HYDRODYNAMIC SIMULATION OF MOVEMENT OF LARVAL FISHES IN WESTERN LAKE ERIE AND THEIR VULNERABILITY TO POWER PLANT ENTRAINMENT

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ABSTRACT

A three-dimensional, time-dependent transport model for yellow perch larvae in western Lake Erie is presented. The model is used to predict the vulnerability of larvae spawned in different sections of Michigan waters to entrainment by the Detroit Edison electrical generating plant at Monroe, Michigan. Independent estimates of larval entrainment for 1975 and 1976 from Michigan waters are compared with the predicted results.

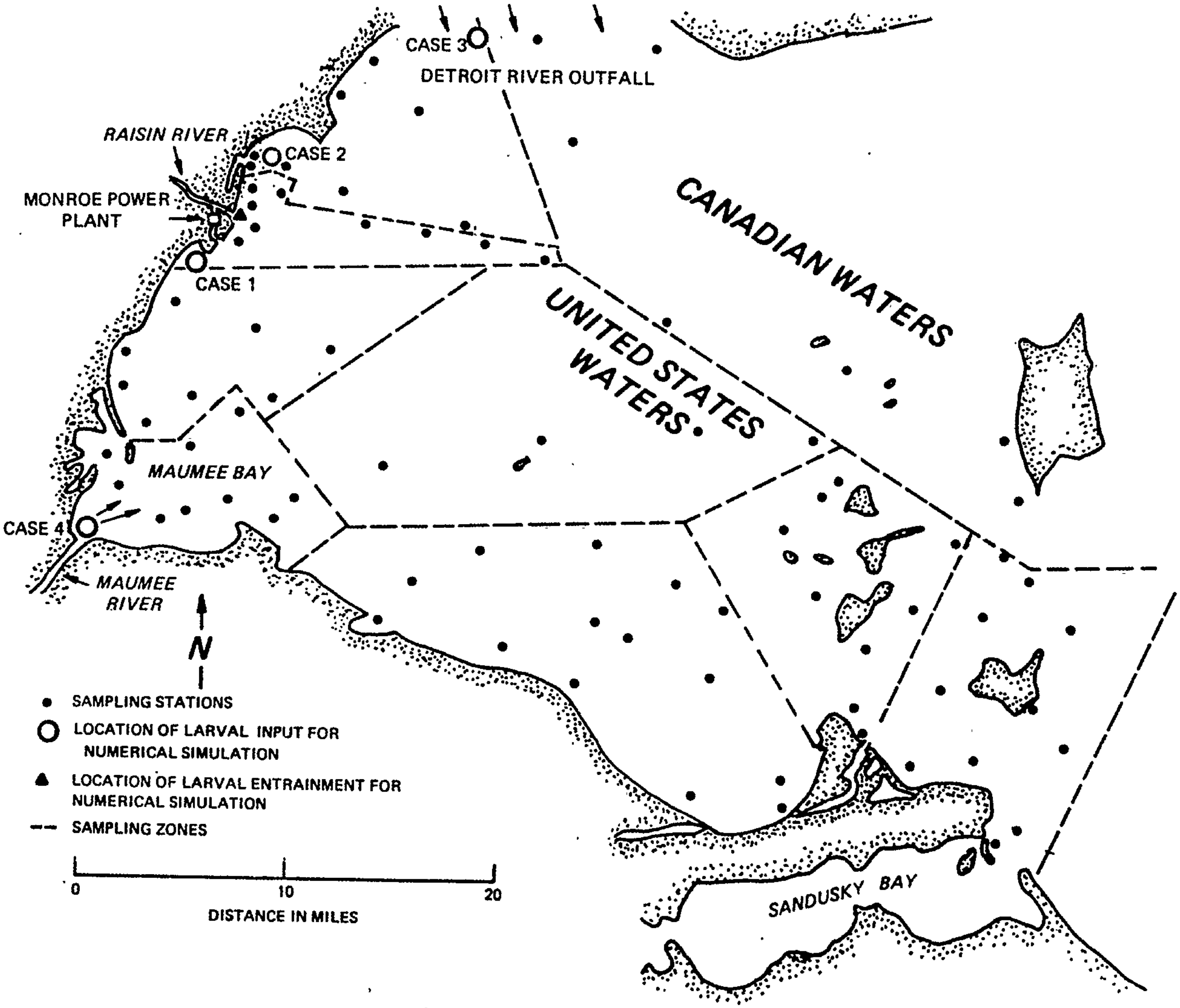
INTRODUCTION

Electrical power generating stations which employ open-cycle, once-through cooling systems for discharging waste heat require large volumes of water - up to eight million cubic meters per day for a plant with a capacity of 3200 megawatts. In an open cycle system, water is pumped from a source into an intake canal or pipe, through a heat exchanger where it accumulates heat energy, and finally into a discharge canal from which the water is returned to the natural environment. Small plants and animals which are carried into the intake with cooling water are said to be "entrained". Extreme physical and sometimes chemical conditions are encountered in the entrainment cycle (7) which cause mortality of up to 100 percent of all living animals that are captured in the relatively high velocity waters at the intake. Extremely large numbers of larval fishes - tens of millions per year of a single species - can be killed due to entrainment in a once-through cooling system. Larvae are transported initially into the vicinity of a cooling water intake by a combination of their own swimming behavior and water circulation. Once larvae arrive in the general vicinity of the intake, a proportion of the population will be transported to an area within the range of capture by intake currents. During their initial life stages, larval fishes therefore risk entrainment even though they may be initially hatched kilometers from the mouth of a cooling water intake. It was exactly this unknown risk of loss of a large part of the Hudson River striped bass population that led to prolonged power plant licensing hearings by the Federal Power Commission (3) during the period 1972-74, before Consolidated Edison of New York was allowed to begin operation of two new plants.

The present study assesses vulnerability of larval yellow perch under typical late spring meterological conditions to entrainment in cooling waters of the Detroit Edison power plant located at Monroe, Michigan (Figure 1). The Monroe plant is the largest electrical power generating station on Lake Erie and has a capacity of 3100 megawatts, with a maximum cooling water pumping capacity of 100 cubic meters per second. Specifically, after operation at 50 percent capacity for one 24 hour period, 4.32×10^6 cubic meters of water is cycled through the system, a volume sufficient to fill a container one kilometer square and 4.3 meters deep. The power plant cooling water intake is located just upstream from the mouth of the Raisin River. Lake and river water mix when entering the cooling cycle, with 5 to 95 percent of daily consumption being withdrawn from Lake Erie, and the remainder from the Raisin River upstream of the intake. There is a chance that larvae produced at a given location in the shoreline waters (0-4 meter depth zone) of the State of Michigan will be transported into the lake area adjoining the mouth of the Raisin River from which cooling water is withdrawn. The purpose of the present study is to assess the likelihood that yellow perch larvae which are hatched in a given location in Michigan waters of the western basin will be transported into the lake area adjoining the mouth of the Raisin River, and then drawn into the cooling water intake.

A previously developed hydrodynamic model for Lake Erie is used to predict the movement of fish larvae assumed to originate at four separate areas shown in Figure 1. The areas just north and south of the intake (Raisin River mouth) are two miles distant, while the areas located at the mouths of the Detroit and Maumee River are 16 and 13 miles distant, respectively. The numerical model calculates the larval transport for ten days, during which substantial numbers of larvae are transported past the intake where cooling water is assumed to be continuously withdrawn at 50% of capacity. Vulnerability to entrainment is defined as the percentage of the total number of

FIGURE 1
Western Lake Erie Fish Larval Study



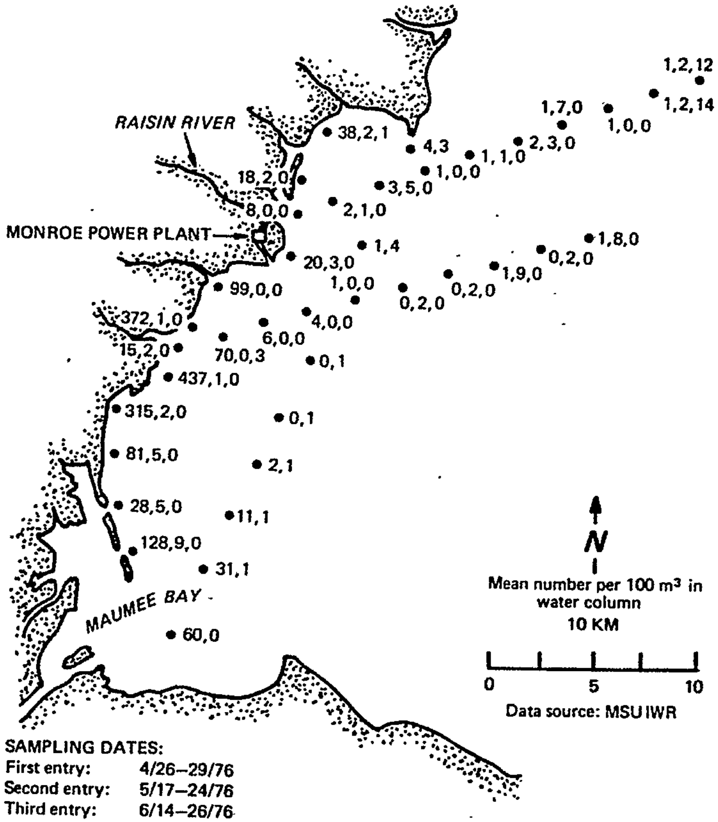
organisms assumed to originate in a given area that are withdrawn by power plant cooling water over a period of ten days. The vulnerabilities of yellow perch larvae to entrainment are calculated with respect to the four separate locations defined in Figure 1. These calculations are compared to estimates (based on field measurements) of percent of larvae produced in Michigan waters in 1975 and 1976 that were entrained by the Monroe power plant.

DISTRIBUTION AND MOVEMENT OF LARVAL YELLOW PERCH IN WESTERN LAKE ERIE

Adult yellow perch spawn in late April or early May in bays, inlets, streams, or along beach fronts of the open lake. Eggs are not attached to solid objects and thus are easily transported by wind driven currents. Eggs hatch in 5-10 days, initiating the yolk-sac or pro-larval stage. They concentrate on the bottom, and soon exhibit a vertical migration in the water column. Lateral movement during this 6-8 day pro-larval stage is believed to be due virtually entirely to dispersive and convective water transport. As larvae increase in size and in swimming ability, they continue to concentrate at the bottom (1,5). Figure 2, representing bottom and surface concentrations, illustrates the highly skewed vertical daytime distribution. Statistical analysis of surface and bottom concentrations (5, Appendix 1) showed highly significant ($p<.005$) differences in surface and bottom concentrations. Similar tests on nighttime concentrations showed that, although

FIGURE 3

Temporal Variation in Lateral Distribution in Western Basin



Mean number per 100 m³ in water column

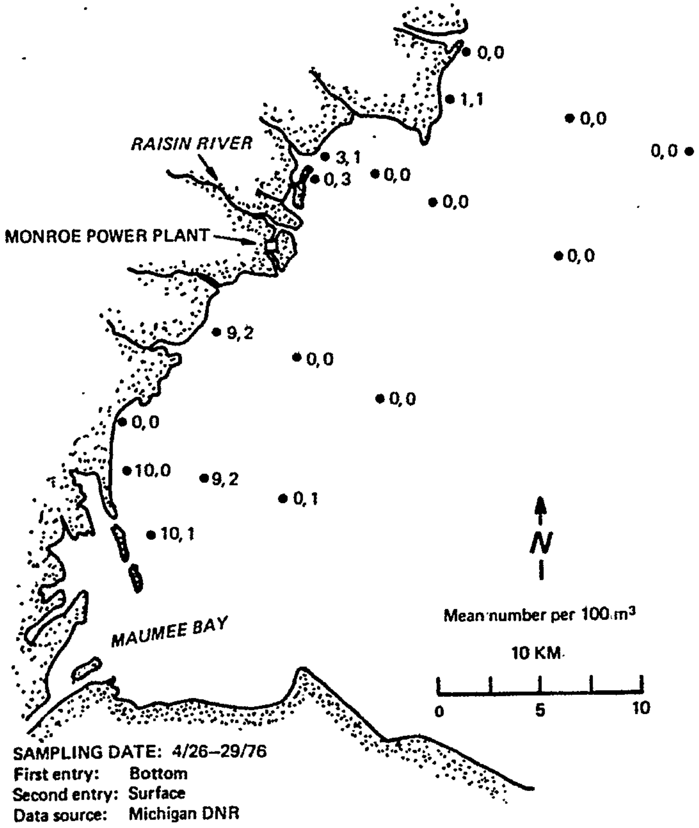
10 KM

Data source: MSU IWR

SAMPLING DATES:
First entry: 4/26–29/76
Second entry: 5/17–24/76
Third entry: 6/14–26/76

FIGURE 2

Comparison of Surface and Bottom Concentrations in Western Basin



Mean number per 100 m³

10 KM

SAMPLING DATE: 4/26–29/76
First entry: Bottom
Second entry: Surface
Data source: Michigan DNR

the vertical distribution was less skewed, bottom concentrations remained significantly higher ($p < .005$) than surface concentrations. Analysis of surface-bottom differences in Ohio waters showed the same skewed vertical daytime distribution. An exception occurred in Maumee Bay where surface concentrations were found to be as high or higher than bottom concentrations. This is probably because Maumee Bay is shallow and well mixed vertically.

Larvae absorb the yolk-sac after 6-8 days and exercise more active lateral swimming behavior which, coupled with continued lateral transport by currents, results in their dispersal throughout the entire sampling area during the following 15-20 days (Figure 3). As maturation progresses, larvae become more capable of avoiding capture by standard larval sampling gear until 100% avoidance occurs 20-30 days after hatching.

Water circulation in the western end of the basin is such that under the predominate southwesterly wind, surface water from Maumee Bay moves northeast along the Michigan shoreline carrying larvae that were hatched in the bay and in beach waters along the shoreline. A percentage of these larvae will be entrained by the Monroe power plant. Simultaneously, water from the northern end of the basin, in the vicinity of the Detroit River outfall, moves along the bottom in a southwesterly direction carrying along with it larvae that were hatched in the Detroit River or possibly in Lake St. Clair. Figure 3 shows two relatively high concentrations at a location south of the Detroit River outfall, indicating that larvae may be moving southwest at that point. Therefore, it is plausible that larvae originating in the Detroit River or Lake St. Clair could be entrained by the Monroe power plant.

DESCRIPTION OF THE MODEL

Summary of the Hydrodynamic Model

The equations for the hydrodynamic model are derived from the time-dependent, three-dimensional equations of motion for a viscous fluid. The basic assumptions used in the model are: (a) Eddy coefficients are used to account for turbulent diffusion effects. The coefficients are taken to be constant, but different values are used for the horizontal and the vertical. (b) The rigid-lid approximation is valid, i.e., the vertical velocity at the undisturbed water surface is zero. This approximation is used to eliminate surface gravity waves and the small time scales associated with them, greatly increasing the maximum time step possible in the numerical computations. (c) The pressure is assumed to vary hydrostatically.

The model equations, as described in detail in (6) are:

1. The three-dimensional, incompressible continuity equation,
2. Two time-dependent, three-dimensional horizontal momentum equations,
3. The Poisson equation for the pressure.

The boundary conditions used with the above equations are as follows: The bottom and shore are taken as no-slip, impermeable surfaces. Inflows or outflows are specified at rivers. A wind-dependent stress is imposed at the water surface. The boundary conditions for the pressure are derived from the appropriate horizontal momentum equation.

The equations and boundary conditions are put into appropriate finite difference form in both space and time. A strictly conservative numerical scheme is used in the model. In addition, a stretching of the vertical coordinate proportional to the local depth is used. With this transformation, the same number of vertical grid points are present in the shallow as in the deeper parts of the lake. This ensures that in the shallow areas there is no loss of accuracy in the computations due to lack of vertical resolution. Refer to (6) for details.

Larval Transport Model

For the present work, the transport and dispersion of the larvae in the turbulent flow will be described in a manner similar to that used for the transport and turbulent dispersion of heat and momentum. Refer to (8) for a summary of this procedure. Larval concentrations are treated as continuous on the length scales considered and as completely conservative substances convected with the local fluid velocities. The only exception to the latter condition is in modeling the experimental observation that the yellow perch larvae tend to concentrate near the bottom of the water column. In this instance, the vertical convection of the larvae is enhanced by a settling velocity. The basic equation used to predict the transport of the larvae is:

$$\frac{\partial C}{\partial t} + \frac{\partial (Cu)}{\partial x} + \frac{\partial (Cv)}{\partial y} + \frac{\partial (Cw)}{\partial z} = \frac{\partial}{\partial x}\left(D_H \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_H \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_V \frac{\partial C}{\partial z}\right)$$

where:

C = larval concentration per unit volume,
x,y = horizontal coordinates,
z = vertical coordinate,
t = time,
u,v = larval (or fluid) velocities in the x and y directions,
w = larval velocity (the sum of the fluid velocity and the settling velocity, w_s, of the larvae relative to the fluid) in the z direction,

D = horizontal eddy diffusivity (8×10^5 cm^2/sec),
D = vertical eddy diffusivity (1.8 cm^2/sec).

The boundary conditions used are that all surfaces have no net flux of larvae through them except at rivers, where the net flux is either into or out of the lake depending on the flow of the river and the magnitude depends on the local larvae concentration. These equation and boundary conditions are finite differenced in space and time consistent with that used for the hydrodynamic model.

Application to Western Lake Erie

The Monroe power plant in western Lake Erie was used for this application because it has the largest cooling water requirements in Lake Erie, and because it is located near the largest spawning areas for yellow perch in the lake. Lake Erie presently provides the largest fish catch for all of the Great Lakes (4). It is estimated that 1.5×10^9 yellow perch larvae are spawned each year in U.S. waters of western Lake Erie (5). As a result, some concern has been raised over the effect of the Monroe power plant intake on the fishing industry. A major project, of which this work is a part, was initiated to study the effect of the water intake on the fishing industry in western Lake Erie.

The hydrodynamic model previously summarized is presently being used in conjunction with a model to predict sediment transport and resuspension in western Lake Erie (9). The model is being used for the spring 1976 period and is being verified with both ship survey data and aircraft overflight scans. In the sediment transport application, the hydrodynamic model is uncoupled from the sediment transport. (Sediment concentrations in the water are assumed to be small enough so that they do not affect the flow.) Since the model is specialized to the western end of the lake, it would consume enormous amounts of computer resources to use a fine numerical grid over the entire lake. To this end, a two-region approach was used: In the western end of the lake, a one mile grid is used, while in the rest of the lake an 8 mile grid is used. These 2 regions are coupled and calculated simultaneously through time. However, because of the less stringent numerical time step restriction in the large grid region, only one time step is taken in this region for each eight time steps in the western end. It is important that the whole lake transport be calculated simultaneously because motions in the central and eastern basins can affect the western end. For the velocities required in the larval transport model, the fluid velocities calculated in the hydrodynamic component of the sediment transport model are used directly.

For the application to the larval transport model, the time-dependent flow will not be used. Insufficient field data are available for larval concentrations to do calculations for an actual episode in time. Instead, flow conditions typical in late spring will be used to illustrate transport of the larvae initially spawned at different locations in the western end of the lake. The calculations for the larval transport, however, will be time-dependent. A southwesterly wind at 10-15 mph is predominant over western Lake Erie in late spring (2) and the steady-state currents for this wind condition are used. All of the larval transport calculations are run for 10 days of time after the initial implantation at a particular site. The period of 10 days is picked because it covers the early life time of the larvae when they are essentially passive in terms of swimming abilities. As larvae start to swim, an additional - and unknown - factor should be included to properly represent larval transport. It is observed even in the early life stages of yellow perch larvae that they tend to concentrate near the lake bottom (refer to previous section on distribution and movement of larvae). To include this behavior in the model, a 'settling velocity' is added onto the vertical fluid velocity to account for the larvae's predeliction for the lake bottom. This settling velocity term does not differentiate actually how - either by swimming or by adjusting of their buoyancy with respect to the water - the larvae concentrate at the bottom; it effectively mimics nature in such a way to describe what is observed.

MODEL RUNS AND RESULTS

A total of 8 separate calculations (4 different locations for larvae implantation, with and without settling velocity) are made, each for a 10 day time period. The value used for the settling velocity is determined from the fact that the surface and bottom measurements of larval concentrations indicate that bottom values are approximately an order of magnitude higher. Based upon a one-dimensional steady state balance of vertical convection and vertical diffusion, a settling velocity is determined that gives approximately an order of magnitude difference in concentrations between the top and bottom. The settling velocity used is .0125 cm/sec.

Figures 4 to 7 show time traces of larval concentrations per unit surface area (integral of concentration over the depth) in the vicinity of the power plant intake for all calculations. Each plot reflects a different initial location (see Figure 1) of the larvae and shows the results with and without settling velocity. The first two cases (larvae intially south and north, respectively, of the intake) initially have larvae implanted at one grid cell each at 100 larvae per unit surface area. Case 3 (larvae in Detroit River) has the 3 grid cells across the mouth of the river each implanted with 100 larvae per unit surface area. Case 4 (larvae in Maumee River) has 2 grid cells across the Maumee Bay each with 100 larvae per unit surface area. In all cases, larvae were initially distributed with all of them at the bottom. Initial numbers of larvae are arbitrary because the transport equation is linear.

FIGURE 4
Time Trace of Larvae Near Intake

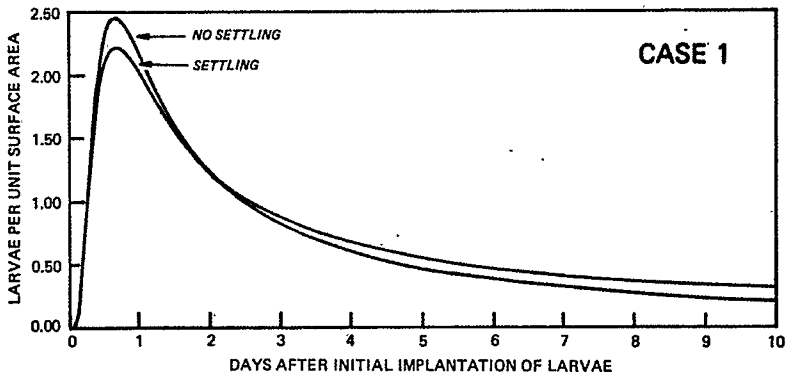


FIGURE 5
Time Trace of Larvae Near Intake

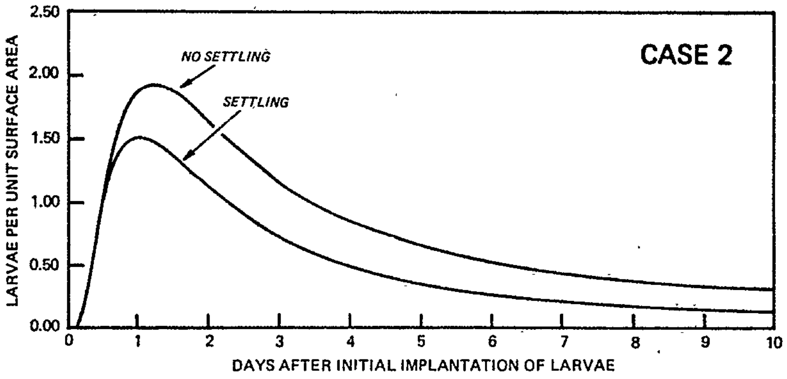


FIGURE 6
Time Trace of Larvae Near Intake

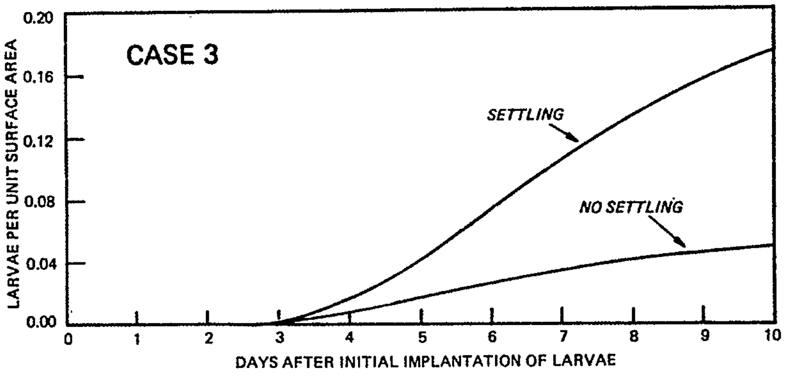
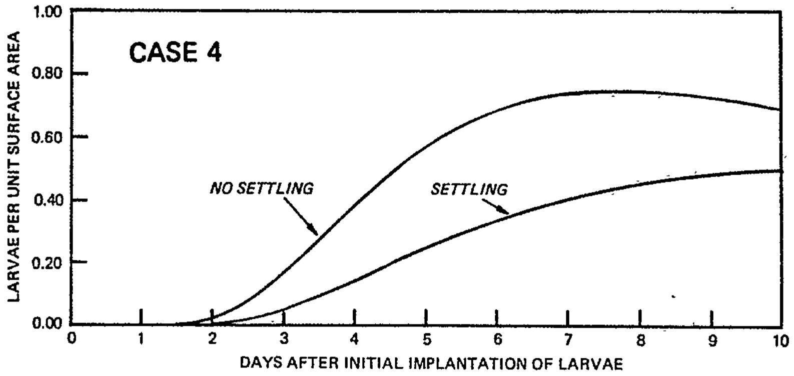


FIGURE 7
Time Trace of Larvae Near Intake



The effect of settling can be seen in Cases 1 and 2. Because of local complexities in currents and vertical diffusion, a time delay occurs in movement of larvae past the intake, the result of which is the crossing over of the two curves for Case 1 only (Figure 4).

The effect of settling is readily seen in the results and is quite dramatic in Cases 3 and 4. These results are easily understood by referring to the plots (Figures 8 and 9) of the horizontal currents at the surface and at the 5/6-depth. (These are currents 5/6 of the distance to the bottom. In the model, these are the calculated currents just above the bottom where all currents are zero.) Surface currents are normally in different directions from and substantially higher than those near bottom. This physically accounts for differences in results when larvae tend to be uniformly distributed vertically (no settling) and when concentrated near bottom (settling).

Horizontal contours of larvae concentrations for Case 3 after 10 days are shown in Figures 10 to 13. These contours are plotted at the surface and at bottom. Comparing the results for the settling and no settling calculations, it is apparent that the concentrations are a) one order of magnitude lower at the surface for the settling case compared to the no settling case and b) one order of magnitude higher at the bottom for the settling case compared to the no settling case. There is also an indication that contours are shifted to the southwest for the settling case. This shifting is obvious when the horizontal contour plots for the vertically integrated larvae concentrations are examined (Figures 14 and 15). These are plots of total numbers of larvae over the water column per unit of surface area. The reason for the shift in concentrations for the two cases is that the currents just south of the Detroit River outfall are along the Canadian shore (eastward) at the surface and are southwest near the bottom. The explanation for a shift to the southwest even in the surface contours for the settling case is due to the large concentrations at the bottom and the resultant vertical diffusion.

Vertically integrated larval concentrations for Case 4 are shown in Figures 16 and 17. With settling, the larval transport appears as a net uniform outward movement from the river. For the other case, the transport is predominantly along the Michigan shore. As before, these results are due to the difference in directions of surface and near bottom currents.

DISCUSSION AND CONCLUSIONS

When the projected mean larval concentrations at the power plant intake are multiplied by the cooling water intake rate ($4.32 \times 10^6 M^3$ per day or 50% capacity) and the products summed over a ten day period, the result is an estimate of the number of larvae entrained which originated ten days earlier at one of the four sources shown in Figure 1. An estimate of the percent entrained is obtained for each case by dividing the calculated number entrained by the hypothetical number originally implanted. The resulting percentages (Table 1) provide estimates of vulnerability to entrainment by the Monroe power plant for yellow perch larvae, originating at specific spawining sites in the western end of the basin. Two estimates are given for each case: settling assumes a skewed distribution of larvae in the water column reflecting the tendency of larvae to settle to the bottom, and no settling assumes that larvae tend to be distributed uniformly in the water column. The settling case is the more realistic as vertical downward migration of larval yellow perch has been observed to occur consistently throughout the western basin. Since water in the western basin moves in different directions at the surface and bottom it is important, as illustrated by Table 1, to include the vertical migratory behavior of the larval species under study. It is assumed in the calculations for Table 1 that equal volumes of water are withdrawn at all depths throughout the water column. This assumption is believed to be realistic due to the geometric configuration of the intake channel at the Raisin River mouth. If larval avoidance of the river mouth is known to occur the percentages given in Table 1 can be reduced accordingly. However, since avoidance is more likely to occur with older larvae, no adjustment of the calculated percentages for avoidance was made. The percentages given in Table 1 do not take into account death of larvae and subsequent removal from the water column. In reality, between 10 and 50 percent of larvae will die or be eaten within 10 days after hatching and cannot be charged to power plant entrainment. However, the percentages in Table 1 are not adjusted for other causes of mortality as only the effect of transport of larvae from spawning sites to the entrainment site is being investigated. The larval transport model can be modified to include a first order decay term.

The chance that a larva will be entrained by the Monroe plant within the first ten days of its existence, given that it hatches in Michigan shoreline waters, varies between 0.006 and 0.04, depending upon its original location. That is, between 6 and 40 out of every 1000 yellow perch larvae hatched in Michigan shoreline waters may be expected to be entrained by the Monroe power plant after ten days of life provided they are not removed from the water column for other reasons. If larvae originate as far away as the Detroit River, approximately one larva out of every 1000 may be expected to be entrained by the Monroe plant, provided it is not otherwise removed from the water column. Larvae which originate within two or three miles north or south of the intake are entrained in approximately equal percentages, the reason being that surface water moves past the intake from the south while water near bottom moves past the intake from the north. Larval settling in the water column produces a slightly higher chance of entrainment when originating just north of the intake. Table 1 suggests that for larvae originating south of the power plant intake along

FIGURE 8
Surface Currents in Western Lake Erie for Southwesterly Wind

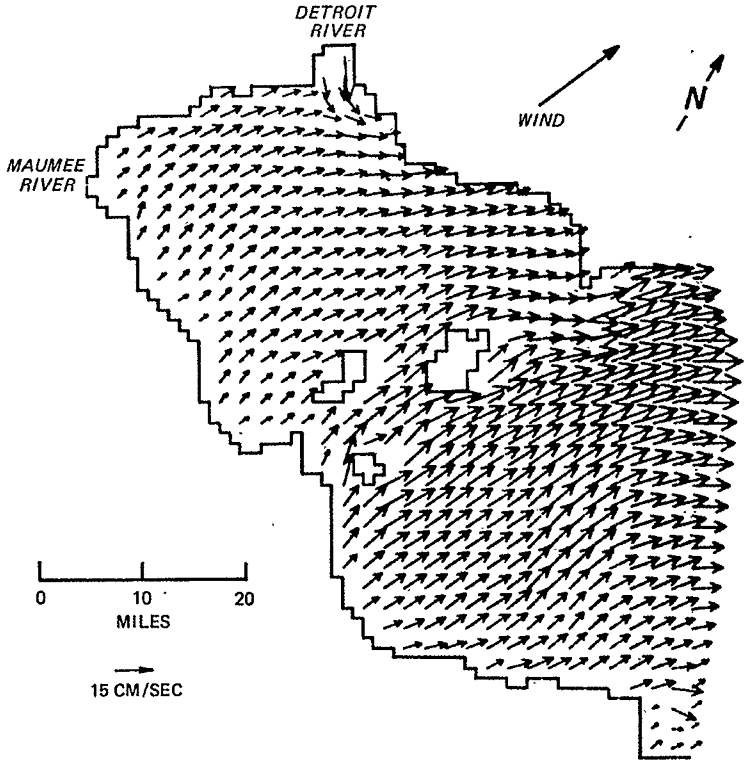


FIGURE 9
Near Bottom Currents in Western Lake Erie for Southwesterly Wind

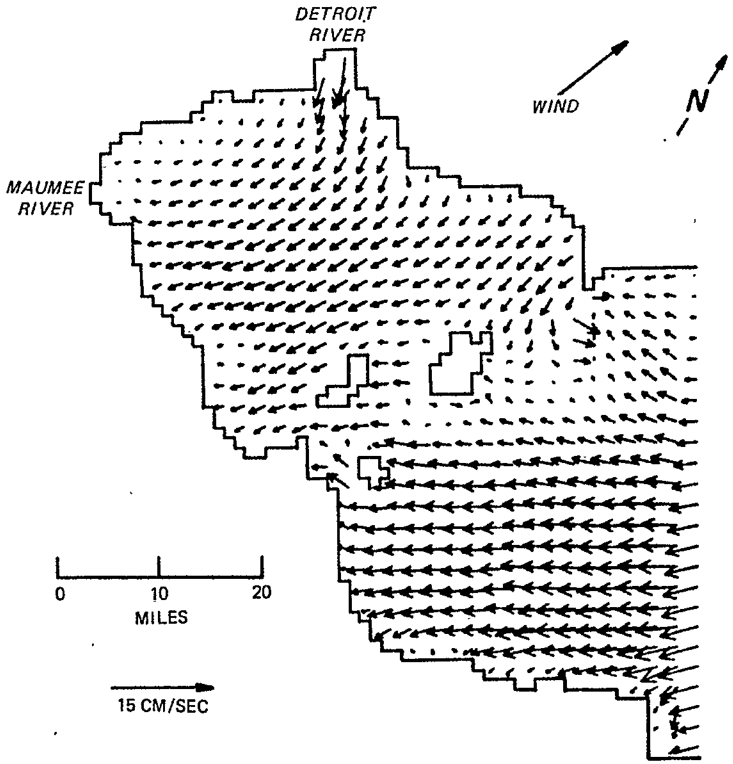


FIGURE 10
Surface Larval Concentrations After 10 Days

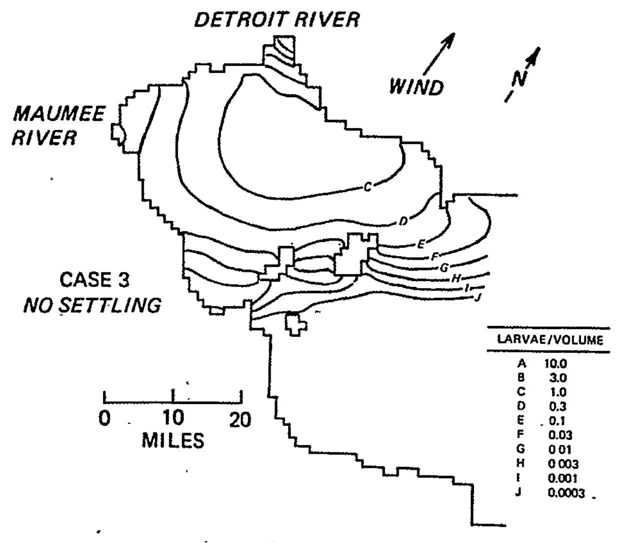


FIGURE 11
Bottom Larval Concentrations After 10 Days

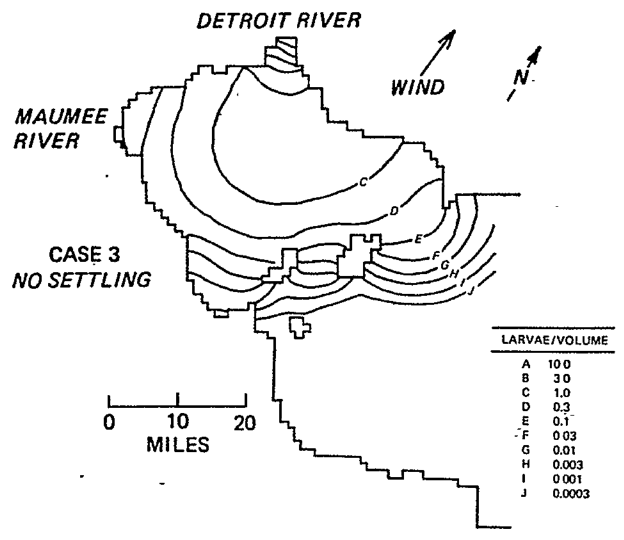


FIGURE 12
Surface Larval Concentrations After 10 Days

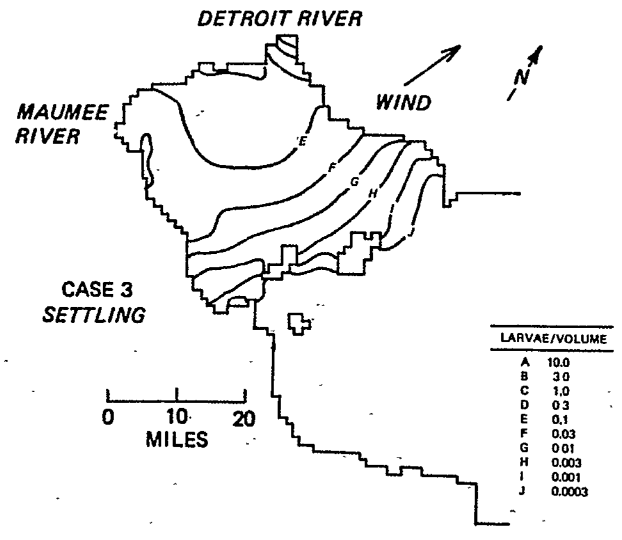


FIGURE 13
Bottom Larval Concentrations After 10 Days

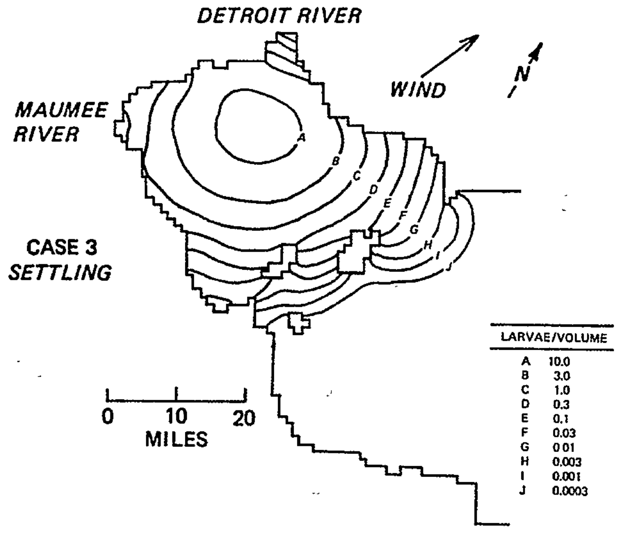


TABLE 1
Percent of Larvae Vulnerable to Entrainment After 10 Days

	CASE 1 SOUTH OF INTAKE	CASE 2 NORTH OF INTAKE	CASE 3 DETROIT RIVER	CASE 4 MAUMEE RIVER
NO SETTLING	3.5	2.6	.03	1.1
SETTLING	3.7	4.0	0.1	0.6

the Michigan shoreline, vulnerability to entrainment is inversly proportional to their distance from the intake.

Although the numerical model only calculates vulnerability to entrainment during the first ten days of larval life, additional numbers entrained beyond the tenth day may be estimated. The time traces of larval density indicate that the percentages shown in Table 1 for the more distant sources would increase substantially, while the percentages corresponding to sources near the intake would increase only slightly. As larvae increase in size their swimming ability becomes an increasingly more dominant factor in their movement, and hence the assumption that no significant lateral swimming motion occurs is suspect. The numerical model does not distinguish between clumps of larvae and an individual larva so far as their movement is concerned. The model requires that all larvae follow the same rules governing vertical and lateral movement regardless of their density.

Estimates of percent entrained shown in Table 1 are consistent with estimates obtained experimentally (5). Based upon analysis of data collected in 1975 and 1975 at all of the Michigan sampling stations shown in Figures 1 and 2, it was estimated that between 1.5 and 3.6 percent of yellow perch larvae produced in Michigan waters were entrained by the Monroe power plant. The present study does not attempt to simulate the estimate obtained from field data. Verification would require a) more detailed knowledge of numbers, locations, and timing of eggs spawned, b) a first order decay term representing larval mortality, c) more detailed meterological conditions, and d) a time-dependent description of cooling water withdrawal.

The importance of three-dimensionality in the numerical model becomes obvious when it is discovered that water in the western basin can simultaneously move in opposite or nearly opposite directions at surface and near bottom at a single location. Approximately equal percentages of larvae entrained when originating two miles north and south of the intake could not have occurred unless larvae were moving in opposite directions past the intake. Lateral movement at a fixed depth is in a constant direction and at a constant speed as required by steady state conditions and hence could not explain such a result. Three-dimensionality does not require the assumption of uniformity in the vertical direction.

The numerical model can also be used to assess vulnerability to entrainment by one or several power plants or other sources of water withdrawal simultaneously positioned at arbitrary locations around the basin shoreline. No additional modification is needed provided total percent loss is five percent or less. For larger losses, the larvae entrained would have to be calculated along with the transport.

Based upon the present study, it is concluded that: a) approximately 1-4 percent of yellow perch larvae spawned in Michigan waters will be entrained by the Monroe power plant under typical late spring conditions, b) larvae entering Lake Erie from the Detroit River can be entrained by the Monroe power plant, c) the model used in this study is a feasible predictive tool for assessing impacts of existing or proposed facility sitings.

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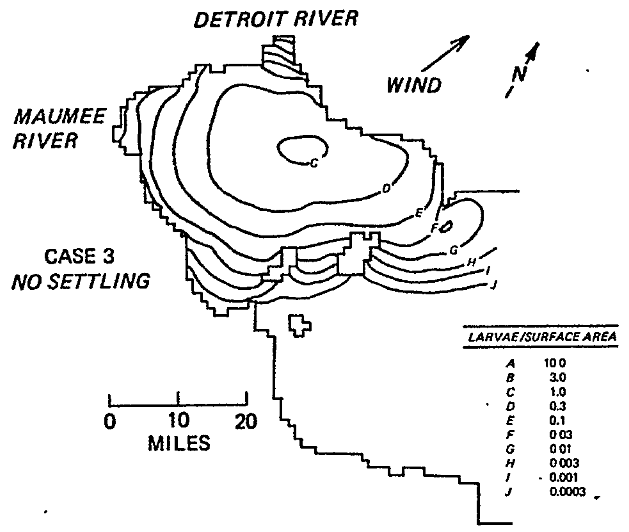
FIGURE 14
Vertically Integrated Larval Concentrations After 10 Days

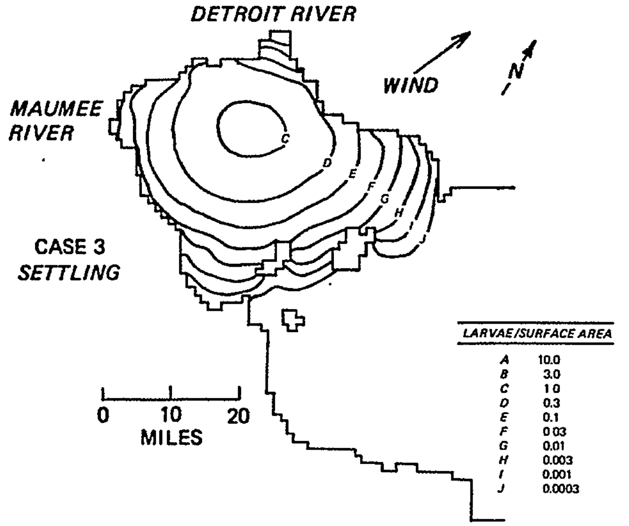
FIGURE 15
Vertically Integrated Larval Concentrations After 10 Days

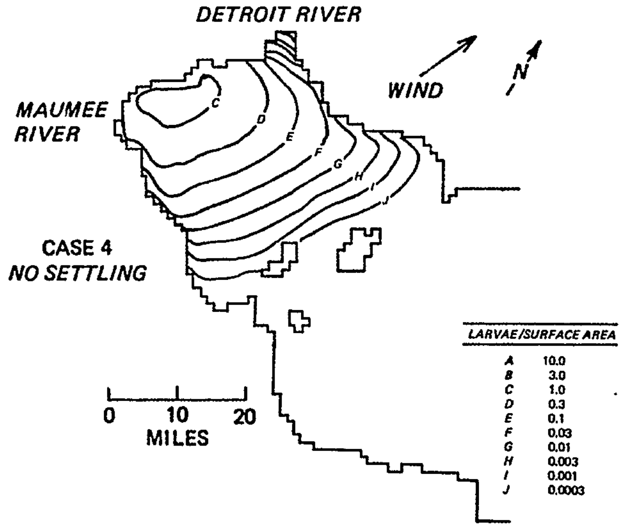
FIGURE 16
Vertically Integrated Larval Concentrations After 10 Days

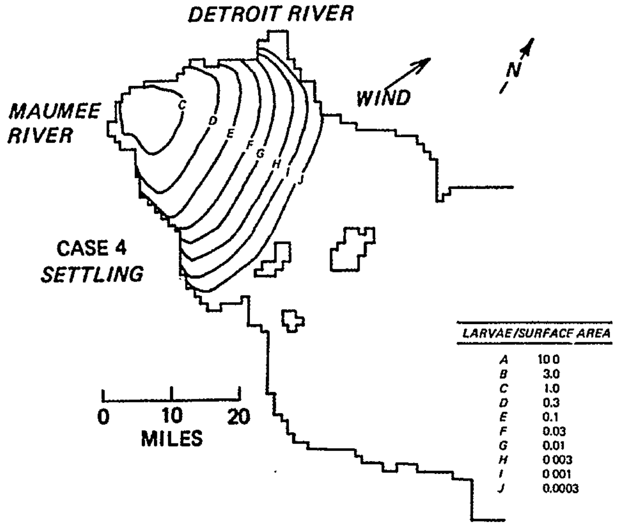
FIGURE 17
Vertically Integrated Larval Concentrations After 10 Days

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