POWER PLANT IMPACT ASSESSMENT: A SIMPLE FISHERY PRODUCTION MODEL APPROACH

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ABSTRACT

The relative abundance of a cohort affected by power plant entrainment mortality as a fraction (R_c) of the abundance of that cohort in the absence of power plant impact can be calculated by $R_c = \exp(-E_i t_i)$ where t_i is the duration of life stage i, and E_i is the entrainment mortality rate at stage i. Rate E_i can be estimated by the ratio of nonsurviving entrained organisms during a given time interval to the mean standing crop of stage i organisms in the source water during that interval. An estimate of adult abundance allows calculation of equivalent adult losses. When insufficient information is available to determine the long-term effect on the population, the fishery "potential yield" formula provides an interim estimate. Relative equilibrium abundance of the affected population (R_e) is approximated by $R_e = 1 - (\Sigma E_i t_i + F_p + F_f)/2M$, where F_p is adult mortality rate due to power plant impingement, F_f is adult mortality rate due to fisheries, and M is adult natural mortality rate. As in the case of the "potential yield" formula, this approximation of long-term equilibrium impact should be discarded when better estimates can be developed.

In recent years considerable effort has been expended in evaluating the impact of fish removals by intake cooling water systems at power plants in the United States. Methods of impact assessment are as diverse as the power plant sites at which the studies have been conducted, but may generally be classified into those which, according to Hackney et al. (1980), 1) offer an "expert" opinion as to the presence or absence of impact, or 2) are fish population models in which the sensitivity of the source water fish populations are examined under varying impingement rates.

The first category of assessments generally attempts to compare losses of organisms owing to power plant operation with sport and commercial fishery harvests and/or estimates of standing stock (DeMartini 1979). For adults, which are subject to impingement, comparison is fairly straightforward. However, for eggs and larvae, which are subject to entrainment, meaningful comparison is less direct. Goodyear (1978) extended a method proposed by Horst (1975) for treating entrained larvae in terms of equivalent adult losses which may then be considered alongside losses because of impingement. The second category of assessments includes more complex models using Leslie matrices (Vaughan and Saila 1976; Horst 1977; Vaughan 1981), differential equations (Hackney et al. 1980), or stock-progeny-recruit models (Christensen et al. 1977).

Several problems are inherent in many of these methods. There is an absence of an impact "scale" which enables the investigator to judge objectively the significance or insignificance of fish removals relative to the source water stock and to removals by fisheries. Additionally, sophisticated methods such as Leslie matrices and Goodyear's (1978) calculation of equivalent adult losses require life history parameters (i.e., fecundity, survivorship), which are often unknown for the species in question, and require substantial expenditures of time and money to obtain. Finally, these models may be difficult to interpret. While the investigator may understand the subtleties of interpretation, agency reviewers often lack the technical background to evaluate the results of complicated models.

The approach presented in this paper will alleviate many of the above problems. The proposed methods draw on techniques and models used in fishery management in order to provide a criterion for significance of impact. Indeed, the objectives of fishery stock assessment are very similar to those of power plant impact assessment. In both cases, we wish to know the effect of removals relative to what the stock can sustain through its density-dependent or other compensatory mechanisms. The models we propose do not require detailed life history information, and are sufficiently simple that the assumptions are apparent and results can be interpreted accordingly.

The methods may be separated into two somewhat independent analyses. The first is short-term assessment, which estimates entrainment impact on a

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single cohort (e.g., year class) in the sense of Goodyear's (1978) equivalent adult mortality. The second analysis estimates the long-term equilibrium impact of combined removals, including entrainment and impingement by one or more power plants, and all other nonnatural removals, including fishery harvests.

SHORT-TERM IMPACT

In the natural state, where no spawning products are removed by entrainment, the adult abundance of a cohort, N'_c (at a reference age T), is given by

$$N'_c = Pe^{-\int_0^T \mu(x)dx} \qquad (1)$$

where P is initial production of newly spawned eggs, x is age, and $\mu(x)$ is per capita natural mortality rate at age x, i.e., $-dN(x)/Ndx$.

A more convenient approximation of Equation (1) is

$$N'_c = Pe^{-\Sigma M_i t_i} \text{ and } T = \Sigma t_i \qquad (2)$$

where t_i is the length of age interval i, and M_i is a per capita natural mortality rate, assumed to be constant over interval i.

In the presence of mortality due to entrainment, the adult abundance of the impacted cohort, N_c (again at reference age T) is given by

$$N_c = Pe^{-\Sigma(E_i + M_i)t_i} \qquad (3)$$

where E_i is the per capita rate of entrainment mortality during age interval i.

The abundance of an impacted cohort relative to an unimpacted cohort is denoted R_c, and is given by

$$R_c = N_c/N'_c \qquad (4)$$

and after substituting Equations (2) and (3), this simplifies to

$$R_c = e^{-\Sigma E_i t_i} \qquad (5)$$

which is related to the conditional mortality rate (m) described by Ricker (1975: equation 1.9; here $m = 1 - R_c$). Note that T need not be specified, since we now need sum over only those age intervals in which E_i is nonzero. This is convenient since fish often cease being entrained at about the same time they cease being available to plankton sampling gear. More important is the fact that Equation (5) requires no knowledge of

life history parameters. The main assumption here is that there is no compensatory change in the per capita rate of natural mortality during early life stages which offsets the added effect of entrainment mortality.

Equation (5) is similar in concept and derivation to recently published methods of calculating impact rate (e.g., Boreman et al. 1981; Jensen and Hamilton 1982). Those methods explicitly include water volumes and are especially appropriate to cases of highly fluctuating water flows. For the purposes of the assessment methods discussed in this paper, either method of calculating impact rate is applicable.

The entrainment mortality rates, E_i, are fairly easy to estimate. Larval mortality may be assumed to conform to a "Type 2 fishery" in the sense of Ricker (1975), wherein natural mortality occurs along with entrainment, and each occurs at a constant per capita rate during each age interval i. If power plant activity is fairly constant over the spawning season, each E_i is constant, and it is unnecessary to distinguish between Ricker's two types of recruitment. According to Ricker's (1975) equation 1.17, the quantity of larvae at stage i removed during a unit time by entrainment (L_i) is related to the mean abundance of larvae at stage i in the source water ($\bar{L}_i^*$) by the equation

$$L_i = E_i \bar{L}_i^* \qquad (6)$$

Therefore, E_i may be estimated by the equation

$$E_i = L_i/\bar{L}_i^* \qquad (7)$$

where L_i is a direct in-plant sample estimate of the quantity of stage i larvae entrained per day (or other convenient short time interval), and $\bar{L}_i^*$ is an estimate of the mean standing crop of stage i larvae over that same time interval in the source water, which may be estimated by quantitative plankton net tows. Note that entrainment rate E_i has units of inverse time according to the time interval used. Care must be taken to assure that time units are consistent throughout the analysis. Also note that i now refers to a stage, as it is generally most convenient to sort samples or planktonic larvae by size or stage categories. The length of time spent in each size category must also be determined. The most direct method may be to examine larval otoliths for daily growth rings (see Brothers et al. 1976) in order to ascertain the number of days (or other time unit employed) spent in stage i. Lacking this direct information on t_i, it may be necessary to assume that the larvae grow at the same

rate as does some better known similar species in a similar environment.

Equivalent adult loss from a cohort (A_c) may be defined as

$$A_c = N_c' - N_c. \tag{8}$$

However, a standing stock of adults often consists of several cohorts. Under the common fishery assumption that the age composition of the standing stock is at equilibrium, overall equivalent adult losses (A_e) from the stock are given by

$$A_e = N' - N \tag{9}$$

where N' denotes unimpacted stock abundance, and N denotes impacted stock abundance, given the same initial production of eggs. Although this equilibrium assumption is often violated, it is nonetheless the basis of management of many fish stocks. Since the quantity R_c describes the ratio for a cohort N_c/N_c', under equilibrium it also describes the population ratio N/N', here denoted R. The latter may be substituted into Equation (9) to give

$$A_e = N' (1 - R) \tag{10}$$

or

$$A_e = N \left(\frac{1}{R} - 1\right). \tag{11}$$

Thus equivalent adult losses can be calculated if adult abundance has been estimated, and this does not require the extensive knowledge of life history parameters demanded by Goodyear's (1978) approach.
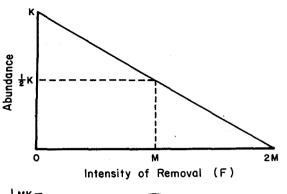
Equations (10) and (11) raise a dilemma with respect to short- and long-term impact. Estimation of short-term impact has been based on the assumption of a fixed initial production of eggs. However, when real data are used, preimpact abundance (N') will usually arise from a larger egg production than does postimpact abundance (N), for the very reason than N' is larger than N, and egg production is itself dependent upon adult abundance. For this reason, Equation (10) is misleading, and will tend to overestimate the amount of adult equivalent losses actually occurring from an impacted stock at equilibrium. However, in most cases, preimpact abundance is unknown, and sampling programs produce estimates of N, which require application of Equation (11). Moreover, Goodyear's (1978) equivalent adult losses are calculated for an impacted stock making Equation (11) appropriate. As will be seen below, our method of estimating long-term equilibrium impact does not require explicit calculation of equivalent adult losses, and avoids the above complications.

LONG-TERM IMPACT

Whereas short-term impact may be described in simple terms of adult equivalent losses, long-term impact is more difficult to quantify. Short-term loss of adults implies loss of reproductive potential (egg production), and this loss is compounded over several generations. If compensatory mechanisms were not present, the impacted population would decline exponentially to extinction, given that it was in equilibrium prior to the impact. Fortunately, there are many types of compensatory mechanisms that allow the population to augment its reproductive rate so that it reaches a new equilibrium in the presence of an increased mortality rate (see Goodyear 1980). For example, lowered adult abundance may lead to increased per capita fecundity, decreased age of first reproduction, and/or increased survivorship at various life stages. Unfortunately, the actual mechanisms are poorly known and can be seldom quantified even for well-studied species. Detailed knowledge cannot be expected in routine impact analyses. Rather, we need simple approximations that will require a minimum of data.

Fishery management has long been concerned with the effect of removal (harvests) rates on fish abundance. Most of the work has been concerned with long-term equilibrium, and many fishery models are directly applicable to impact analysis. In particular, the "production model" (see Ricker 1975, Chapter 13), by means of simplifying assumptions, requires minimal knowledge of life history parameters. One of the simplest production models is the Graham-Schaefer model, which is constructed on the assumption of logistic population growth. The model assumes that equilibrium stock abundance declines linearly with an increasing rate of harvest (fraction of stock removed per unit time). The maximum net productivity in terms of total harvest by a fishery is therefore assumed to be achieved at a stock size which is exactly one-half the virgin level of abundance or carrying capacity, K (Fig. 1).

Normally, the production model is useful when a long time series of catches and fishing efforts (rates of removal) is available. In such cases, the production curve can be estimated from the data by statistical regression. On the other hand, there are many fisheries for which there is no history of exploitation, or for which the required data were never collected. Here, we may draw on the "potential yield" formula, first proposed by Alverson and Pereyra (1969), promulgated by Gulland (1970, 1971), and critically reviewed by Francis (1974). This approximation assumes that net productivity is maximal when abun-
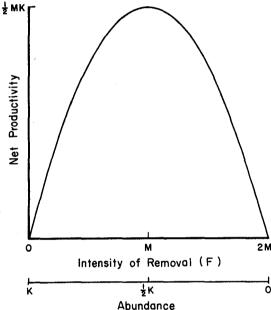
FIGURE 1.—The Graham-Schaefer production model scaled according to the "potential yield" formula (K is virgin abundance or carrying capacity, M is rate of natural mortality).

to zero when the rate of removals is twice the rate of adult natural mortality (M). Thus, based on linearity, we have

$$N_e = N'_e \left(1 - \frac{F}{2M}\right) \qquad (12)$$

which predicts long-term equilibrium abundance in the presence of removal rate F. In parallel with our treatment of short-term impact, the long-term equilibrium abundance of a harvested or impacted stock relative to the abundance of the virgin stock is denoted R_e, and is given by

$$R_e = N_e/N'_e \qquad (13)$$

and according to Equation (12), we have the approximation

$$R_e = \left(1 - \frac{F}{2M}\right). \qquad (14)$$

Equation (14) says that we can estimate the impact of all removals, given the total rate of removals and the rate of adult natural mortality.

The total rate of removals (F) includes entrainment (E) and impingement (F_p) by all power plants operating in the area of the stock, and all fisheries (F_f) exploiting the stock:

$$F = \Sigma E + \Sigma E_p + \Sigma F_f. \qquad (15)$$

The removal rate due to entrainment (E) is estimated by the method presented in the previous section, i.e.,

$$E = \Sigma E_i t_i. \qquad (16)$$

Impingement (F_p) and fishing (F_f) mortality rates may be estimated by a method similar to Equation (7):

$$F_p = I/\bar{N}* \qquad (17)$$

and

$$F_f = C/\bar{N}* \qquad (18)$$

where I is the number of adults impinged in a year, C is the annual fishery harvest, and $\bar{N}*$ is the mean abundance of the stock over the year.

The natural mortality rate is a difficult parameter to estimate. Ricker (1975) reviewed many of the methods. In some cases it may be necessary to assume a value of M, based on comparison with better known species. One useful method, based on comparative growth and environmental parameters, has been described by Pauly (1980). If a mortality rate can be es-

dance is at one-half the virgin level, and at this point the rate of fishery removals (F) is equal to the rate of natural mortality of adults (M). While many criticisms can be leveled at the potential yield formula, in actual practice it is often the only available basis of fishery management (e.g., North Pacific Fishery Management Council 1979a, b; Pacific Fishery Management Council 1982).

The production model corresponding to the potential yield formula is shown in Figure 1. The assumed relationship between equilibrium abundance (N_e) and rate of removal (F) is linear, giving the usual parabolic yield curve. Equilibrium abundance is at carrying capacity (K, denoted N'_e in this paper), when there are no removals. From inspection of Figure 1, the model predicts that equilibrium abundance falls

timated, for example, based on age frequency, the estimate will often be the total mortality rate of adults (Z), where

$$Z = M + \Sigma F_p + \Sigma F_f. \qquad (19)$$

The natural mortality rate can be obtained from

$$M = Z - \Sigma F_p - \Sigma F_f. \qquad (20)$$

If fish are being removed from the stock by several power plants and fisheries, the impact by a single entity cannot be considered in isolation. Our proposed method of long-term impact assessment allows an integrated assessment of impact, but also allows dissection into individual contributions to the total impact. Equation (15) states that the total rate of removals (F) is the sum of the individual instantaneous rates of removal. Since Equation (15) is a linear function, the fraction of the total impact which is attributable to any particular entity is the ratio of the sum of its contributions to total F from all sources as in Equation (15).

CRITERIA FOR IMPACT EVALUATION

Removal of fish from a stock, whether by a fishery or by a power plant, will usually lead to lowered equilibrium abundance. The previous section has presented a method for estimating the approximate reduction in abundance which has taken place. We must now determine whether this impact is "acceptable." In the case of a fishery where tangible values can be assigned to the catch and the stock, optimal catch rates and population sizes can be defined (Roedel 1975; Clark 1976). However, losses to a power plant produce no direct consumptive benefit, and, in many cases, the impacted stock is not subject to a fishery and therefore has no conventional value.

Fortunately, there exists a precedent for evaluating impacts on nonvalued species. The Marine Mammal Protection Act, enacted by the United States in 1972, requires that marine mammals be managed for optimum sustainable population size (OSP). Subsequently, the term was given a working definition: "Optimum sustainable population is a population size which falls within a range from the population level of a given species or stock which is the largest supportable within the ecosystem to the population level that results in maximum net productivity. Maximum net productivity is the greatest net annual increment in population numbers or biomass resulting from additions to the population due to reproduction and/or growth less losses due to natural mortality." (Gehringer 1976).

While power plants clearly do not directly impact marine mammals, the principle of optimum sustainable population size as defined above may be extended to fish and invertebrates as well. Since OSP is defined to fall within a range, impact is unacceptable when it causes population size to fall below the lower limit of that range, which is the point of maximum net productivity. In the logistic model assumed by our long-term impact assessment, maximum net productivity occurs at one-half the virgin, unimpacted population size. This gives a simple criterion for acceptable impact: Abundance should not be driven below one-half of its unimpacted level. In terms of the long-term impact model and its assumptions, this criterion is equivalent to saying that the rate of removal should not exceed the adult rate of natural mortality.

EXAMPLE APPLICATION

This example is based on data collected during 1978 for the purpose of estimating power plant impact on topsmelt, *Atherinops affinis*, inhabiting a California estuary.[4] Topsmelt is a bay-dwelling species with demersal eggs and a short (2-3 mo) spawning period. Topsmelt eggs hatch to produce 6 mm larvae, and larvae >15 mm are not entrained. Larvae were categorized by two length stages, 6-10 mm and 11-15 mm. Based on laboratory growth rate experiments for a closely related atherinid, the California grunion, *Leuresthes tenuis*, duration of these two stages is about 14 d each.

Standing stock and entrainment data (Table 1) are averages for the 3-mo spawning period based on biweekly sampling. Since larvae are concentrated near the surface during daylight hours, larval standing stock estimates are determined based on daytime surface larval densities sampled by a neuston net. These density values are extrapolated to the area of the estuary and a depth of 1 m. The mean entrainment rates are adjusted for variation in cooling water flow during each of the sampling periods. All entrained larvae are assumed to die. The short-term impact of the power plant is estimated to reduce recruitment strengths to 98% of their unimpacted value. Based on seine catches, the standing stock of adult topsmelt in the estuary was 5.4×10^5 fish. Since the power plant has long been operational, equi-

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[4]Because the power plant impact study has not completed the official review process, the proprietor wishes not to be identified at this preliminary stage.

TABLE 1.—Example calculation of short-term impact by entrainment of top-smelt larvae. n.e. indicates not estimated.

Stage	Entrainment (L_i) larvae/day	Standing stock (L_i^s) larvae	Entrainment rate (E_i) per day	Stage duration (t_i) days	$E_i t_i$
Eggs	0	n.e.	n.e.	n.e.	0
Larvae					
6-10 mm	4.0×10^4	5.3×10^7	7.5×10^{-4}	14	1.1×10^{-2}
11-15 mm	2.0×10^3	3.0×10^6	6.7×10^{-4}	14	0.9×10^{-2}
16 + mm	0	n.e.	n.e.	n.e.	0
Sum					2.0×10^{-2}

Equation (5): $R_c = \exp(-2.0 \times 10^{-2}) = 0.98$.
Equation (11): $A_e = 5.4 \times 10^5 (0.98^{-1} -1) = 1.1 \times 10^4$ fish.

valent adult losses are estimated by Equation (11) and are 1.1×10^4 fish.

Estimation of long-term impact requires information on all sources of mortality. The annual estimate of adult impingement by the power plant, based on 360 d of sampling, is 5,147 fish. According to California Department of Fish and Game records, there were no commercial landings of topsmelt in 1978, and recreational fishermen landed <1,000 topsmelt in this area (we use 1,000 fish for this example). Total mortality rate was estimated by regressing log abundance against age (Ricker 1975), giving an instantaneous total mortality rate (Z) of 1.8. Nonnatural mortality rates of adults were negligible (Table 2), giving a natural mortality rate of $M = 1.8$. Application of the long-term impact approximation (Equation (14)) indicates that topsmelt may be near 99% of their unimpacted abundance despite impacts by both power plants and fisheries. The majority of impact on the local resource is probably due to power plant operation, with entrainment impact being about twice as large as impingement impact. In any case, this estimated small reduction in long-term abundance indicates that there is no cause for concern with regard to power plant impact on topsmelt abundance in this estuary.

DISCUSSION

This approximation of long-term impact is not intended to be a substitute for proper studies of population dynamics. Rather, just as in the case of fishery management, it is intended to be a working approximation which should be discarded as more definitive information and analyses become available. In the case of impact assessment there will always be a suite of organisms, particularly invertebrates, which undoubtedly are impacted, but lack sufficient "status" to justify the expense of close monitoring and study. For these organisms, approximation is the most that reasonably can be asked. In this respect the potential yield approximation is well established in fishery

TABLE 2.—Example calculation of long-term impact from all sources of topsmelt mortality.

Source of impact	Catch (fish)	Mean standing stock (fish)	Coefficient of mortality
Impingement	5,147	5.4×10^5	1.0×10^{-2} (F_p)
Fishery	1,000	5.4×10^5	0.2×10^{-2} (F_f)
Entrainment	(see Table 1)		2.0×10^{-2} $(\Sigma E_i t_i)$
Sum			3.2×10^{-2}

Equation (20): $M = 1.8 - 1.0 \times 10^{-2} - 0.2 \times 10^{-2} = 1.8$.
Equation (14): $R_e = 1 - (3.2 \times 10^{-2}/3.6) = 0.99$.

management and should therefore be an equally applicable approximation for power plant impact assessment.

It is likely that the bases of the approximation can be improved in two ways. First, organisms may be classifiable into types with various productivity curves, of which the logistic is a special case. For example, Fowler (1981) observed that species with high reproductive rates and short life-spans show most density-dependent compensation at low population levels, whereas species with low reproductive rates and long life-spans show most of their density-dependent compensation near carrying capacity. Thus, it may be possible to specify the shape of the curves in Figure 1 as a function of observable or measurable traits of specific organisms. The second improvement consists of developing better scaling criteria for the production curve, once its shape has been established. A survey of population growth rates of many species could form the basis of an empirical estimator of compensatory capacity; the use of natural mortality rate may not be appropriate in many cases. Clearly, an improved approximation method would be of value both to fishery management and to power plant impact assessment.

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