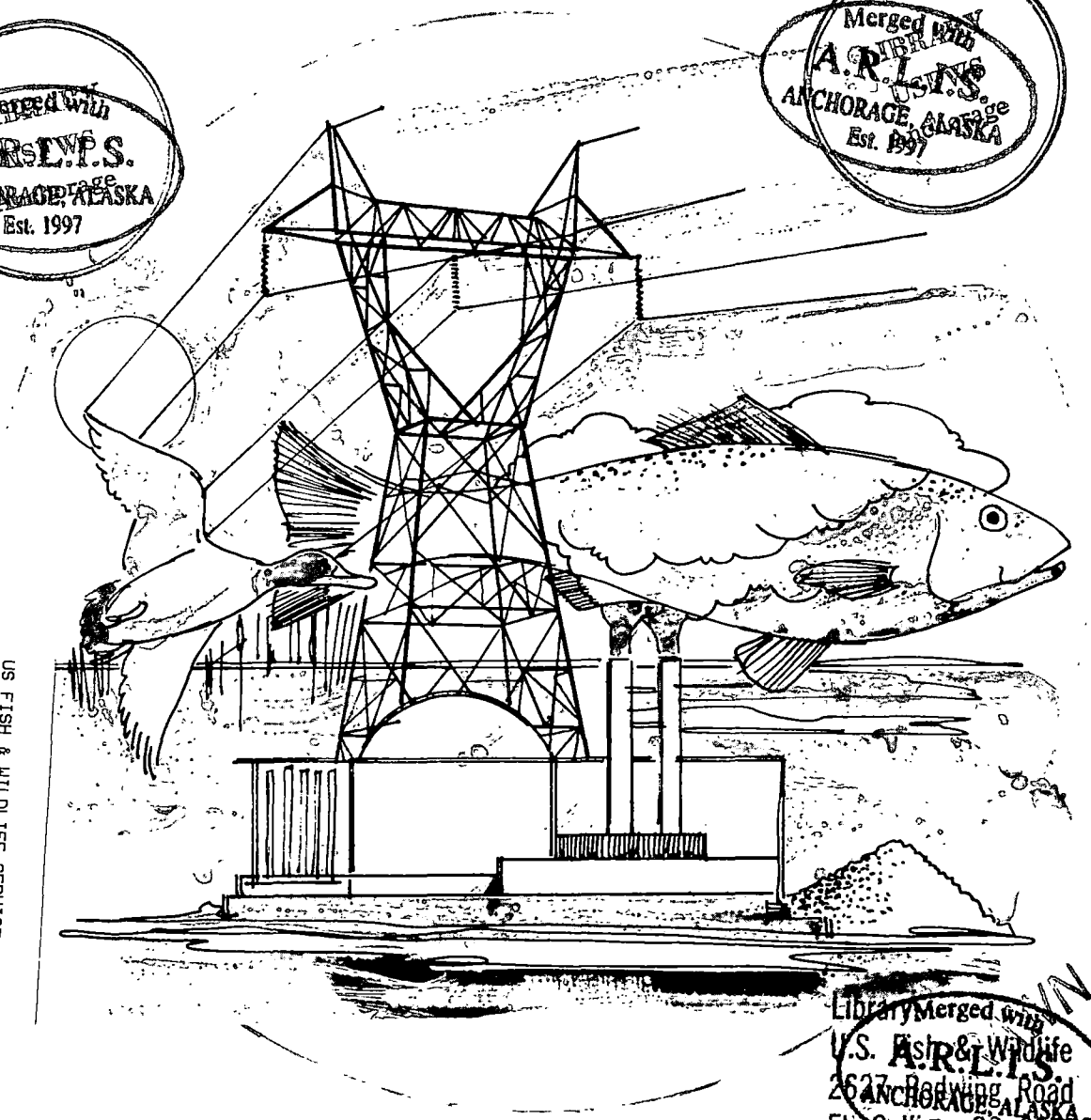
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FWS/OBS-78/65
July 1978

Entrainment Impact Estimates Using the Equivalent Adult Approach



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ENTRAINMENT IMPACT ESTIMATES USING THE EQUIVALENT ADULT APPROACH

by

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ENTRAINMENT IMPACT ESTIMATES

USING THE EQUIVALENT ADULT APPROACH

Abstract

One approach to analyzing the importance of entrainment of fish eggs and larvae by power plants has been to estimate the number of adults which would have resulted from the entrained larvae. Certain limitations of a commonly used model can lead to serious underestimates of the actual impact. These limitations are discussed and an alternative formulation is presented which will reduce the bias. The approach is also expanded to provide estimates of the reduction in numbers of fish captured by fishermen.

INTRODUCTION

One approach to assessing the importance of entrainment mortality of eggs and larvae of fish and shellfish by power plants is to estimate the number of adult organisms which this loss represents. This concept was introduced by Horst (1975) as a "simplistic approach" that could be used when it is not possible to employ more sophisticated methods because of the lack of available data. He formulated the model as follows:

$$N_a = S_\ell \, N_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where N_a = number of adults that would have resulted from the entrained larvae,

S_ℓ = survivorship from larvae to adulthood, and

N_e = number of larvae killed by entrainment.

The paramater S_ℓ of equation (1) can be defined for a population that is in equilibrium if the average lifetime fecundity of adult females (F_a) and the survival probability from a newly spawned egg to larvae are known. At population equilibrium each adult female produces a sufficient number of eggs during her lifetime to replace herself; thus, the probability of an egg surviving to produce an average adult female is equal to the reciprocal of the average lifetime fecundity. If it is assumed, in addition, that one adult male is produced for each adult female, then the probability (S) of an egg surviving to become an adult is

$$S = \frac{2}{F_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

and the probability of a larva surviving to become an adult is

$$S_{\ell} = S/S_e = \frac{2}{S_e F_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where S_e = the survival probability from a newly spawned egg to an entrained larvae.

Thus the estimate of the number of adults lost using the Horst formulation is dependent on the parameters S_e, F_a, and N_e. The value of the parameter N_e must be determined from field sampling and may be subject to considerable bias or error because of inappropriate sampling or data reduction procedures. However, it is assumed here that the number of larvae killed by entrainment can be accurately determined.

In Horst's formulation the estimate of survival from egg to entrained larvae (S_e) is assumed to be constant for all entrained larvae, and this is a potential source of substantial error, as noted by Saunders (1977) and Dahlberg (1977). The value of S_e is actually a function of the age of the affected larvae. This point is important because of the low survival rate typically associated with the younger larval stages. Most of the larvae that are entrained tend to be the younger ages, but most of the impact may be associated with the older, less abundant larvae. In this situation an estimate of the mean S_e which would be representative for most of the entrained larvae, the younger ones, would underestimate the impact.

ALTERNATIVE MODEL

The above source of error could be reduced by rewriting equation (1) to include several age classes of larvae as follows:

$$N_a = \sum_{i=1}^{n} N_i S_i \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where n = number of larval age classes that are subject to entrainment mortality,

N_i = number of age class i larvae that are killed by entrainment,

S_i = survival probability from age class i to adulthood,

$$S_i = \frac{2}{S_{e,i} F_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$S_{e,i}$ = survival probability from egg to age class i, and

F_a = average lifetime fecundity of a female recruit.

The use of equation (4) requires estimates of the number of larvae entrained for each larval age class (N_i) and the rate of survival from the egg stage to each age class (S_i). If the durations of the selected age class intervals are sufficiently long that the survival probabilities of older individuals of the age class are significantly higher than the younger ones, than the number of adults predicted using equation (4) may still underestimate the true impact. This tendency can be an important consideration because it is generally very difficult to determine the age of larvae precisely enough to allow the age class interval to be reduced sufficiently to eliminate this bias.

ESTIMATES OF EGG TO LARVA SURVIVAL

Because of the difficulty in aging larval fish it is often desirable to describe mortality as a function of length rather than age (Swedberg and Walburg 1970). Data on abundance of larvae, grouped by body length categories, can be used to estimate a probability of survival from one length class to the next during the period that larvae are vulnerable to entrainment. Using this latter approach, the number of adults that would have resulted from larvae killed by entrainment can be estimated by rewriting equation (4) as follows:

$$N_a = \sum_{\ell=1}^{k} N_\ell S_\ell \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where k = number of larval length classes that are subject to entrainment mortality

N_ℓ = number of length class ℓ larvae that are killed by entrainment

S_ℓ = survival probability from length class ℓ to adulthood

$$S_\ell = \frac{2}{S_{e,\ell}\, F_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$S_{e,\ell}$ = survival probability from egg to length class ℓ.

The estimate of survival fraction by length can be obtained from cumulative catch data segregated into length classes. If the plot of the log of the cumulative catch against length is a straight line (Figure 1) then mortality is a constant function of length and the instantaneous rate of mortality with increasing length is defined as:

$$d = -\ln \frac{N_{\ell+1}}{N_\ell} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

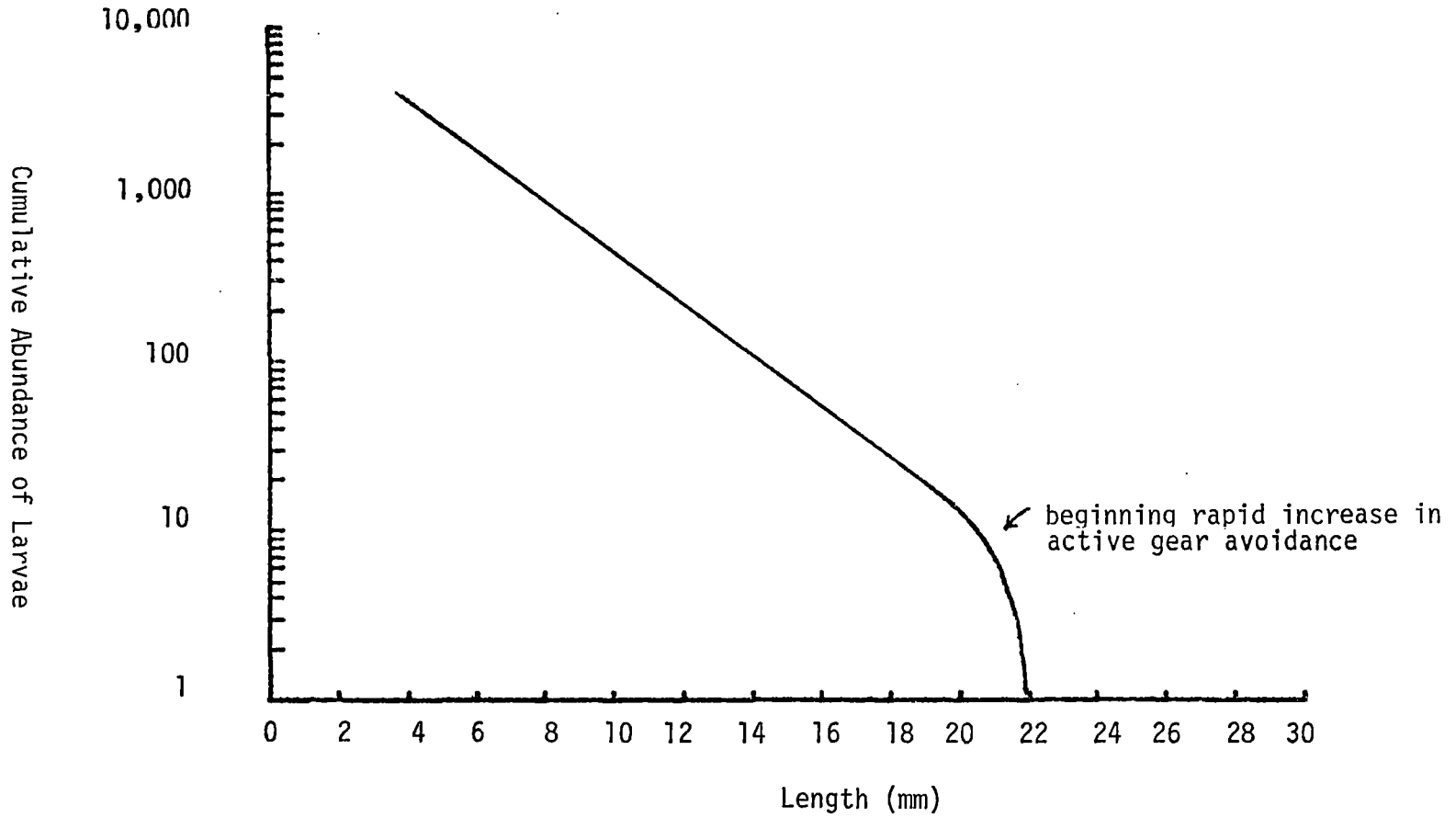


Figure 1. Hypothetical example of situation where larval mortality is a constant function of length during a period of growth where the larvae are equally susceptible to capture by the sampling gear.

where d = instantaneous total mortality during length class ℓ,

$N_{\ell+1}$ = cumulative catch for length class $\ell + 1$

N_{ℓ} = cumulative catch for length class ℓ

and,

$$S_{e,\ell} = He^{-d(L_{\ell}-h)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where H = fraction of eggs that hatch,

L_{ℓ} = length of length class ℓ, and

h = length at hatching.

If the plot of the log of the cumulative catch against length is not a straight line (Figure 2), then mortality is not a constant function of length and equations (8) and (9) are not applicable. In this case, the value of $S_{e,\ell}$ can be estimated as follows:

$$S_{e,\ell} = H \frac{N_{\ell}}{N_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

where H = fraction of eggs that hatch,

N_{ℓ} = number of larvae of length class ℓ, and

N_o = initial number of larvae.

Equations (9) and (10) both assume that the change in cumulative catch as a function of length reflects the true population change in abundance. This assumption requires the sampling to be non-selective by length and the sampling effort to be constant throughout the period that larvae grow through the various length classes (i.e., the probability of an individual being captured at a given length must be the same for all length classes). This method assumes that length increases linearly with time during the entrainment period. Violation of this assumption will introduce some bias into the impact estimates.

ESTIMATES OF AVERAGE LIFETIME FECUNDITY OF "ADULTS"

In addition to the estimate of $S_{e,\ell}$, the parameter S_{ℓ} of equation (6) requires an estimate of the average lifetime fecundity of adult females (F_a). For species which spawn more than once during their lifetime, the value of F_a is not likely to be the same as the average fecundity of the extant adults, but is a function of age of recruitment to the spawning population, frequency of spawning, relative fecundity of

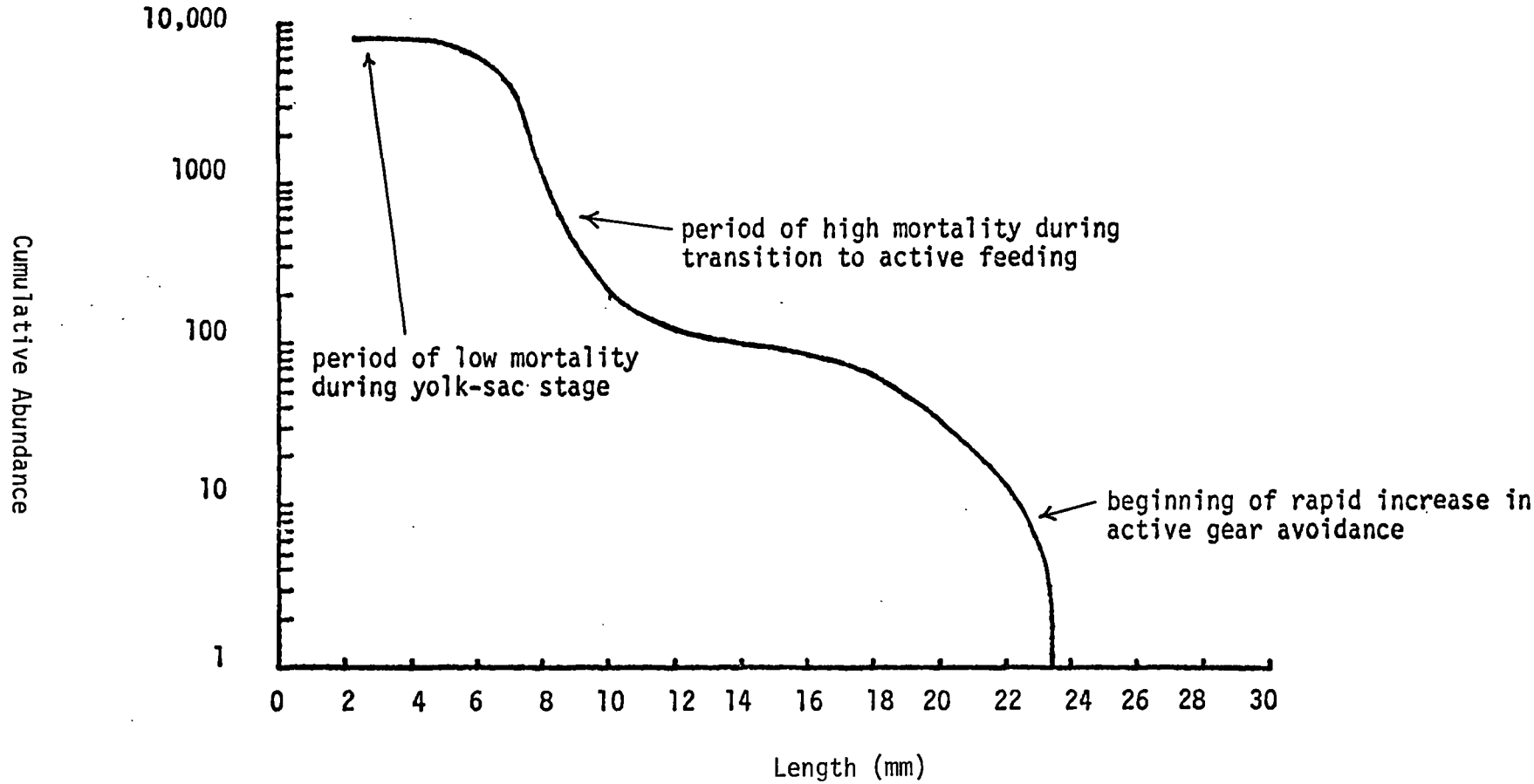


Figure 2. Hypothetical example of situation where mortality is not a constant function of body length during the period that larvae are vulnerable to the sampling gear.

each age class, and total survival between age classes. The average lifetime fecundity equals the average fecundity of adults in the population only when the age structure of the adult population conforms to the stable age distribution that would exist at equilibrium.

To determine average lifetime fecundity of an adult female it is necessary to define the age at which the individual becomes an adult. Two alternative definitions are considered here: (1) an adult is a recruit to the age class in which spawning is first observed, or (2) an "adult" is an individual in the first age class that is recruited to a fishery. If we assume that females spawn only once each year, then for either definition, the average lifetime fecundity of a female recruit to the "adult" population is given by:

$$F_a = \sum_{j=a}^{m} P_j S_j E_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where a = age of recruitment of the "adult" population,

m = number of age classes in the population,

P_j = fraction of females that are mature in age class j,

S_j = survival probability from recruitment to age class j, and

E_j = average fecundity of mature females of age class j.

If recruitment to the "adult" population is considered to occur at the instant that spawning occurs then the value of S_j is given by:

$$S_j = e^{-Z(j-a)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where Z is the instantaneous rate of total mortality.

E_j in equation (11) is the average number of eggs deposited by mature females of the j^{th} age class. Fecundity estimates based on counts of eggs in the ovaries of females are generally somewhat higher than the number of eggs that are actually spawned because some of the ova remain in the ovary after spawning. The unspawned eggs can be accounted for by reducing the fecundity estimates derived in this manner by the proportion of eggs that remain in spent females.

PROJECTIONS OF IMPACT

After the values for $S_{e,\ell}$, N_ℓ, and F_a have been determined, the number of potential adults that are eliminated by entrainment can be estimated using equation (6):

$$N_a = \sum_{\ell=1}^{k} N_\ell \, S_\ell$$

where $$S_\ell = \frac{2}{S_{e,\ell} \, F_a} .$$

The reduction in numbers of fish captured by the fishery (N_f) can be estimated as:

$$N_f = \frac{N_a F}{Z} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where F is the instantaneous rate of fishing mortality.

LIMITATIONS

Estimates of the losses of adults using the equivalent adult approach presume that there is no density dependent mortality occurring between the time that the larva is killed by entrainment and the time it would have been recruited to the "adult" population. However, if these estimates are assumed to represent the long term impact of entrainment losses then density dependent effects are assumed to operate between generations. This conclusion results from the fact that a reduction in adults in one generation is implicitly assumed to not reduce the number of adults recruited to the following generations. Otherwise there would be feedback between generations that would cause the impact of the power plant to become more severe with time.

There is for some populations, of course, a possibility of feedback between generations. Thus, the equivalent adult methodology provides little insight into the long term viability of the affected populations and should be used only to obtain a first approximation of the severity of potential losses. In applications, special consideration should be given to the accuracy of the estimates of the number of larvae killed by entrainment, and to the fraction of eggs that survive to become larvae.

EXAMPLE

A hypothetical power plant withdraws its cooling water from a lake which supports a popular sport fishery. An intensive sampling program in the lake and at the power station has provided the data needed to use the equivalent adult approach outlined herein. Fish are recruited to the fishery when they become 3 years of age and are exposed to an annual instantaneous fishing mortality of 0.29 thereafter. Some are mature at age 4, all are mature by age 8, and they spawn once each year. The reduction in numbers of fish captured by the fishery is estimated as follows:

Step 1. The average lifetime fecundity of a 3 year-old-female recruit is estimated by use of equation (11) to be 534,507 eggs (Table 1),

Step 2. The instantaneous rate of larval mortality with increasing length was estimated to be 0.43 (Table 2),

Step 3. Estimates of survival from egg to the midpoint of each larval length class ($S_{e,\ell}$) were made using equation (9) (Table 3),

Step 4. Estimates of survival from the midpoint of each larval length class to 3 year-old recruit were made using equation (7) (Table 3),

Step 5. The estimate of the reduction in 3 year-old recruits as a result of entrainment mortality was made using equation (6) (Table 4), and

Step 6. The number of catchable fish lost to the fishery as a result of entrainment mortality is determined as follows:

$$N_f = \frac{N_a F}{Z}$$

$$N_f = \frac{(836500)\ (0.29)}{0.5108}$$

$$N_f = 470{,}000$$

Table 1. Determination of the average lifetime fecundity (F_a) of a 3-year-old recruit to a hypothetical fish population where the annual mortality rate (Z) is 0.5108. The fraction of females within each age class (P_j) and the fecundity of mature females within each age class (E_j) are known.

Age	S_j	P_j	E_j	$P_jS_jE_j$
3	1.000	0.00		0
4	0.600	0.10	425,000	25,500
5	0.360	0.25	550,000	49,500
6	0.216	0.50	750,000	81,000
7	0.130	0.75	950,000	92,340
8	0.078	1.00	1,200,000	93,312
9	0.047	1.00	1,400,000	65,318
10	0.028	1.00	1,700,000	47,589
11	0.017	1.00	1,900,000	31,913
12	0.010	1.00	2,100,000	21,163
13	0.006	1.00	2,200,000	13,303
14	0.004	1.00	2,300,000	8,344
15	0.002	1.00	2,400,000	5,224

$$F_a = \sum_{j=3}^{15} P_jS_jE_j = 534,507$$

Table 2. Seasonal length frequency distribution of larvae needed to estimate the instantaneous rate of mortality on length (d).

Length class (ℓ)	Length (mm)	Number collected
1	6.0 - 6.9	952
2	7.0 - 7.9	618
3	8.0 - 8.9	389
4	9.0 - 9.9	168
5	10.0 - 10.9	235
6	11.0 - 11.9	216
7	12.0 - 12.9	66
8	13.0 - 13.9	59
9	14.0 - 14.9	20

$$d = -\ln \frac{\sum_{\ell=2}^{9} N_\ell}{\sum_{\ell=1}^{9} N_\ell} \; *$$

$$d = -\ln \left(\frac{618+389+168+235+216+66+59+20}{952+618+389+168+235+216+66+59+20} \right)$$

$$d = 0.43$$

*This equation was adapted from Section 2.1.4 of Ricker (1975).

Table 3. Estimates of $S_{e,\ell}$ and S_ℓ, by use of equations (5) and (7), for each length class of larvae entrained by a hypothetical power plant. Parameter estimates are 0.01, d = 0.43, F_a = 534507, and h = 4mm. The midpoint of each length class was used as an estimate of L_ℓ of equation 9.

Length class (ℓ)	Length (mm)	Survival probability from egg to length class ℓ ($S_{e,\ell}$)*	Survival probability from length class ℓ to age 3 (S_ℓ)
1	6.0 - 6.9	3.41×10^{-3}	1.09×10^{-3}
2	7.0 - 7.9	2.22×10^{-3}	1.69×10^{-3}
3	8.0 - 8.9	1.44×10^{-3}	2.60×10^{-3}
4	9.0 - 9.9	9.39×10^{-4}	3.98×10^{-3}
5	10.0 - 10.9	6.11×10^{-4}	6.12×10^{-3}
6	11.0 - 11.9	3.98×10^{-4}	9.40×10^{-3}
7	12.0 - 12.9	2.59×10^{-4}	1.44×10^{-2}
8	13.0 - 13.9	1.68×10^{-4}	2.22×10^{-2}
9	14.0 - 14.9	1.09×10^{-4}	3.43×10^{-2}

*Note that length at hatching (h) is 4mm which is 2mm less that the first length class for which data are available. In performing the calculation of $S_{e,\ell}$, the value of d was assumed to be correct for these smaller length classes. In real world applications, the reliability of such extrapolations should be evaluated with respect to the type of bias that might be introduced.

Table 4. Estimate by use of equation (6) of the loss of 3 year-old recruits as a result of entrainment mortality.

Length class (ℓ)	Length (mm)	Mean density (#/1,000 m^3)	Plant flow (1,000 m^3)	Fraction killed	N_ℓ ($X10^{-7}$)	S_ℓ ($X10^3$)	Adults ($X10^{-4}$)
1	6.0 - 6.9	250	$3x10^5$	0.50	3.75	1.09	4.09
2	7.0 - 7.9	200	$3x10^5$	0.60	3.60	1.69	6.08
3	8.0 - 8.9	175	$3x10^5$	0.70	3.68	2.60	9.57
4	9.0 - 9.9	100	$3x10^5$	0.80	2.40	3.98	9.53
5	10.0 - 10.9	80	$3x10^5$	0.90	2.16	6.12	13.21
6	11.0 - 11.9	50	$3x10^5$	0.95	1.43	9.40	13.44
7	12.0 - 12.9	20	$3x10^5$	0.95	0.57	14.40	8.21
8	13.0 - 13.9	15	$3x10^5$	0.95	0.43	22.20	9.55
9	14.0 - 14.9	10	$3x10^5$	0.95	0.29	34.30	9.95
Sum of adults							83.65

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