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Use of Conventional Fishery Models to Assess Entrainment and Impingement of Three Lake Michigan Fish Species[1]

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Abstract

Two conventional fishery stock assessment models, the surplus-production model and the dynamic-pool model, were applied to assess the impacts of water withdrawals by electricity-generating plants, industries, and municipalities on the standing stocks and yields of alewife *Alosa pseudoharengus*, rainbow smelt *Osmerus mordax*, and yellow perch *Perca flavescens* in Lake Michigan. Impingement and entrainment estimates were based on data collected at 15 power plants. The surplus-production model was fitted to the three populations with catch and effort data from the commercial fisheries. Dynamic-pool model parameters were estimated from published data. The numbers entrained and impinged are large, but the proportions of the standing stocks impinged and the proportions of the eggs and larvae entrained are small. The reductions in biomass of the stocks and in maximum sustainable yields are larger than the proportions impinged. The reductions in biomass, based on 1975 data and an assumed full water withdrawal, are 2.86% for alewife, 0.76% for rainbow smelt, and 0.28% for yellow perch. Fishery models are an economical means of impact assessment in situations where catch and effort data are available for estimation of model parameters.

The combined capacity for water withdrawal by all power-plant, industrial, and municipal water intakes on Lake Michigan exceeds 4.8×10^{10} m^3 per year. Although many intakes are not operated continuously or at full capacity, the volume withdrawn is large. Entrainment of fish eggs and larvae in water passing through intake screens and impingement of larger fishes on intake screens during water withdrawal has caused concern. In this study, two conventional stock assessment models were applied to estimate fish abundances and to simulate the impact on standing stocks and yields of water withdrawals from Lake Michigan.

To estimate the effect of entrainment and impingement, the sizes of the populations must be known. Direct estimates of abundance are difficult and costly for large populations, so abundances were estimated with models. Two different models were applied to give two nearly independent estimates. The models are based on different assumptions and two different sets of data are used for nearly all parameter estimates.

The most frequently impinged and entrained species in Lake Michigan are alewife *Alosa pseudoharengus*, yellow perch *Perca flavescens*, and rainbow smelt *Osmerus mordax*, so the impact on these species was assessed. All three species support small commercial fisheries. Yellow perch and rainbow smelt are also important to sport fishermen. Alewife and rainbow smelt are important forage fish for lake trout *Salvelinus namaycush* and other stocked salmonids.

Acquisition and Development of Data

Data were obtained from environmental-impact studies at 15 power plants located on Lake Michigan (Fig. 1) and from federal and state resource agencies. Most plants were sampled in 1975. The sampling schedules and methods varied among plants; methods are summarized by Spigarelli et al. (1981). Power-plant data sets that spanned less than 1 year were expanded to a full year by linear extrapolation from the last data entry to zero at the end of the year or from zero to the first data entry for the year.

[1] Work performed under the auspices of the United States Environmental Protection Agency.

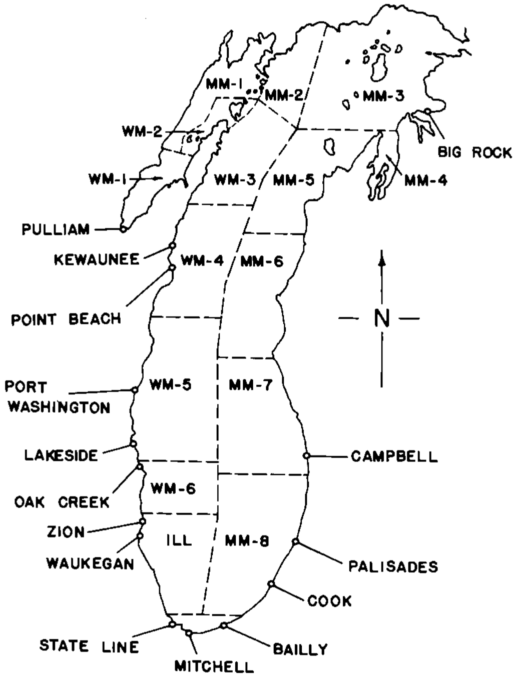

FIGURE 1.—*Locations of sampled power plants on Lake Michigan. Symbols and broken lines define fishery statistical districts.*

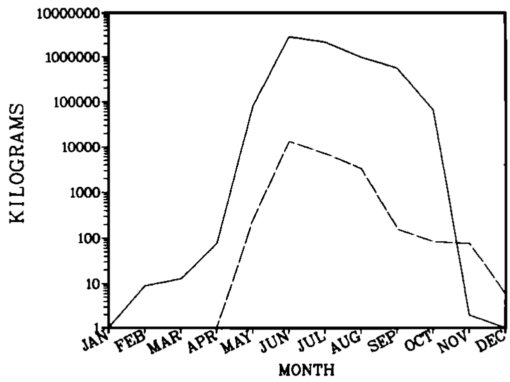

FIGURE 2.—*Commercial alewife catch from Lake Michigan district WM-1 (solid line) and observed alewife impingement (dashed line) at Pulliam Power Plant during 1975.*

Daily average flow rates were obtained for each plant, and daily impingement and entrainment estimates were calculated for each plant with a weighted linear interpolation. Daily values were summed by month and year for each plant. For each of the three species, biomass impinged and number of eggs and larvae entrained were calculated.

Model calculations assumed that power plants withdrew water at their full design flows, and that all impinged and entrained fish and fish eggs died. Thus, the estimates and simulation results presented are worst-case assessments.

The annual alewife impingement at the sampled power plants was estimated as 9.17×10^5 kg (Table 1). Impingement was strongly depen-

TABLE 1.—*Observed impingement of alewives, rainbow smelt, and yellow perch at 15 Lake Michigan power plants in 1975, and actual and maximum potential water withdrawal. Estimated annual totals are extrapolations to the full year.*

Power plant	Total flow (m^3/year)	Maximum flow (m^3/year)	Alewife (kg)	Rainbow smelt (kg)	Yellow perch (kg)
Zion	2.04×10^9	3.48×10^9	6.80×10^5	2.48×10^3	6.90×10^1
Cook	1.32×10^9	3.27×10^9	5.11×10^3	5.10×10^1	3.97×10^2
Bailly	4.71×10^8	6.70×10^8	4.52×10^3	1.70×10^1	4.40×10^1
Pulliam	3.34×10^8	7.75×10^8	2.46×10^4	2.73×10^2	2.14×10^3
Kewaunee	6.70×10^8	8.22×10^8	4.84×10^3	4.75×10^2	4.00×10^1
Point Beach	1.21×10^9	1.53×10^9	3.74×10^4	1.26×10^3	3.90×10^1
Port Washington	5.74×10^8	1.09×10^9	6.11×10^4	8.95×10^2	2.30×10^1
Lakeside	2.64×10^8	8.73×10^8	1.40×10^3	2.00×10^0	3.00×10^0
Oak Creek	1.64×10^9	2.45×10^9	3.29×10^4	3.76×10^3	1.06×10^2
Waukegan	9.32×10^8	1.43×10^9	2.80×10^4	3.77×10^2	3.80×10^1
Stateline	1.02×10^9	1.65×10^9	2.19×10^4	2.30×10^1	8.20×10^1
Mitchell	5.11×10^8	8.23×10^8	3.68×10^3	4.00×10^0	4.60×10^1
Campbell	4.17×10^8	5.97×10^8	1.10×10^3	1.07×10^1	7.14×10^0
Palisades	1.22×10^8	1.19×10^8	1.22×10^1	2.27×10^{-1}	1.13×10^{-1}
Big Rock	8.20×10^7	9.55×10^7	3.51×10^0	2.38×10^0	2.04×10^0
Total observed	1.16×10^{10}		9.07×10^5	9.63×10^3	3.03×10^3
Estimated annual total		1.97×10^{10}	9.17×10^5	9.77×10^3	3.11×10^3

TABLE 2.—*Estimated total numbers of alewife, rainbow smelt, and yellow perch eggs and larvae entrained during 1975 sampling period at 15 sampled power plants on Lake Michigan; estimated annual totals are extrapolations to the full year. N/A means not available.*

Power plant	Total flow (m^3)	Alewife		Raibow smelt		Yellow perch	
		Eggs	Larvae	Eggs	Larvae	Eggs	Larvae
Zion	5.52×10^8	4.73×10^8	4.39×10^6	4.47×10^7	3.13×10^6	N/A	N/A
Cook	1.30×10^9	6.21×10^8	6.51×10^7	7.86×10^6	2.91×10^5	4.05×10^6	6.37×10^4
Bailly	6.16×10^8	3.86×10^9	3.80×10^7	4.14×10^6	2.87×10^5	1.24×10^4	1.42×10^4
Pulliam	1.52×10^8	2.93×10^8	4.84×10^4	6.87×10^5	2.52×10^4	2.32×10^6	5.17×10^5
Kewaunee	5.33×10^8	4.71×10^7	6.03×10^5	9.85×10^5	9.45×10^6	N/A	N/A
Point Beach	8.08×10^8	4.11×10^6	3.31×10^5	0	1.21×10^6	N/A	N/A
Port Washington	3.42×10^8	2.70×10^6	2.95×10^5	1.16×10^5	2.99×10^5	0	5.64×10^3
Lakeside	1.41×10^8	3.07×10^6	6.29×10^5	0	0	N/A	N/A
Oak Creek	8.93×10^8	6.14×10^6	1.59×10^6	5.96×10^4	4.41×10^6	N/A	N/A
Waukegan	4.08×10^8	2.93×10^9	1.18×10^7	2.73×10^7	1.37×10^5	N/A	N/A
Stateline	5.26×10^8	7.12×10^8	2.97×10^6	3.61×10^6	8.07×10^4	N/A	N/A
Mitchell	2.24×10^8	1.51×10^9	7.41×10^6	2.32×10^5	1.34×10^6	N/A	N/A
Campbell	3.35×10^8	6.48×10^4	2.25×10^3	1.24×10^2	1.49×10^3	0	0
Palisades	9.94×10^7	0	7.00×10^0	1.40×10^1	1.30×10^1	0	0
Big Rock	1.07×10^8	0	1.05×10^1	5.47×10^2	1.43×10^2	0	0
Total observed	7.04×10^9	1.05×10^{10}	1.33×10^8	8.98×10^7	2.06×10^7	6.38×10^6	6.01×10^5
Estimated annual total		1.11×10^{10}	2.01×10^8	3.10×10^8	2.71×10^7	6.77×10^6	6.12×10^5

dent on time of year and location. Almost 90% of the alewives were impinged at only 4 of the 15 plants. Maximum impingement of alewives occurred from May through July; this reflects the inshore spawning migrations of adults rather than seasonal changes in total cooling-water flow. Alewife impingement and commercial catch of alewife follow the same seasonal pattern (Fig. 2). Both the fishery and the power plants capture alewives as they move inshore to spawn.

An estimated 1.11×10^{10} alewife eggs and 2.01×10^8 alewife larvae were entrained at the 15 sampled intakes in 1975 (Table 2). Entrainment of alewife eggs was highest from May through August and entrainment of larvae was highest from June through September. No eggs were entrained from October to March and no larvae were entrained from January through April.

Rainbow smelt impingement at the sampled intakes was estimated at 9.77×10^3 kg in 1975 (Table 1). Four plants on the western shore of Lake Michigan accounted for about 94% of the total impingement. Peaks in rainbow smelt impingement occurred during the spawning period in April and smaller peaks also occurred in July and October; impingement decreased during the winter months. An estimated 3.10×10^8 rainbow smelt eggs and 2.71×10^7 larvae were entrained at the 15 sampled intakes in 1975 (Table 2). Entrainment was highest in April for eggs and highest in May and August for larvae. Entrainment occurred from March through June for eggs and from May through November for larvae.

Yellow perch impingement at the sampled intakes was estimated as 3.11×10^3 kg in 1975 (Table 1). Almost 85% of the total biomass was impinged at three power plants. Impingement was highest in late fall and early winter, but a spawning-related peak occurred in May. An estimated 6.77×10^6 eggs and 6.12×10^5 yellow perch larvae were entrained in 1975 (Table 2). Eggs were entrained between March and July and larvae were entrained between May and July.

Impingement and entrainment data represent fish losses at 15 of the 22 power plants located on Lake Michigan. To assess the total impact of water withdrawal we developed a list of all other water intakes and their capacity flows. Annual impingement and entrainment for unsampled intakes was estimated by multiplying the mean impingement and entrainment rates at all sampled plants in the same fishery statistical district by the capacity flows at unsampled intakes. The 15 sampled power plants account for almost 50% of the water withdrawn (Table 3).

TABLE 3.—*Estimates of biomass impinged (kg) and numbers of eggs and larvae entrained for three fish species at all power plant, municipal, industrial, and other water intakes on Lake Michigan, 1975. Full design flows are assumed.*[a]

Species	Impact	Total all power plants	Municipal industrial	Total all intakes
Alewife	Impingement	1.65×10^6	4.56×10^5	2.10×10^6
	Egg entrainment	4.56×10^{10}	2.83×10^{10}	7.39×10^{10}
	Larvae entrainment	1.10×10^9	2.14×10^8	1.31×10^9
Yellow perch	Impingement	1.25×10^4	6.20×10^2	1.31×10^4
	Egg entrainment	4.75×10^7	6.49×10^5	4.81×10^7
	Larvae entrainment	3.08×10^6	1.81×10^5	3.26×10^6
Rainbow smelt	Impingement	1.66×10^4	2.07×10^3	1.86×10^4
	Egg entrainment	4.71×10^8	1.44×10^8	6.15×10^8
	Larvae entrainment	6.75×10^7	1.53×10^7	8.28×10^7

[a] Annual maximum flows: total, all power plants, 4.18×10^{10} m^3; total, municipal and industrial, 6.51×10^9 m^3; total, all intakes, 4.83×10^{10} m^3.

Model Development

The surplus-production and dynamic-pool models were applied for stock assessment. Surplus production is the amount of biomass that can be removed from a population without causing a change in population size. Biomass removed is replaced by increased reproduction and growth. In the surplus-production model it is assumed that surplus production is some function of population size. The most widely applied surplus-production model is the logistic model in which change in yield and biomass with respect to time are given by the equations (Jensen 1976):

$$\frac{dY}{dt} = qEB; \quad (1)$$

$$\frac{dB}{dt} = kB - \frac{k}{B_\infty}B^2 - qEB; \quad (2)$$

B = biomass of the exploited stocks (kg);
q = catchability coefficient (unit of effort × time)$^{-1}$;
k = population growth constant (year^{-1});
Y = cumulative yield from the fishery (kg);
E = fishing effort (variable units);
B_∞ = the environmental carrying capacity in terms of biomass (kg);
t = time in years.

The model was expanded to include impingement and entrainment. For the ith water intake the accumulation of impinged fish biomass with respect to time is

$$\frac{dI_i}{dt} = f_i Q_i B; \quad (3)$$

I_i = biomass (kg) impinged at the ith water intake at time t;
Q_i = volume flow at the ith water intake (m^3/year);
f_i = impingement coefficient at the ith intake (m^{-3}).

The total impingement at n water intakes at time t is

$$I = I_1 + I_2 + \ldots + I_n, \quad (4)$$

and the rate of impingement lakewide is

$$\frac{dI}{dt} = \sum_{i=1}^{n} f_i Q_i B. \quad (5)$$

The rate of entrainment of eggs at the ith water intake is

$$\frac{dP_i}{dt} = p_i Q_i G; \quad (6)$$

P_i = number of eggs entrained at the ith water intake;
G = abundance of eggs in the lake (numbers);
p_i = egg entrainment coefficient (m^{-3}).

To relate entrainment of eggs to biomass of the exploited stock, we assume egg production is proportional to stock biomass. This is equivalent to the assumption that a percentage reduction in eggs results in the same percentage reduction in biomass of the exploited stock; there is no density dependence. Most fishery scientists assume prerecruitment mortality is density dependent (Beverton and Holt 1957; Ricker 1975). Our assumption is conservative

TABLE 4.—*Total catch and effort for alewife, rainbow smelt, and yellow perch in Lake Michigan, 1960–1977. (United States Fish and Wildlife Service, Great Lakes Laboratory, Ann Arbor, Michigan.)*

	Alewife		Yellow perch		Rainbow smelt	
Year	Yield	Effort[a]	Yield	Effort[a]	Yield	Effort[b]
1960	1,057,103	2,621	1,489,562	57,444	1,479,932	4,841
1961	1,449,346	2,327	2,574,813	98,958	715,538	2,620
1962	3,456,625	8,501	2,039,568	59,269	702,333	2,186
1963	2,448,165	24,582	2,210,272	50,186	526,710	2,045
1964	5,326,641	11,546	2,646,878	91,459	404,620	959
1965	6,353,358	7,425	695,885	49,878	419,599	1,124
1966	13,155,789	12,118	406,440	30,426	503,533	1,087
1967	19,054,064	16,742	573,967	27,501	554,953	812
1968	12,285,364	11,462	235,669	15,364	811,191	944
1969	13,330,230	10,050	291,719	15,719	1,125,453	641
1970	15,114,488	10,203	313,820	17,628	923,976	482
1971	13,450,181	7,599	338,270	18,324	588,707	369
1972	14,076,502	7,767	465,686	20,050	312,880	177
1973	16,584,780	11,872	339,997	20,372	393,846	336
1974	20,663,696	10,131	587,902	32,909	774,028	341
1975	15,961,428	7,730	344,354	22,946	527,318	208
1976	17,786,288	7,918	387,206	31,864	983,727	303
1977	21,959,808	7,931	439,831	44,057	331,362	300

[a] Equivalent pound-net lifts.
[b] Equivalent trap-net lifts.

and increases the impact of entrainment on stock biomass and yield because there is no compensatory decrease in natural mortality. The relation between eggs and biomass is

$$G = \left(\frac{B}{2}\right)EUB, \tag{7}$$

where EUB is the number of eggs produced per unit of female biomass. Lakewide, the change in biomass as a result of egg entrainment, $(\mathrm{d}B/\mathrm{d}t)_P$, is (see Appendix for derivation)

$$\left(\frac{\mathrm{d}B}{\mathrm{d}t}\right)_P = -\sum_{i=1}^{n} p_i Q_i B. \tag{8}$$

The rate of larval entrainment at the ith water intake is

$$\frac{\mathrm{d}H_i}{\mathrm{d}t} = h_i Q_i L; \tag{9}$$

H_i = number of larvae entrained at the ith water intake;
L = abundance of larvae in the lake (numbers);
h_i = larval entrainment coefficient (m^{-3}).

The abundance of larvae was related to egg abundance by the survival equation

$$L = (1 - \phi)G, \tag{10}$$

where ϕ is an egg mortality coefficient. The lakewide change in exploitable biomass resulting from larvae entrainment, $(\mathrm{d}B/\mathrm{d}t)_H$, is (see Appendix for derivation)

$$\left(\frac{\mathrm{d}B}{\mathrm{d}t}\right)_H = -\sum_{i=1}^{n} h_i Q_i B. \tag{11}$$

Equations (1)–(11) combine to give the biomass equation

$$\frac{\mathrm{d}B}{\mathrm{d}t} = kB - \frac{k}{B_\infty}B^2 - qEB - \sum_{i=1}^{n} f_i Q_i B - \sum_{i=1}^{n} p_i Q_i B - \sum_{i=1}^{n} h_i Q_i B. \tag{12}$$

Application of Equation (12) requires estimation of three biological parameters and many related to the water intakes.

In the dynamic-pool model, growth and mortality are modeled as functions of age. The structure and parameters of this model are easily interpreted biologically and this model has been widely applied for stock assessment. The conventional equations applied for yield, mortality, and growth are

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = FNW; \tag{13}$$

$$\frac{\mathrm{d}N}{\mathrm{d}x} = -(M + F)N, \quad x > x_c; \tag{14}$$

TABLE 5.—*Estimates of biological parameters for the surplus-production model: population growth constant,* k*; carrying capacity,* B_∞*; and catchability coefficient,* q.

Species	k (year^{-1})	B_∞ (kg)	q (effort time^{-1})
Alewife	0.30	400,000,000	0.00001
Yellow perch (lakewide)	0.20	15,000,000	0.0000014
Yellow perch (Green Bay)	0.20	7,000,000	0.0000015
Rainbow smelt	0.50	20,000,000	0.0001

$$\frac{dW}{dx} = 3KW_\infty e^{-Kx}(1 - e^{-Kx})^2; \qquad (15)$$

Y = annual yield;
F = instantaneous fishing mortality coefficient (year^{-1});
N = number of individuals of age x;
W = weight of an individual of age x (kg);
M = instantaneous natural mortality coefficient (year^{-1});
W_∞ = asymptotic individual weight (kg);
K = growth coefficient (year^{-1});
x_c = age when individuals become vulnerable to fishing (years).

The relation between the rate of impingement and biomass is the same as in the surplus-production model (Equation 5). The impact of impingement occurs through an increase in mortality; with impingement the mortality equation becomes

$$\frac{dN}{dx} = -(M + \sum_{i=1}^{n} f_i Q_i)N, \quad x_I \leq x < x_c; \qquad (16)$$

$$\frac{dN}{dx} = -(M + F + \sum_{i=1}^{n} f_i Q_i)N, \quad x \geq x_c, \qquad (17)$$

where x_I is the age when fish first become vulnerable to impingement. Biomass of the exploited stock is

$$B = \int_{x_c}^{\infty} NW \, dx, \qquad (18)$$

which gives, on substitution and integration,

$$B = RW_\infty e^{-\left(M + \sum_{i=1}^{n} f_i Q_i\right)(x_c - x_I)} \cdot \sum_{m=0}^{3} \frac{U_m e^{mKx_c}}{F + M + \sum_{i=1}^{n} f_i Q_i + mK}, \qquad (19)$$

where $U_0 = 1$, $U_1 = -3$, $U_2 = 3$, and $U_3 = -1$. The number of fish of age x_I is recruitment, R. The above biomass equation was applied to calculate biomass of the exploited stock.

Entrainment of eggs and larvae operates on the recruitment term. The equations for rate of entrainment of eggs and larvae are identical to those for the surplus-production model (Equations 6 and 9). In the dynamic-pool model, however, change occurs in the number of eggs and larvae over time. Change in the number of eggs is given by

$$\frac{dG}{dx} = -\left(M_1 + \sum_{i=1}^{n} p_i Q_i\right)G, \qquad (20)$$

where M_1 is an egg natural mortality coefficient. The initial number of eggs is $G(0) = EUB \cdot B/2$ and the number of eggs at age x is

$$G(x) = G(0)e^{-\left(M_1 + \sum_{i=1}^{n} p_i Q_i\right)x}. \qquad (21)$$

Change in the number of larvae with respect to age is

$$\frac{dL}{dx} = -\left(M_2 + \sum_{i=1}^{n} h_i Q_i\right)L, \qquad (22)$$

where M_2 is a natural mortality coefficient for larvae. The number of individuals of age x_I, when fish first become vulnerable to impingement, is

$$R = G(0)e^{-\left(M_1 + \sum_{i=1}^{n} p_i Q_i\right)\Delta x_1 - \left(M_2 + \sum_{i=1}^{n} h_i Q_i\right)\Delta x_2}, \qquad (23)$$

where Δx_1 is the duration of the egg stage in years and Δx_2 is the duration of the larval stage. In this model, mortality during the prerecruitment stages is density independent, which will increase the impact of entrainment. The recruitment equation can be substituted into the biomass equation to give an equation for assessment of the combined impacts of entrainment and impingement on the biomass of the standing stock and yield.

Parameter Estimation

The biological parameters of the surplus-production model, k, B_∞, and q, were estimated from the commercial fishery catch and effort data for the years 1960–1977 (Table 4). The data are recorded separately for each of several fishery statistical districts (Fig. 1), and for each species the catch is recorded separately for each

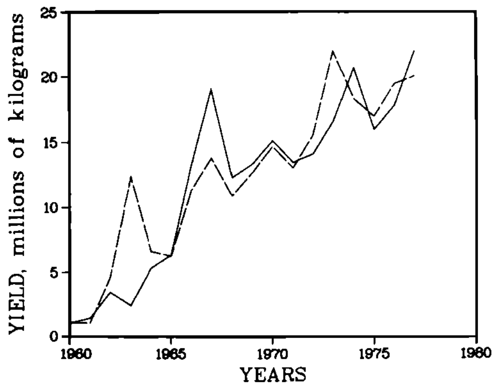

FIGURE 3.—*Observed yield (solid line) and yield predicted by the surplus-production model (dashed line) for alewife in Lake Michigan.*

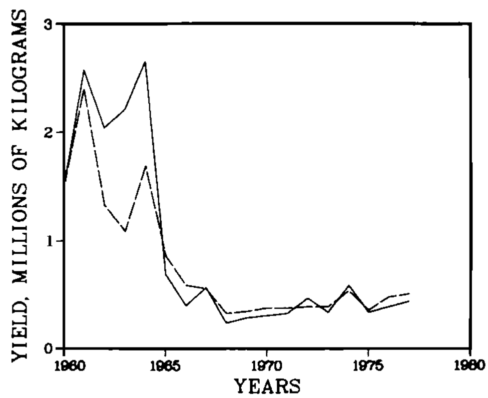

FIGURE 4.—*Observed yield (solid line) and yield predicted by the surplus-production model (dashed line) for yellow perch in Lake Michigan.*

type of fishing gear. To enable use of data for all districts and all years, a standard gear was selected for each species and the total effort necessary to make the observed catch with the standard gear was calculated as

$$\text{total effort} = \frac{\text{total catch}}{\text{CPUE with standard gear}},$$

where CPUE is catch per unit of effort.

For estimation of k, B_∞, and q (Table 5) nonlinear least squares was applied to minimize the residual sum of squares between the observed and calculated yields (Pella and Tomlinson 1969). For a set of parameters, calculated yields were obtained from the solution of the yield equation (Equation 1). The solution to the yield equation was approximated by use of the trapezoidal rule and the necessary biomass values were calculated from the solution of the biomass equation (Equation 2).

To estimate the proportion of larvae entrained, the egg mortality coefficient, ϕ, must be estimated. Estimates of egg mortality vary from 50% to 75% for yellow perch in Lake Erie (Patterson 1979), but estimation of mortality under natural conditions is difficult and few data are available. Under the assumption of an equilibrium between population size and egg production, the mortality of the prerecruitment life stages can be calculated. Under the assumption that most of this mortality occurs in the egg stage, ϕ was set at 0.99 for all species. This large value does not influence the estimate of egg-entrainment impact but it is likely to result in an overestimate of larval-entrainment impact because it underestimates the number of larvae.

Estimates of the number of eggs produced per unit of biomass, EUB, were obtained from the literature. The number of eggs produced per kilogram of alewife female was estimated as 368,000 which is 14,000 eggs per female of average weight (Norden 1967). From data published by Brazo et al. (1975), yellow perch egg production was estimated as 65,000 per kilogram, which is about 17,000 per average female. Rainbow smelt egg production per kilogram of female was estimated as 1,000,000, which is about 15,000 eggs per average female of age 2 and length 153 mm (Van Oosten 1940; Bailey 1964).

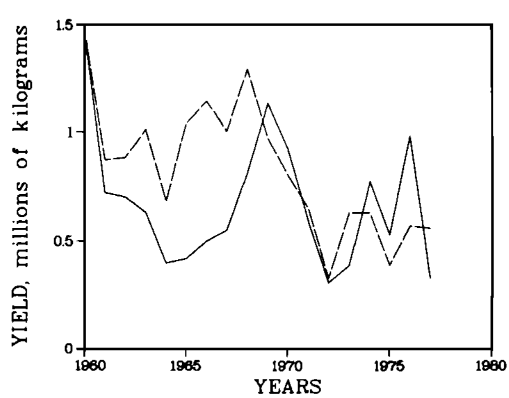

FIGURE 5.—*Observed yield (solid line) and yield predicted by the surplus-production model (dashed line) for rainbow smelt in Lake Michigan.*

TABLE 6.—*Entrainment and impingement coefficients for Lake Michigan power plants.*

Species	Coefficient	Surplus-production model			Dynamic-pool model		
		Mean	Maximum	Minimum	Mean	Maximum	Minimum
Alewife	Impingement	0.11×10^{-12}	0.27×10^{-12}	0.25×10^{-15}	0.89×10^{-13}	0.36×10^{-12}	0.21×10^{-15}
	Egg entrainment	0.17×10^{-13}	0.17×10^{-12}	0.64×10^{-17}	0.69×10^{-14}	0.38×10^{-11}	0.14×10^{-15}
	Larvae entrainment	0.22×10^{-15}	0.17×10^{-14}	0.28×10^{-20}	0.69×10^{-16}	0.39×10^{-13}	0.36×10^{-17}
Yellow perch	Impingement	0.67×10^{-14}	0.64×10^{-12}	0.99×10^{-16}	0.30×10^{-13}	0.60×10^{-12}	0.12×10^{-15}
	Egg entrainment	0.29×10^{-14}	0.18×10^{-13}	0.62×10^{-16}	0.49×10^{-15}	0.75×10^{-13}	0.26×10^{-15}
	Larvae entrainment	0.39×10^{-16}	0.36×10^{-14}	0.71×10^{-16}	0.40×10^{-16}	0.15×10^{-13}	0.79×10^{-16}
Rainbow smelt	Impingement	0.37×10^{-13}	0.31×10^{-12}	0.79×10^{-16}	0.38×10^{-13}	0.32×10^{-12}	0.81×10^{-16}
	Egg entrainment	0.22×10^{-13}	0.16×10^{-12}	0.30×10^{-16}	0.12×10^{-11}	0.84×10^{-11}	0.16×10^{-14}
	Larvae entrainment	0.21×10^{-14}	0.26×10^{-14}	0.91×10^{-19}	0.89×10^{-13}	0.49×10^{-12}	0.48×10^{-17}

The fits of the surplus-production model to the observed catch data are good for alewife and yellow perch (Figs. 3 and 4). The coefficients of determination R^2 are 0.78 for alewife, 0.85 for yellow perch, and 0.28 for rainbow smelt. The model does not accurately describe the catch of rainbow smelt from 1960 to about 1969 (Fig. 5) but since 1970 the fit is better ($R^2 = 0.56$).

Estimates of the impingement and entrainment coefficients (Table 6) were obtained from the surplus-production model by replacing the differential equations with difference equations. The resulting estimators are

$$f_i = \frac{\Delta I_i}{Q_i B^*},$$
$$h_i = \frac{\Delta H_i}{Q_i B^*}, \quad \text{and}$$
$$p_i = \frac{\Delta P_i}{Q_i B^*}. \qquad (24)$$

Numerators are the observed biomass impinged and the observed numbers of eggs and larvae entrained. For application of the surplus-production model, the average biomass during the year, B^*, was estimated from the surplus-production model. Water-flow, entrainment, and impingement data are in Tables 1 and 2.

Parameter estimates for the dynamic-pool model (Table 7) were obtained directly from the literature or were calculated from data therein. Length, weight, and age data for alewife were reported by Brown (1972). The growth parameters ($K = 0.31$; $W_\infty = 0.12$ kg) were estimated from these data by conventional procedures (Gulland 1969) and the exponent in the length-weight equation is 3.01. The total instantaneous mortality coefficient Z was estimated as 0.50 from age structure data reported by Edsall et al. (1974). With the estimate of q obtained with the surplus-production model and the observed average fishing effort, the instantaneous fishing mortality coefficient was estimated as $F = qE = 0.06$.

Much of the biological data for yellow perch in Lake Michigan is summarized by Brazo et al. (1975). From these data the growth parameters were estimated as $K = 0.45$ and $W_\infty = 1.0$ kg. It was assumed that the slope of the length-weight relation was 3. The total mortality coefficient was estimated as 0.36, and from q and the average fishing effort, the fishing mortality coefficient was estimated as 0.06. Parameters for rainbow smelt were estimated from Bailey's (1964) data.

The equations for parameters related to power plants in the surplus-production model were applied for the dynamic-pool model (Table 6). Biomass in these equations was estimated by the dynamic-pool model.

Impact Assessment

Both the surplus-production model and the dynamic-pool model were applied to estimate stock biomass, the proportions of the standing stocks impinged, and the proportions of eggs and larvae entrained. The surplus-production model also was applied to estimate the reductions in biomass and yield resulting from increased entrainment and impingement. Applications of the surplus-production and dynamic-pool models were kept as independent as possible so a comparison of the results obtained by the two models could be used as a basis for evaluation. Of the dynamic-pool mod-

TABLE 7.—*Estimates of parameters for the dynamic-pool model for alewife, yellow perch, and rainbow smelt in Lake Michigan.*

Parameters	Symbol	Alewife	Yellow perch	Rainbow smelt
Asymptotic weight (kg)	W_∞	0.1164	1.0	0.03
Average weight (kg)	W_{avg}	0.0392	0.265	0.0140
Catchable age (year)	x_c	2.0	3.0	2.0
Impingeable age (year)	x_I	1.0	1.0	1.0
Instantaneous fishing mortality coefficient (year^{-1})	F	0.06	0.06	0.03
Instantaneous natural mortality coefficient (year^{-1})	M	0.50	0.30	0.40
Age at maturity (year)	x_{mat}	2.0	2.00	2.0
Growth parameter (year^{-1})	K	0.31	0.45	0.56
Eggs per unit biomass (kg)	EUB	368,000	65,316	1,073,370
Egg mortality coefficient (year^{-1})	M_1	11.51	11.51	11.51
Larvae mortality coefficient (year^{-1})	M_2	5.50	5.50	5.50
Duration of egg stage (year)	Δx_1	0.10	0.10	0.10
Duration of larvae stage (year)	Δx_2	1.00	1.00	1.00

el parameter estimates, only the value for F came from the surplus-production model. The estimates of percentages impinged and entrained under the assumption of full flow at the 15 power plants are listed in Table 8. Alewives were the most frequently impinged and entrained, and the percentages of the alewife population impinged and entrained were also the highest, among the three species.

The proportions of biomass impinged are similar within each species for both models, but the estimates of proportions entrained are considerably different for the two models (Table 8). All of the parameters for estimation of impingement impact were estimated directly from the data, but for estimation of entrainment impact key parameters were of necessity estimated indirectly. Apparently, these estimates are not accurate. Although the percentages of eggs and larvae entrained are higher with the dynamic-pool model, the impact of entrainment on the biomass of the standing stock and yield is still small compared to the impact of impingement. If the impacts of entrainment were large, there would have been a need to more accurately estimate the egg and larvae mortality parameters.

The surplus-production model was applied to estimate the impact of the total capacity for water withdrawal from Lake Michigan—4.8×10^{10} m^3/year—and to simulate the impact of increased water withdrawals on the biomass of the standing stock and the maximum sustainable yield. Under equilibrium conditions where $dB/dt = 0$, the biomass equation with average impingement and entrainment coefficients f, p, and h is

$$B = B_\infty - \frac{qEB_\infty}{k} - \frac{(f + p + h)B_\infty}{k}. \quad (25)$$

With these coefficients, the relation between biomass and withdrawal flow for alewife is $B = 2.79 \times 10^8 - 0.00002Q$ (Fig. 6), the equation for yellow perch is $B = 1.23 \times 10^7 - 0.0003Q$, and the equation for rainbow smelt is $B = 1.56 \times 10^7 - 0.000002Q$. Increasing the volume of water withdrawn results in a slow linear decrease in the size of the standing stock. The impact of impingement is larger than that of entrainment. At withdrawals of 4.8×10^{10} m^3/year, biomasses are reduced 2.86% for alewife, 0.28% for yellow perch, and 0.76% for rainbow smelt, compared with no-flow conditions. When maximum entrainment and impingement coefficients (Table 6) are applied to the total flow, there is about a 10% decrease in biomass.

The impact of water withdrawal on the max-

TABLE 8.—*Estimates of percentages entrained and impinged at 15 Lake Michigan power plants operating at full water flow, calculated with surplus-production and dynamic-pool models.*

Species	Impact	Surplus-production	Dynamic-pool
Alewife	Impingement (kg)	0.25	0.21
	Egg entrainment	0.04	0.90
	Larvae entrainment	0.90	2.0
Yellow perch	Impingement (kg)	0.07	0.05
	Egg entrainment	0.007	0.02
	Larvae entrainment	0.03	0.14
Rainbow smelt	Impingement (kg)	0.15	0.15
	Egg entrainment	0.00008	0.043
	Larvae entrainment	0.00033	0.174

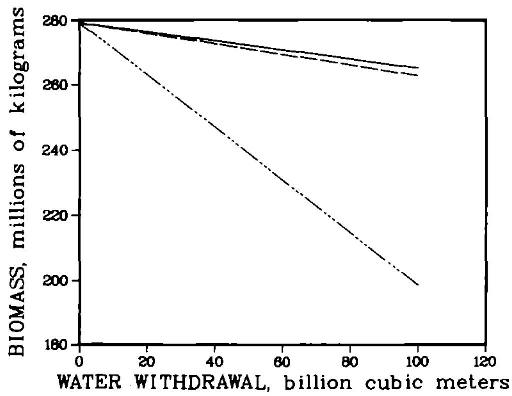

FIGURE 6.—*Effects of water withdrawal on the biomass of alewife in Lake Michigan when average impingement (top line), average impingement and entrainment (middle line), and maximum impingement and entrainment (bottom line) coefficients are applied to the surplus-production model.*

imum sustainable yield, MSY, can be found from the equilibrium yield equation

$$Y_e = kB - \frac{k}{B_\infty}B^2 - (f + h + p)QB, \qquad (26)$$

where Y_e is the annual equilibrium yield. In the presence of water withdrawals the biomass at which the maximum sustainable yield occurs is

$$\frac{[k - (f + h + p)Q]B_\infty}{2k}, \qquad (27)$$

and substitution of this biomass into the equilibrium yield equation gives

$$MSY = \frac{kB_\infty}{4} - \frac{(f + h + p)Q}{2} + \frac{B_\infty[(f + h + p)Q]^2}{4k}. \qquad (28)$$

The relationship between water withdrawal and maximum sustainable yield is not linear but the second degree term is small and a linear relationship is adequate. For average entrainment and impingement coefficients, the relation between water withdrawal and MSY are $MSY = 3 \times 10^7 - 0.000025Q$ for alewife, $MSY = 5 \times 10^5 - 0.0000006Q$ for yellow perch, and $MSY = 2.5 \times 10^6 - 0.0000006Q$ for rainbow smelt. Increased water withdrawal causes a slow decrease in the MSY. At a withdrawal rate of 4.8×10^{10} m^3/year, the reductions in MSY are 4% for alewife, 0.5% for yellow perch, and 1.2% for rainbow smelt.

Discussion

Our estimates of biomass impinged are higher than those reported by Kelso and Milburn (1979). Their estimate of the average weight of an impinged fish (0.075 kg) applied to their observed total number impinged in Lake Michigan gives 1.15×10^6 kg impinged. They assumed that this was an underestimate because it was made from a regression of numbers impinged on rated megawatt capacity. Using full design volume flow, we assume our estimate of 1.65×10^6 kg impinged is an overestimate. Despite the differences in assumptions and methods applied, these two estimates are reasonably close.

Kelso and Milburn (1979) reported that the number of fish impinged amounted to 25% of the total commercial catch on the Great Lakes. Most impinged fish are small alewives and a more meaningful comparison of impingement with the commercial catch is in terms of biomass for each species. Our estimates of biomass impinged and the 1975 commercial catch statistics (Table 4) indicate that under the assumption of full flow, impingement amounted to 10% of the commercial catch of alewife, 3.6% of that of yellow perch, and 3.1% of that of rainbow smelt.

Our estimate of the number of larvae entrained also is higher than that of Kelso and Milburn (1979). We estimated the total number of larvae entrained at conventional power plants under the assumption of full flow as 4.21×10^8. Applying a regression of number entrained on rated megawatt capacity, Kelso and Milburn (1979) estimated 1.96×10^8 larvae were entrained. These two estimates are in reasonable agreement despite the different assumptions applied.

To obtain impact assessments, the observed amounts impinged and entrained must be given relative to the sizes of the populations in the lake. Direct estimation of the biomass of a fish stock is difficult and assessment of the impact of entrainment and impingement is done most easily with a model that describes the response of a population to these impacts. Fishery models are relatively simple. Effort has been directed at parameter estimation rather than toward more elaborate models. The logistic surplus-production model was developed during the late 1920s and 1930s by Volterra (1928), Hjort et al. (1933), and Graham (1935). The assumptions and limitations of the surplus-production model are well known and are discussed in some detail by Pella and Tomlinson (1969) and Jensen (1976). Estimation of model parameters has been examined by Schaefer (1957), Pella and Tomlinson (1969), Fox (1970), Schnute (1977), Mohn (1980), and Uhler (1980). After successful development of methods for parameter estimation by Schaefer (1957), the model was widely applied for stock assessment (Schaefer 1957; Pella and Tomlinson 1969; Schaaf and Huntsman 1972; Jensen 1976, 1978). Laboratory studies have verified the general model structure (Silliman 1971).

Application of an early form of the dynamic-pool model to the fishery for Pacific halibut *Hippoglossus stenolepis* by Thompson and Bell (1934) was one of the most successful in fishery management (Ricker 1975). The mathematics of the model were developed mainly by Beverton and Holt (1957) and Ricker (1944). The model has been applied widely and its advantages and limitations are well known. Development and application of the model are discussed in detail by Gulland (1969).

The impact of impingement can be assessed just as that of a fishery. On the Great Lakes, both fisheries and power plants catch fish as the latter move toward shore; both operate largely on spawning stocks (Fig. 2). Seasonal fluctuations are not considered in conventional fishery assessment and they were not considered in this assessment of power plants. To model the impact of entrainment substantial modifications of the models are necessary; in this study the simplest modifications were applied. The models fit the data well and the results obtained by applying the two different models are in general agreement.

Biomass estimates generated by the models were compared with trawl-based estimates of biomass made by the United States Fish and Wildlife Service. Hatch et al. (1981) estimated the adult alewife biomass vulnerable to bottom trawling as 86,000,000 to 131,600,000 kg in 1975. We estimated biomass as 206,000,000 kg with the surplus-production model and 237,000,000 kg with the dynamic-pool model (Table 9). The 1975 rainbow smelt biomass in Lake Michigan was estimated as 13,700,000 kg by Hatch (personal communication). We estimated the biomass of rainbow smelt as 25,000,000 kg with the surplus-production

TABLE 9.—*Estimates of species biomass (kg) in 1975 determined for Lake Michigan by the United States Fish and Wildlife Service (Hatch 1981), surplus-production model, and dynamic-pool model (kg).*

Species	Fish and Wildlife Service	Surplus-production model	Dynamic-pool model
Alewife	122,000,000	206,000,000	237,000,000
Yellow perch		11,000,000	25,000,000
Rainbow smelt	14,000,000	25,000,000	15,000,000

model and 15,000,000 kg using the dynamic-pool model (Table 9). The biomass estimates obtained with the models are somewhat higher than those based on sampling with bottom trawls, which are probably underestimates (Hatch et al. 1981). Yellow perch biomass was estimated as 11,000,000 kg with the surplus-production model and 25,000,000 kg with the dynamic-pool model, the first such estimates for the Lake Michigan population.

Lakewide application of the models assumes complete mixing of stocks within the lake. To determine what influence this assumption might have on the results, the impact of the Pulliam Power Plant on yellow perch in Green Bay was investigated with the surplus-production model. The parameter estimates for Green Bay are $q = 0.0000015$, $k = 0.20$, and $B_\infty = 7{,}000{,}000$ kg (Table 5). The carrying capacity B_∞ of Green Bay is estimated at about 50% of the lakewide carrying capacity. The growth rates and catchability coefficients are about the same in Green Bay and Lake Michigan. The fit of the model in Green Bay is similar to the lakewide fit, and the pattern of catches is similar.

The impingement and entrainment coefficients are higher when the impact on Green Bay is assessed than when the impact on Lake Michigan is assessed. This is expected because the biomass available to the Pulliam Plant is considerably reduced when only Green Bay is under consideration. The estimate of the proportion of yellow perch in Lake Michigan impinged at the Pulliam Power Plant is 0.50×10^{-3}. The proportion of the biomass in Green Bay impinged is 1.0×10^{-3}. The yellow perch population of Green Bay in 1975 was about 50% of the lakewide estimate for 1975. From the proportion of biomass in the lake impinged and the percent of the population of the lake estimated to be in Green Bay the proportion impinged in Green Bay is estimated as 0.50×10^{-3}, which is identical to the estimate obtained for Green Bay data.

This study indicates that conventional fishery models can be usefully applied for environmental-impact assessment. Accurate assessment of entrainment requires more accurate estimation of larva and egg mortality parameters than was attempted in this study, but the approach taken here appears satisfactory for identification of situations that represent threats to fisheries. Although large numbers of alewife, rainbow smelt, and yellow perch are killed by entrainment and impingement, the proportions of the populations affected are relatively small. Still, the loss of fish biomass is not negligible, and entrainment and impingement impacts need to be considered in the design of new intake facilities.

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Appendix

Derivation of Equation (8)

The relation between egg production and biomass is (Equation 7)

$$G = \left(\frac{B}{2}\right)EUB.$$

From this equation

$$B = \frac{2G}{EUB},$$

and differentiation gives

$$\frac{dB}{dt} = \frac{2}{EUB}\frac{dG}{dt}.$$

This same relation applies for eggs entrained at a power plant,

$$\left(\frac{dB}{dt}\right)_P = \frac{2}{EUB}\left(\frac{dG}{dt}\right)_P,$$

where $(dG/dt)_P$ is the rate of change in number of eggs in the lake as result of entrainment. The rate of loss of eggs from the lake as result of entrainment equals the rate of accumulation of eggs at the power plant, hence, $(dG/dt)_P = -dP/dt$. Therefore,

$$\left(\frac{dB}{dt}\right)_P = -\frac{2}{EUB}pQG,$$

but $G = (B/2)EUB$ and, therefore,

$$\left(\frac{dB}{dt}\right)_P = -pQB.$$

This equation is applied to each power plant and the equations are summed to give Equation (8).

Derivation of Equation (11)

The relation between larvae production and egg production is (Equation 10)

$$L = (1 - \phi)G.$$

Substitution for G (Equation 7) gives

$$L = (1 - \phi)\frac{EUB}{2}B,$$

and differentiation gives

$$\frac{dL}{dt} = (1 - \phi)\frac{EUB}{2}\frac{dB}{dt}.$$

This same relationship applies to larvae entrained at a power plant, hence,

$$\left(\frac{dL}{dt}\right)_H = (1 - \phi)\frac{EUB}{2}\left(\frac{dB}{dt}\right)_H,$$

where $(dL/dt)_H$ is the rate of change in larvae in the lake as a result of entrainment at the power plant. The rate of loss from the population equals the rate of accumulation at the power plant, $(dL/dt)_H = -dH/dt$, and

$$\frac{dH}{dt} = -(1 - \phi)\frac{EUB}{2}\left(\frac{dB}{dt}\right)_H.$$

Substitution from Equation (9) on the left side gives

$$hQL = -(1 - \phi)\frac{EUB}{2}\left(\frac{dB}{dt}\right)_H,$$

but $L = (1 - \phi)G$ and $G = (EUB/2)\cdot B$, so,

$$hQ(1-\phi)\left(\frac{EUB}{2}\right)B = -(1-\phi)\left(\frac{EUB}{2}\right)\left(\frac{dB}{dt}\right)_H,$$

and cancellation of similar terms gives

$$\left(\frac{dB}{dt}\right)_H = -hQB.$$

This equation is applied to each power plant and the resulting equations are summed to give Equation (11).