

# Simulating the Lateral Transport of Ichthyoplankton in the Potomac Estuary<sup>1</sup>

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**ABSTRACT:** Previous simulations of potential ichthyoplankton entrainment by power generating stations on the Potomac estuary have not included the influence of lateral transport in distributing eggs and larvae over the nursery area. Therefore, two-dimensional, vertically-averaged hydrodynamic and kinematic models of passive organism transport were developed to represent advective and dispersive processes near the proposed Douglas Point Nuclear Generating Station. Although the more refined model did not substantially alter the estimate of ichthyoplankton entrainment, it did reveal that lateral inhomogeneities in hydrodynamics could engender severalfold differences in entrainment probabilities on opposite sides of the estuary. Models of higher resolution and greater biological detail did not project greater total entrainment by the Douglas Point plant, because the volume of nontidal flow past the site was large in comparison to the proposed rate of cooling water withdrawal.

## Introduction

Anadromous fishes are the mainstay of the commercial fish harvest from the North American estuaries. In Maryland, for example, striped bass (*Morone saxatilis*) leads all other fish in dollar value of annual harvest, with the yearly catch averaging close to 1,500 metric tons over the last 39 years. However, stocks of east coast anadromous fishes have generally been in decline during the past decade.

It is widely accepted that the most significant mortalities for anadromous fishes occur during the early planktonic or juvenile life stages, and subsequent yearclass strength is roughly proportional to the size

of the cohort of fingerlings (Chadwick et al. 1977). Therefore, attention must be focused upon any factors critical to the survival of eggs and larvae. One such factor is the cropping of eggs and larvae due to large withdrawals of tidal waters by power generating stations. Entrainment losses from power plants are commonly estimated through model calculations based on assumptions about the behavior of the organisms and the effects of the physical environment.

Unfortunately, there is no unique model for a given entrainment scenario. Among eight separate models of striped bass entrainment by the planned Cornwall pumped storage plant and the Indian Point Nuclear Unit #2, both on the Hudson estuary, there was little agreement as to the fraction of the early spawn which would be cropped (Wal-

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lace 1975). Estimates ranged from 2.8% to 110% (Lawler 1972; Eraslan 1974).

Ideally, one should be able to compare model results against independent data so as to choose that model with the best "predictive" powers. Such verification, however, is not always as easy or unambiguous as it might sound. First, independent data sets do not always exist. Even when they do, they are often not compatible with the spatial and temporal intervals of the model. Even in those cases where data acquisition was well-planned, questions necessarily remain about the variability of phenomena at sub-grid scales and between sampling times.

Lacking suitable data for direct verification, Wallace (1975) expressed a preference for the results of the Lawler model because of the qualitative detail which that simulation includes. Wallace may well be correct in her preference for that particular simulation. Certainly, to ignore a process which is controlling the variable of interest will result in unreliable or faulty prediction. But it is not correct to claim that a model of greater detail will necessarily yield more reliable predictions (Ulanowicz 1979). One cannot say *a priori* whether adding more qualitative detail and finer spatial resolution will fortify or erode the predictive ability of a model.

The problem posed by the entrainment of striped bass ichthyoplankton is not confined to the Hudson River estuary. The tidal freshwater reach of the upper Potomac estuary is the spawning area for a large fraction of the breeding stock of striped bass migrating up Chesapeake Bay. Here, too, are situated several existing fossil fuel generating stations and the site of a proposed nuclear facility (Douglas Point). The Maryland Power Plant Siting Program has commissioned at least two independent modeling efforts (see Warsh 1975) to forecast the entrainment of striped bass eggs and larvae by the intake of the proposed nuclear cooling system.

The primary purpose of this article is to summarize the methodology and results of one of those efforts. We have employed an intermediate field, two-dimensional, horizontal hydrodynamic model to simulate the transport and entrainment of striped bass

ichthyoplankton in the vicinity of Douglas Point. This model is hydrodynamically of higher resolution (but biologically more simplified) than an earlier effort by Warsh (1975). Warsh, in turn, cites an even more rudimentary estimate of entrainment. Taken as a whole, these three models form an interesting gradation in hydrodynamic detail. Comparing the results of the three representations provides a counterpoint to the Hudson River controversy and an interesting example of the costs and benefits of greater resolution and detail.

#### A Rudimentary Estimate

Many estimates can be approached strictly from a dimensional point of view by identifying characteristic scales of length, mass, time and temperature associated with each of the component processes (Long 1963; O'Brien and Wroblewski 1973). A theorem in dimensional analysis (attributed to Buckingham-Pi, Long 1963) states that when  $m$  parameters contain  $n$  fundamental dimensions,  $m-n$  independent dimensionless groupings can be formed. When any of the dimensionless groups differs substantially from unity, it will either dominate (control) the coupled set of processes or be of such minor import that it may be ignored.

Of particular interest in the case under study is the ratio of the two flow rates affecting the entrainment process (Warsh 1975). The net nontidal flow going past the plant at any one time is governed by the freshwater input up to the given point in the river. During May and June the average flow rate is about 370 m<sup>3</sup> per s (peak tidal flow is about 6500 m<sup>3</sup> per s), whereas the intended withdrawal rate is about 2.25 m<sup>3</sup> per s. The ratio of withdrawal rate to nontidal flow rate (0.006) should control the degree of entrainment.

#### A Behavioral Model

To refine estimates such as the one above, the Applied Physics Laboratory of The Johns Hopkins University was contracted to model how larval behavior and development might affect their dispersion and entrainment (Warsh 1975).

To simulate hydrographic transport, a tidally-averaged, two-dimensional, lateral-

ly-averaged kinematic model was used. The entire estuary was divided longitudinally into 1.85 km segments. Each longitudinal segment was further separated into ten equally-thick layers. The fractions of transport in each layer were calculated from tidally-averaged current profiles obtained from field measurements taken by the Chesapeake Bay Institute. Nontidal flow was driven by riverine inflows measured weekly at Washington, D.C.

Spawning distributions were determined by data gathered during the 1974 field program of the Potomac River Fisheries Program (see next section). Several patterns of vertical migration were studied. The uniform vertical distribution was contrasted to scenarios in which the eggs sank (either slowly or rapidly) and the larvae either rose or dived. Eggs and larvae younger than 19 days were assumed to have no appreciable swimming behavior, but older organisms were assumed to gain in swimming ability in a linear fashion until age 91 days. Directional swimming was not attempted, rather the mobility of the larvae was assumed to augment the horizontal diffusion process. Entrainment avoidance was also assumed to increase at a constant rate from 19 to 91 days of age.

As a result of running the model and observing the sensitivity of the calculated entrainment to various changes in behavioral parameters, estimated yearly entrainment was put at 0.6% with uncertainties in larval behavior allowing for as much as 1.2% of the year's spawn to be destroyed at the intake.

#### The Potomac River Fisheries Program (PRFP)

To help assess the impact of electric generating facilities upon striped bass eggs and larvae and to portray the distributions of ichthyoplankton in a quantitative manner, a large scale data acquisition program was carried out in the upper Potomac estuary. Although the sampling design presented here is specific to the 1974 survey, no significant alterations to the program were made in subsequent years. Twelve transects were established along the study area from 69 km above the mouth (in the oligohaline) region to 151 km, well into the fresh-

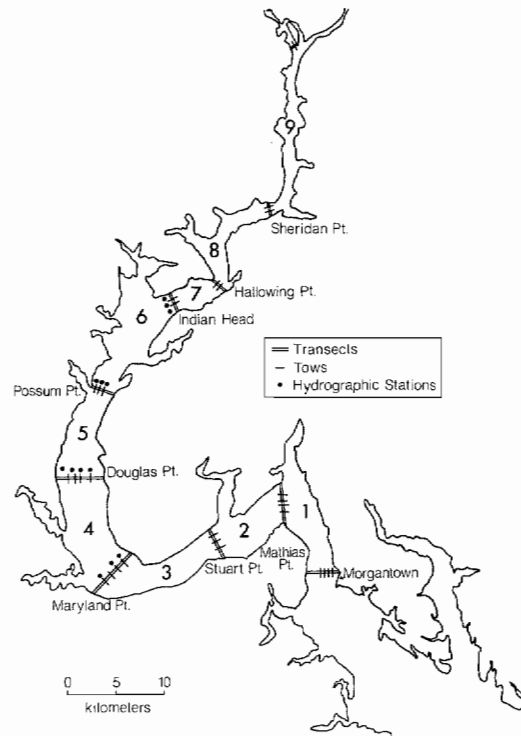


Fig. 1. Potomac River Fisheries Program ichthyoplankton tow sites and hydrographic stations.

water region and above the major area of spawning activity. The transects divided the estuarine reach into equal volume ( $2 \times 10^8 \text{ m}^3$ ) segments, each having a length greater than a single tidal excursion (Fig. 1). One boat sampled all transects weekly throughout the 17-week duration of the spawning and developmental periods. Several vertically oblique tows were taken perpendicular to each cross-stream transect at 38 separate locations (total for all 12 transects) as shown on Fig. 1.

All ichthyoplankton were identified to species (where possible) and were counted for each tow. Striped bass ichthyoplankton were further classified into four life stages: eggs, yolk-sac larvae, finfold larvae, and post-finfold larvae. Further details of the sampling program and later modifications are described by Polgar et al. (1976), Polgar (1977), Boynton et al. (1977), Mihursky et al. (1976) and Setzler et al. (1978).

To assess the role of tidal currents in establishing the observed ichthyoplankton distributions, a hydrographic survey of the

region of greatest spawning activity was undertaken during the beginning of the 1974 spawning season. Thirteen current meter stations were established along the Maryland Point, Douglas Point, Possum Point and Indian Head transects as shown in Fig. 1. Divided among the 13 stations were 21 Model 1301 Braincon Histogram recording current meters. Current speed and direction were automatically recorded at 10-min intervals over a 15-day period from April 23 through May 8.

#### The Horizontal Tidal Wave Model

Previous statistical analysis of the egg and larvae data indicated significant differences in lateral occurrence (shallows vs. channel) of eggs and larvae (Polgar et al. 1975). Furthermore, tidal averages and progressive vector diagrams of the current measurements indicated a drift towards the Virginia shore at almost all stations and depths. It was apparent that lateral inhomogeneities were present.

A full, three-dimensional hydrodynamic model incorporating all modes of the behavior was clearly impractical. Warsh had already demonstrated that, above the salt wedge, swimming behavior and vertical position of the organisms were not crucial to overall entrainment estimates. Furthermore, the freshwater region under study was well mixed in the vertical direction. It appeared to us to be sufficient to simulate dispersion in the longitudinal and lateral directions, i.e., via a two-dimensional, vertically-averaged model. A treatment of hydrodynamic events on a time scale short with respect to a tidal cycle was necessary for two interrelated reasons. First, the river in the study region is only a few kilometers wide, and appreciable lateral transport might occur during an interval of an hour or so. Second, progressive vector diagrams suggested lateral drift was the result of events occurring over only a small segment of the tidal cycle.

#### The Hydrodynamic Algorithm

Because this study was not for the development of hydrodynamical modeling techniques, we chose to modify and use an existing two-dimensional, vertically-averaged algorithm (Leendertse 1967). The

computations are numerical approximations of momentum and mass balances for shallow water, long wavelength gravity waves (i.e., the semidiurnal tides). While the inertial and gravitational forces tend to dominate the momentum balances, Coriolis "force" and boundary stresses (wind stress and bottom friction) are also included. We simplified the input requirements to the Leendertse algorithm by writing a series of three "screening" routines which automatically format the input data. The screening routines, modified Leendertse program and the dispersion algorithms described below are listed by Ulanowicz et al. (1979).

As with any finite-difference hydrodynamic model, it is necessary to provide information on the tides and/or currents at the open water boundaries (near Indian Head and Maryland Point in our model). We chose to drive our simulation by specifying the tidal heights at the boundaries according to the formula

$$\psi = \psi_0 + A \sin[2\pi(t + \phi)/\omega]$$

where  $\psi_0$  is the average height of the point above sea level,  $A$  is the amplitude of the tidal wave,  $\phi$  is the phase of the tide with respect to an arbitrary reference point and  $\omega$  is the semidiurnal tidal constant. We felt the qualitative aspects of tidal dispersion would be adequately represented by the semidiurnal tide, and therefore neglected the lower frequency tidal components. The initial values of  $\psi_0$ ,  $A$  and  $\phi$  for each boundary cell were taken from the USCGS tidal height tables. The model was calibrated by making slight adjustments to the  $\psi_0$  and  $A$  parameters until velocities at certain internal points agreed with the data taken at the same location. The calibrated difference in  $\psi_0$  (ca. 1.8 cm) was approximately  $\frac{1}{3}$  of the height difference reported in the USCGS tables.

To characterize a typical tidal cycle from the time series of observed velocities we represented each component series by a fifth-order Fourier polynomial of the form

$$v_i = B_i + \sum_{n=1}^5 C_{in} \sin[2\pi n(t + \phi_i)/\omega]$$

where  $v_i$  is the approximated component of velocity at point  $i$ ,  $\phi_i$  is the phase difference at point  $i$ , and  $B_i$  and  $C_{in}$  are six coefficients

determined from the current data by the method of least squares. Since any one station consisted of a string of several current meters, the velocity at the corresponding grid point was taken to be the vector average of the polynomial velocities over depth. The output of the model was then compared with the horizontally-averaged velocities synthesized from the data. If one plots the components of the velocity vector over a full tidal cycle, the tip of the vector will generate an ellipse-like trajectory. A comparison of the "phase-plane" trajectories of the model output and the synthesized data are shown in Fig. 2.

### The Dispersion Routine

Because the young larvae do not have appreciable swimming ability and because Warsh found position in the well-mixed water column did not dramatically affect his results, we assumed the ichthyoplankton were being passively transported by the water currents. There are a number of horizontal kinematic models which simulate the dispersion of passive substances. We chose to modify Hess and White's (1976) version of the Leendertse (1970) routine.

While the dispersion algorithm may be run as a subroutine of the hydrodynamic program, it was very costly to execute the hydrodynamic simulation over the many tidal cycles necessary for this study. Thus, we used the dynamic program to synthesize a single complete tidal cycle. This simulated tidal cycle was used repetitively to drive the kinematic model.

A legitimate concern in using any dispersion routine is the error in numerical dispersion induced by the finite difference scheme. In our scheme, the numerical error dominates over the dispersion due to small-scale turbulence, but both of these effects are quite small in comparison to the dispersion resulting from large scale tidal advection. Even when concentration gradients are as steep as 25% per kilometer of river, numerical diffusion is only 7% of advective dispersion (Ulanowicz et al. 1979). Hence, we may expect a good simulation of actual dispersion over times greater than a tidal cycle.

Since computer costs precluded analyzing a steady release of eggs over a wide

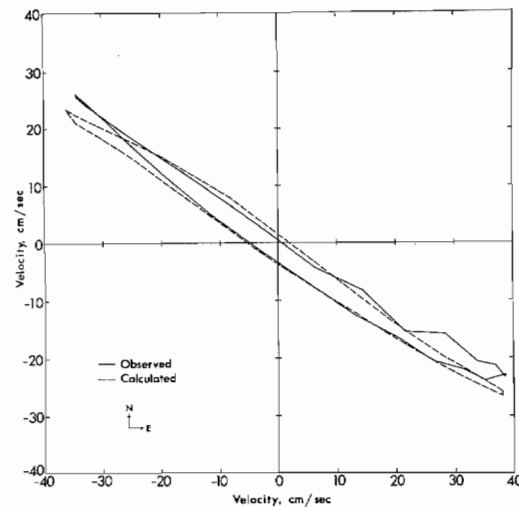


Fig. 2. Phase plane comparison of observed and predicted current velocity vectors at middle station, Maryland Point transect.

area of the spawning grounds, we chose to follow the course of a single clutch of eggs released several kilometers above Douglas Point. Many qualitative aspects of the mid-field dynamics around Douglas Point were evident through this simulation. Entrainment was represented by withdrawal of  $2.25 \text{ m}^3$  per s from the appropriate grid and calculating the number of ichthyoplankton removed. The areal extent of the model was constrained to the reach between Indian Head and Maryland Point (40 km) so that withdrawals from other power plants outside this range were not included. No natural mortality of the animals was programmed into the simulation. While this exaggerates the absolute number of eggs entrained, it will not change the entrainment percentage if natural mortality is considered spatially uniform.

Specifying concentrations at open water boundaries can be a difficult task. Fortunately, the release point is distant enough from the open water boundaries that it takes a long time for the open boundary conditions to affect the concentrations near the middle of the grid (about 20 tidal cycles). The concentrations at the model boundary, where water is flowing out of the system, are taken to be linear extrapolations of gradients near that boundary as corrected by advection (Hess and White

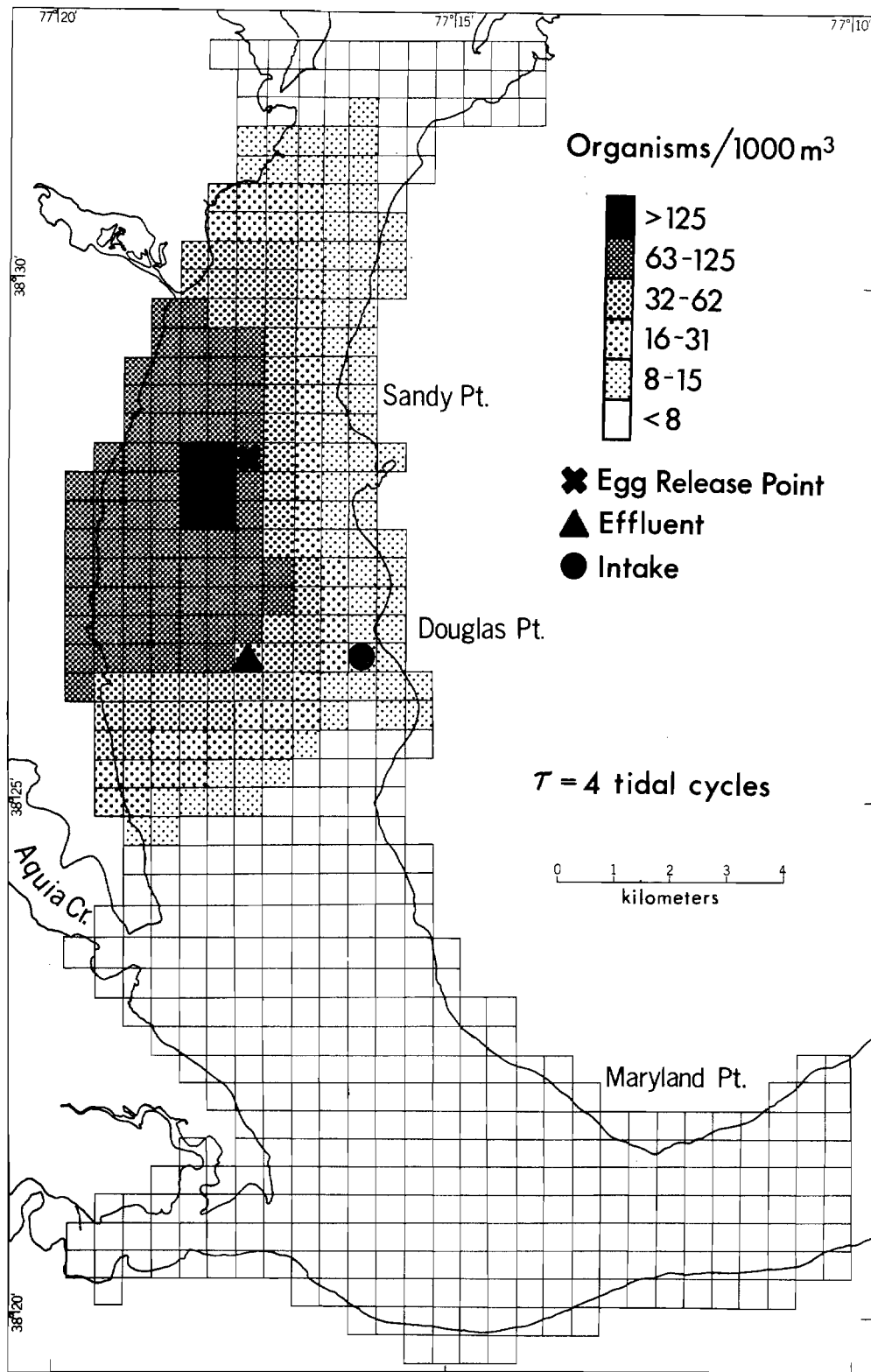


Fig. 3. Predicted concentration patterns of ichthyoplankton 4 tidal cycles after release at point indicated.

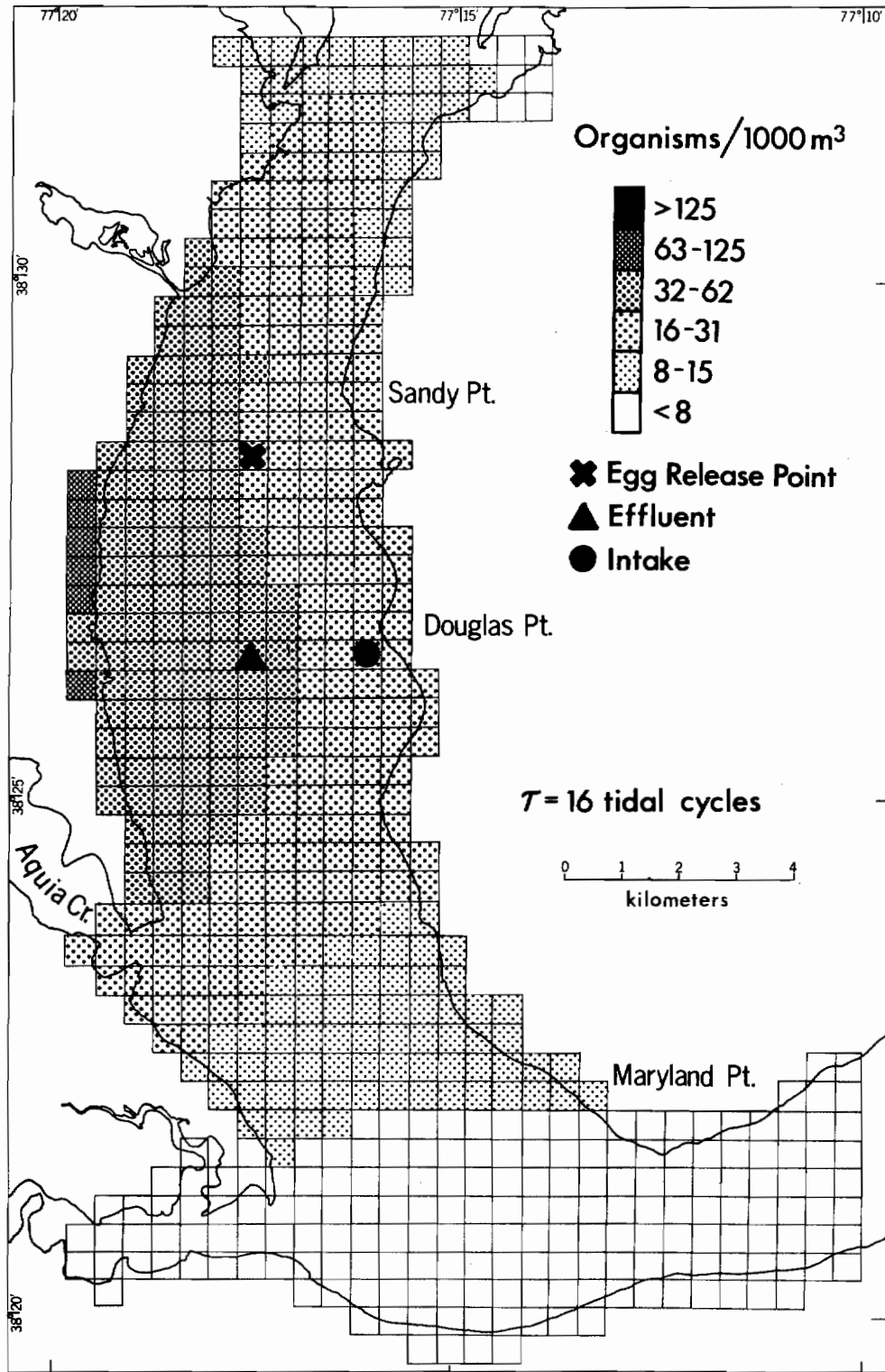


Fig. 4. Predicted concentration patterns of ichthyoplankton 16 tidal cycles after release at point indicated.

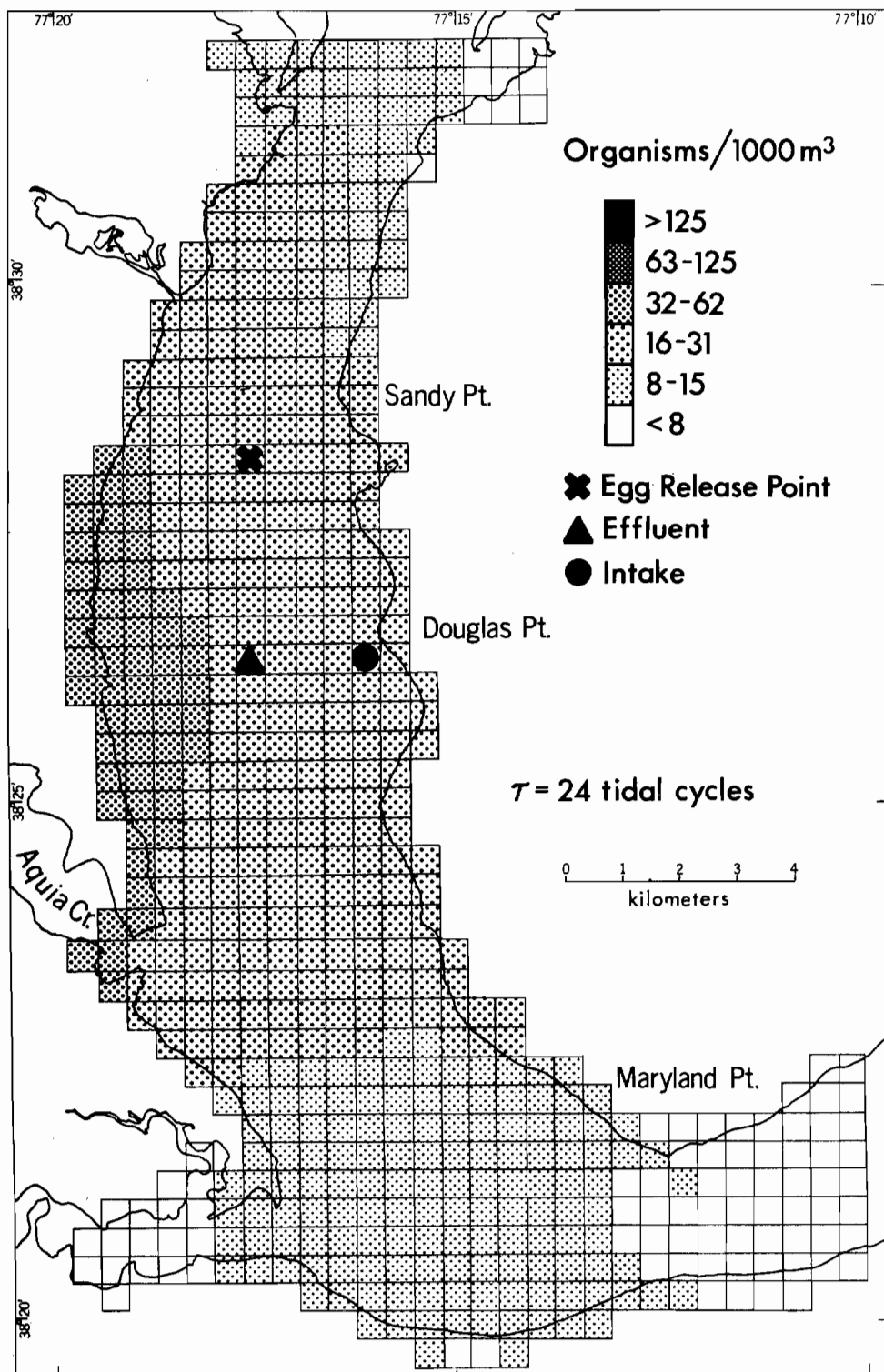


Fig. 5. Predicted concentration patterns of ichthyoplankton 24 tidal cycles after release at point indicated.



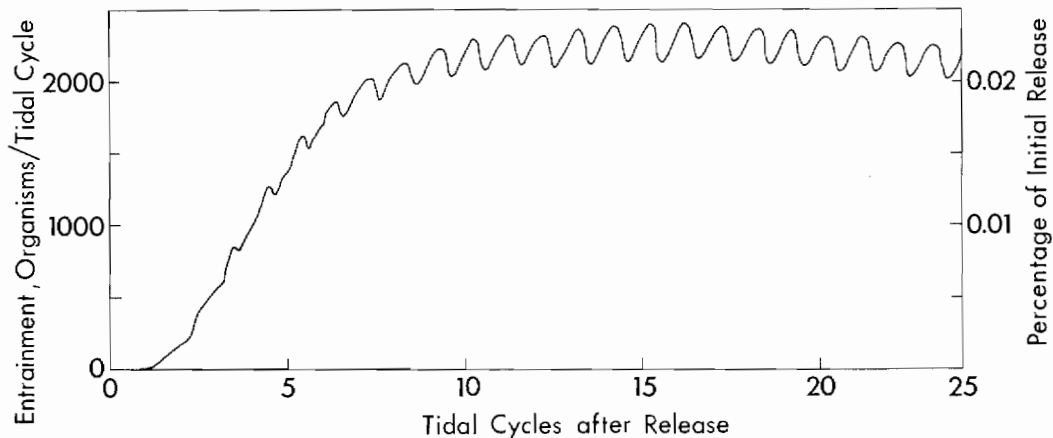


Fig. 6. Instantaneous rates of entrainment by the proposed Douglas Point Nuclear Generating Station. Based on a hypothetical release of eggs 3.5 km upstream and in the middle of the estuary.

1976). Specifying concentrations when water is flowing inward is more difficult. Hess and White (1976) integrated the amount of material flowing out of the system during one-half of the cycle and specified conditions at the end points during the half-cycle of inward flow so that a controllable fraction of what left would flow back in. We employed Hess and White's strategy, allowing a reasonable amount of the material to return into the system.

#### The Simulation

Ten million eggs (an arbitrary number—relative concentrations are the important variables to follow) were released in a segment 3.5 km upstream from the proposed site and midway between the shores of the estuary. This segment was far enough distant from the intake so that inordinate entrainment would not occur very soon after release, but at the same time it was close enough to the power plant that the lateral pattern of egg distribution would not be uniform by the time the eggs drifted into the plume area. Egg distributions (without mortality) were simulated for twenty-four subsequent tidal cycles. Figures 3, 4, and 5 portray the concentration distributions at the end of tidal cycles 4, 16, and 24, respectively.

The dominant feature of the simulated profiles is the gradual westward drift of the ichthyoplankton towards the Virginia shore

and downstream. This drift is probably related to the curvature of the river bed throughout the domain being modeled. After four full-tidal cycles the peak is over a kilometer southwest of the release point (Fig. 3). After 16 cycles the pulse has flattened along the western shore (Fig. 4). Even after 24 cycles the lateral gradient has not completely decayed, with most of the eggs located along the Virginia shore on their way downstream (Fig. 5). Another release closer to the Maryland shore yielded similar results.

The instantaneous entrainment rates at Douglas Point are plotted in Fig. 6. It takes approximately eight tidal cycles for the egg release diffusion front to travel to the region of the intake. During the next eight cycles, entrainment plateaus at a rate of approximately 2,275 organisms per cycle (or 0.023% of initial per cycle) followed by a decline as organisms are advected out of the region being modeled.

The tidally-averaged entrainment rate can be fitted by the empirical function

$$E = 2275[1 - \exp(-.04123\tau^2)] \exp(-.0009013\{\tau - 15.07\}^2)$$

where  $E$  is the entrainment rate in organisms per cycle and  $\tau$  is the time measured in tidal cycles since the release of the eggs. This function, when integrated over a suitably long interval, yields a total entrainment of about 91,500 organisms or 0.92%

of the number initially released. This is greater than the 0.6% cumulative entrainment of Warsh, as might be expected from the proximity of the release point to the intake.

The capture of fish eggs and larvae would have been higher still, had the site been located directly across the estuary. There the inflow would have been cropping animals from the wave of greatest larval concentrations. We estimated from concentration contours that entrainment rates directly across the river from Douglas Point would reach a high of about 10,000 organisms per cycle, or 2.6% total entrainment.

#### Discussion and Conclusions

Based on this study at Douglas Point, it is obvious that the ratio of intake rate to riverine flow is the primary parameter controlling the impact upon the juvenile population. Intake flow is so small a fraction of net river flow that, except in very extraordinary conditions (e.g., concentrated spawning in the immediate vicinity of the intake), the intake cannot entrain more than 3% of any spawn. Further research may show that even small incremental mortalities of a few percent can substantially alter adult stocks, but having to make an environmental decision based on entrainment estimates ranging from 0.6% to 2.6% appears less difficult than if the impact had ranged from 20% to 80% (as is characteristic of the Hudson River situation). In this case, the two models of increased behavioral and hydrodynamic resolution provided little refinement to the original entrainment estimate.

We are not suggesting that all environmental assessment revert to simplistic analyses. Even in this instance the higher resolution models were helpful in evaluating details that may be useful in estimating entrainment at other locations. For example, Warsh's analysis shows that the vertical position of larvae in the water column is not likely to affect horizontal distributions in tidal reaches above the salt wedge. In contrast, our two-dimensional model indicated that, if a reach of an estuary has high geometric curvature, it may be quite important which bank of the river the intake is drawn from.

We conclude that coarser models of biological-physical interaction are often quite adequate to the task of evaluating environmental impact. Quantitative methods for evaluating the adequacy of a given scale of model aggregation are under development (Halfon and Reggiani 1978). Biological and physical details are not in themselves criteria for judging the prediction ability of a given model. When further refinement of a model is necessary, it is usually only one or a few of the numerous actual processes which need be included to achieve the desired level of precision. We suggest that dimensional analysis is a useful tool for the preliminary identification of these rate-controlling processes.

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