
1540 DATA 0.05,0.15,0.3,0.3
1550 DATA 0.15,0.25,0.2,0.2
1560 DATA 0.35,0.25,0.2,0.2
1570 DATA 0.25,0.15,0.1,0
1580 DATA 0.125,0.075,0,0
1590 DATA 0.075,0.025,0,0
```

Appendix C (cont.).

```
1600 DATA 0,0,0,0
1610 DATA 0,0,0,0
1620 REM:
1630 REM: INPUT NATURAL MORTALITY RATES FOR EACH LIFE STAGE
1640 FOR L=1 TO L9
1650 READ Z(L)
1660 NEXT L
1670 DATA 0,0,0,0
1680 REM:
1690 REM: INPUT LIFE STAGE TO AGE CONVERSION MATRIX
1700 FOR J=1 TO J9
1710 FOR L=1 TO L9
1720 READ X(J,L)
1730 NEXT L
1740 NEXT J
1750 DATA 1,0,0,0
1760 DATA 0,1,0,0
1770 DATA 0,1,0,0
1780 DATA 0,0,1,0
1790 DATA 0,0,1,0
1800 DATA 0,0,0,1
1810 REM:
1820 REM: INPUT EGG RECRUITMENT PROPORTIONS
1830 FOR I=1 TO I9
1840 READ R(I)
1850 NEXT I
1860 DATA 0.15,0.2,0.3,0.2,0.15,0,0,0,0,0
1870 REM:
1880 REM: INPUT REGION VOLUMES
1890 FOR K=1 TO K9
```

Appendix C (concluded).

```
1900 READ V(K)
1910 NEXT K
1920 DATA 400000,380000,360000,340000,320000
1930 DATA 300000,280000,260000,240000,220000
1940 REM:
1950 REM: INPUT PROPORTION OF POWER PLANT FLOWS FROM EACH REGION
1960 FOR P=1 TO P9
1970 FOR K=1 TO K9
1980 READ W(P,K)
1990 NEXT K
2000 NEXT P
2010 DATA 0,0,0.5,0.5,0,0,0,0,0,0
2020 DATA 0,0,0,1,0,0,0,0,0,0
2030 DATA 0,0,0,0,0,1,0,0,0,0
2040 DATA 0,0,0,0,0,1,0,0,0,0
2050 DATA 0,0,0,0,0,0,1,0,0,0
2060 RETURN
2070 REM:
2080 REM: CALCULATE INSTANTANEOUS ENTRAINMENT MORTALITY RATES
2090 E=0
2100 FOR P=1 TO P9
2110 W1=P8(I,P)
2120 FOR L=1 TO L9
2130 F1=F(P,L)
2140 FOR K=1 TO K9
2150 E(K,L)=E(K,L)+F1*W1*W(P,K)/V(K)
2160 NEXT K
2170 NEXT L
2180 NEXT P
2190 RETURN
```


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