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AN ANALYSIS OF 1974 STRIPED BASS SPAWNING SUCCESS IN THE POTOMAC ESTUARY[1]

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ABSTRACT: The Potomac River Fisheries Program is concerned with the long-term effects of power plant ichthyoplankton entrainment on striped bass *(Morone saxatilis)* recruitment. Since striped bass population fluctuations are determined strongly by environmental conditions during spawning and early development, assessment of power plant-induced ichthyoplankton mortalities must consider the mechanisms controlling spawning success.

Ichthyoplankton distributions for 1974, spawning population abundance and fecundity, and environmental conditions were considered for analysis. Loss of the early part of the spawn (including the peak) accounted for the highest mortalities among ichthyoplankton. This was due to the proximity of these distributions to the salt wedge where transport into regions unfavorable to survival seems to have occurred. The later, successful portion of the spawn occurred further upstream, in fresh tidal portions of the river. The sequence of events leading to an assessment of factors affecting ichthyoplankton survival are evaluated. Due to high early mortalities in ichthyoplankton, 1974 spawning success was low, and a poor yearclass is projected.

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INTRODUCTION

Since the early 1970's, the Maryland Power Plant Siting Program has been sponsoring research to determine the impact of power plant operations on the State's aquatic resources in the Chesapeake Bay and its tributaries. Because, at present, there are two large power plants with once-through cooling systems operating in the upper tidal portion of the Potomac—and another facility proposed in the oligohaline region of the river—a great deal of the power plant-related research has been conducted in the Potomac.

The conservation of commercial and sport fish species is of primary concern. Salinity regimes in the estuary and seasonal habitat use by anadromous and other fish species produce distinct biogeographical zones in which finite populations—or specific life stages of given populations—may be impacted by the operation of even a single power facility. Therefore, a region-wide Potomac River Fisheries Program was initiated in 1974 to investigate the extent of possible fish stock depletions through entrainment of early life stages into power plant cooling systems. Although other species also are being studied, the early life stages of the striped bass *(Morone saxatilis)*, one of the most important fish resources in the State of Maryland, have been singled out for detailed investigation in the program. Historical data and preliminary estimates by Morgan and Wilson (16) indicate that Potomac striped bass contribute approximately 20% of the fishable stock in the Chesapeake Bay region.

Several previous studies in the Potomac have demonstrated that the striped bass population here is an identifiable and indigenous race, continually returning to the river to spawn (12, 15, 17). Here, as in other systems with striped bass populations, the ichthyoplankton abundances of striped bass vary considerably from year to year, as does the catch of adult stock. However, except as an indicator of potential egg production, spawning stock size and ichthyoplankton abundances are not clearly related. Analyses of historical catch records by Koo (9) and Bigelow and Schroeder (4) indicate that adult striped bass populations are dominated by single yearclasses, with irregular periodicity. The success of particular yearclasses is attributable apparently as much to the size and fecundity of the parent stock as to environmental conditions prevailing during spawning and early development. It is these conditions that largely determine the extent of survival of ichthyoplankton stages to juveniles. Juvenile abundance is thought to reflect the size of a particular yearclass. The key to understanding population fluctuations in time, therefore, is to identify environmental factors controlling spawning success and to determine the characteristics of the adult stock.

The information and preliminary results of the program discussed here concentrate on the mechanisms that produced the degree of spawning success observed in 1974. The temporal and spatial properties of ichthyoplankton distributions have been analyzed for this year. Relative and absolute adult abundances also have been estimated, together with age, weight, sex, and maturity properties of the population. Using estimates of abundances and mortalities of various ichthyoplankton stages, along with environmental and detailed flow measurements, we have identified factors that influenced overall survival of ichthyoplankton in 1974.

The program has been continued in 1975, and there are plans to extend it at least through the 1976 spawning season. With three years of detailed information at hand, we intend to close the loop between ichthyoplankton production and adult stock size. Simulation modeling of the 1974 observations, which will further refine and quantify the results presented here, are underway.

REVIEW OF SOME FACTORS INFLUENCING SPAWNING SUCCESS

Although there is extensive literature on the natural history and dynamics of striped bass populations, little has been done to comprehensively assess the role of environmental patterns in determining spawning success. Indications from the literature are that a delicate balance exists between the response of the striped bass spawning stock to environmental cues setting off the spawning process and the subsequent time history of key environmental changes (temperature, salinity, and flow) influencing the survival of eggs and larvae. In the critical early life stages, for example, currents may sweep eggs and larvae into temperature, salinity, or other water quality regimes unfavorable to their survival (13). Albrecht (1) has shown that suspension of the semi-buoyant eggs is required for successful hatching and has estimated that water movements on the order of 30 cm/sec are necessary for suspension in estuaries.

In natural systems, observations indicate low occurrences in salinities greater than a few parts per thousand, implying that egg and larval transport into salt wedges may be an important factor in survival. Although laboratory experiments by Bayless (3) indicate that survival and growth of striped bass larvae apparently are enhanced in salinities ranging from 3.5 to 14.0 ppt, eggs and larvae in the field are found at much lower salinities. Eggs have been found in salinities as high as 6 ppt (2, 7), but most investigations reveal that spawning and survival is optimal in fresh or only slightly saline waters: Carlson and McCann (5) reported eggs in salinities less that 0.1 ppt in the Hudson River, and Farley (8) found striped bass egg concentrations in salinities of 0.18 ppt or less in the Sacramento-San Joaquin River system. In the latter system, Radtke and Turner (21) found the spawning process blocked at 0.35 ppt. Transport processes may also affect other biological requisites for survival. For example, larvae may be transported into regions without suitable or sufficient food supplies.

The onset of spawning in relation to the displacement of the upstream migrating adult stock from the salt wedge, and the generally downstream direction of flow, are both critical in early survival. If, for example, a quick temperature rise triggers spawning downstream, close to the saltwedge, the e [illegible] may be subject to high natural mortality by transport into higher salinities or into regions lacking food organisms for the larvae, even though the higher temperatures favor survival by decreasing hatching and larval development times. The optimal range for peak spawning is generally 14-17°C. Shannon and Smith (22) and Pearson (18) demonstrated that egg incubation time decreases as temperature increases: from 58 hours to 28 hours as temperature is increased from 16°C to 30°C, and from 48 hours to 36 hours as temperature is increased from 18°C to 22°C, respectively. Investigations of the synergistic effects of salinity and temperature on hatching showed that eggs do not survive above 1 ppt (23) at higher temperatures.

The magnitude of freshwater runoff (and therefore transport) influences spawning success by affecting both salinity and temperature structures in the upper estuary, as well as plankton productivity and detrital levels. The relationship between amounts of runoff and flow and the development of thermal and salinity regimes is not clear in the Potomac. In combination with variations in spawning stock size, these factors may induce a large range in spawning success, accounting for the appearance of nonlinear dominant yearclass phenomena.

SAMPLING PROGRAM DESIGN

In order to gain as full an understanding of population dynamics relationships as possible, it was necessary to sample all phases of the population: adults, ichthyoplankton, and juveniles. Because spawning and developmental events are serially related, sampling of successive stages also served an experimental control function in the measurement of events in each stage. Maintaining a comprehensive program design, including information on the movements and redistribution of all stages, was especially important in this study because the approximately 60-river mile segment study area was logistically too large for extensive replication of measurements. Therefore, we were forced to rely on consistency assessments of results for control as the spawning process developed.

The sampling grid consisted of 12 transects, comprising a total of 38 sampling stations, which spanned the Potomac from below Morgantown up to Washington, D. C. (Fig. 1). Transects were spaced to have equal water volume between each transect pair (200×10^6 m^3) and separations greater than a tidal excursion distance.

Details of the entire sampling program are described in (14), (10), (24) and (16). In this paper we shall concentrate on ichthyoplankton distributions in deeper river areas, characteristics and movements of the adult stock, and river hydrography.

Absolute abundance of adult bass during spawning was determined by acoustic surveys, a method developed for the program (24), while relative abundances were obtained from gill net sampling of the spawning population. Gill net stands of four mesh sizes (to ensure that no adult classes of striped bass would be

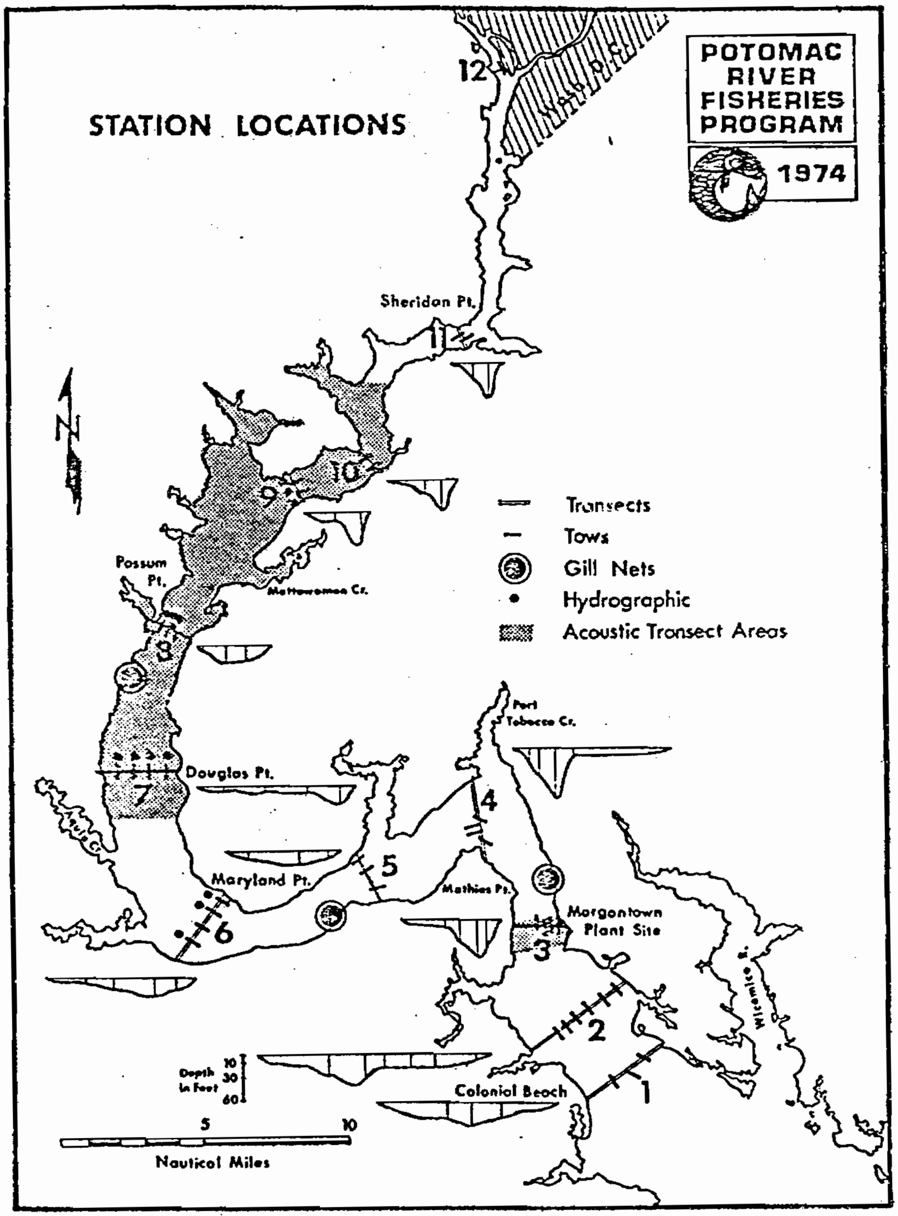


Figure 1. Locations of weekly, oblique, ichthyoplankton tow stations along 12 Potomac River transects. Current meter stations, gill net locations and acoustic fish survey areas are also shown.

excluded) were deployed between transects 3 and 4, 5 and 6, and 7 and 8 (Fig. 1). After separation from other species, the striped bass were weighed, their length measured, and the specimens then were dissected to determine sex, age, and sexual maturity—all measures for determining the potential productivity of the population. Acoustic surveys were carried out to count the striped bass adults and trace their movements (24). Detailed work around the gill net stands being sampled provided the necessary calibration of acoustic target strength with size distribution and made extrapolations of striped bass distributions possible in the entire spawning area. The combined gill net sampling and acoustic programs led to estimates of potential egg production and also identified the river areas in which spawning was taking place.

Ichthyoplankton sampling was carried out at all 38 sampling stations weekly throughout the duration of the spawning and developmental periods (from 2 April 1974 to 19 August 1974). Egg and larval distributions across and along the axis of the river and in shore and tributary areas were examined, while hydrographic studies correlated transport processes in the river with the evolution of ichthyoplankton distributions. (A full description of current meter deployment and data recovery and analyses may be found in Refs. 19 and 20.) Starting at the bottom, a 0.5-mm mesh net, 1 m in diameter, was towed through the water column to vertically integrate samples. Water volumes of approximately 50 m^3 were strained at each successive 3-m depth layer. Depending on river depth, total volume strained varied from station to station. Strained volume was monitored and computed from net-mounted flow meters with on-board readouts. At each ichthyoplankton station, temperature, salinity, turbidity, dissolved oxygen, and light intensity data were collected. Ichthyoplankton were identified and enumerated to taxa and species (where possible).

Variations in vertical ichthyoplankton distributions from day to night were investigated with two paired 0.5-m bongo nets that could be lowered to discrete depths, opened for sampling, and then reclosed for retrieval.

Distributions of juvenile bass (30-45 days old, at least 30 mm long) in the river shallows were also determined by shore seine netting at 35 stations.

Data from various program elements were cataloged in a unified data system. Field and laboratory information were recorded on coded forms, integrating physical and biological data in standardized formats.

INTERPRETATION OF ICHTHYOPLANKTON SURVEY RESULTS

Major factors determining the longitudinal patterns of eggs and larvae are the movements of the adult population during spawning and the advective action of net non-tidal river flows in transporting these distributions generally downstream. In fact, the input of eggs by the adult stock is some continuous function of time during a finite period, while adult movement takes place longitudinally and generally upstream. At the same time, net flows are transporting surviving ichthyoplankton uniformly downstream if the process takes place in the freshwater portion of the estuary. Therefore, a correlation may exist between temporal and spatial variations. In the meantime, large mortalities are experienced by both eggs and larvae.

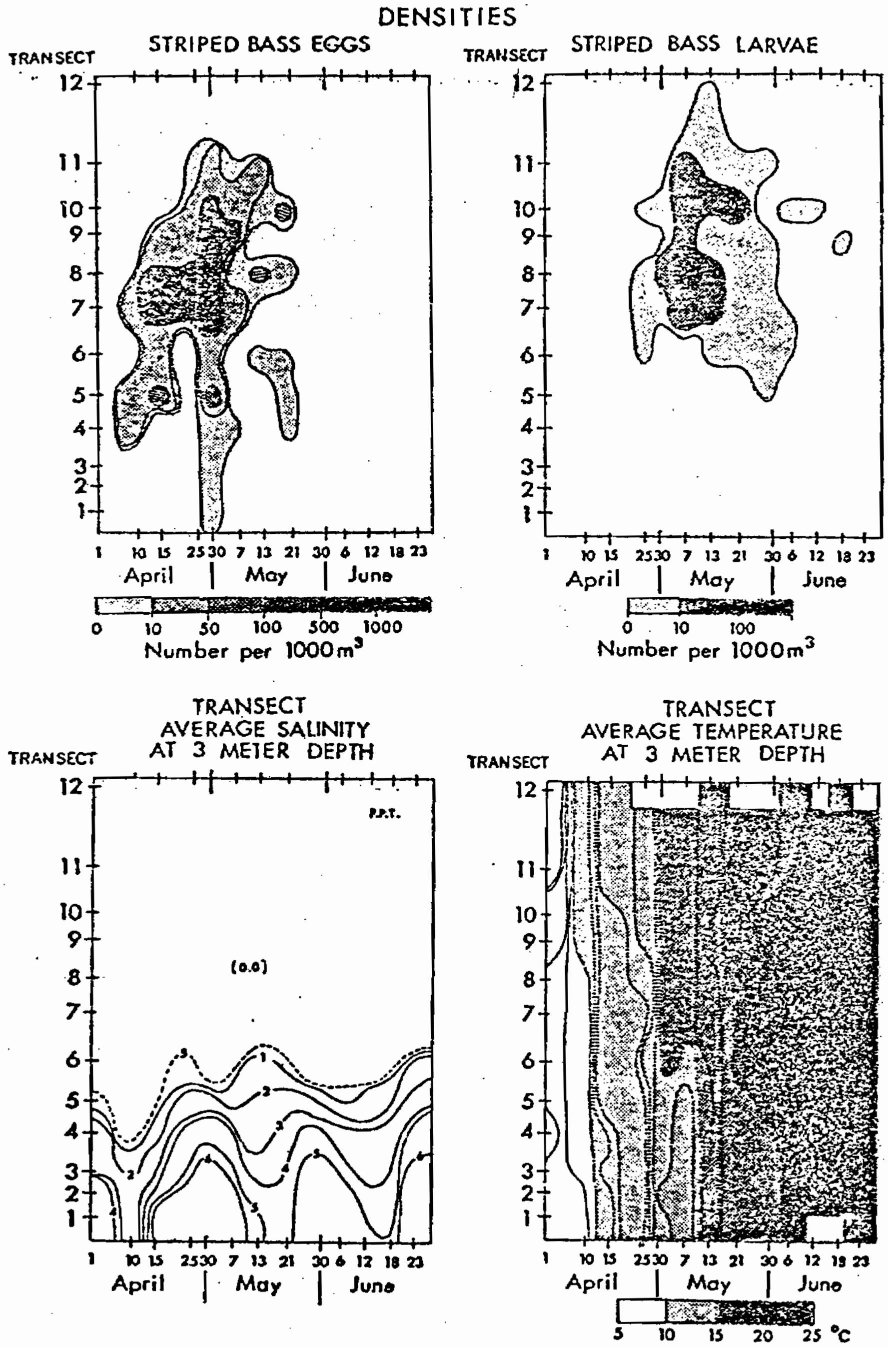
In order to trace this process, ichthyoplankton samples were separated into the egg stage and three distinct larval phases of development: yolk-sac larvae (up to 12 days old), finfold larvae (up to 24 days old), and post-finfold larvae. Lengths of the larvae were also measured. These properties provided a reasonable capability for tracing the development of distributions. Yolk-sac larvae were the most abundant stage after eggs, and, in some analyses where there were relatively few later developmental stages found, all later larval stages were combined with this category.

Fig. 2 presents composite time and space (longitudinal) patterns of eggs, total larvae, salinity and temperature. The spatial axis denoting transect locations is scaled to true river mile distances between transects. For the purposes of this presentation, density values for stations within each transect are appropriately weighted, taking into account sample volumes that reflect river cross-sectional area and depth. Both temperature and salinity are presented at the 3-m level. The river throughout the sampling period was generally isothermal with depth, and detailed temperature-salinity analyses are presently underway.

Spawning began around 10 April 1974 at transects 4 and 5. It is noteworthy that at this time temperatures (~10°C) were below those reported as optimum for spawning and hatching of eggs. We believe that a rapid temperature rise triggered premature spawning. Salinities in these areas were below 1 ppt at this time, a normal range for spawning. The general positive slope of the egg time-space distribution implies that spawning proceeded continually further upstream in time. As the spawning process developed, temperatures increased over the whole spawning region, generally monotonically and uniformly. With the exception of one sampling date (cruise 5-30 April, 1974), all eggs were found above the 1 ppt salinity isopleth.

The spawning peak occurred at transect 7 on cruise 5 (30 April 1974). Approximately 70% of the eggs obtained during the whole sampling period were collected on this date at this transect. Temperature reached 15°C, and the salinity was essentially 0 ppt during the peak spawning activity.

Analysis showed that both the onset and peak of spawning were related to the rate of temperature rise. It seems, therefore, that temperature gradients in time, rather than the value of temperature alone, may also be responsible for discrete spawning events. After peaking, spawning activity proceeded at a continually reduced rate, moving upstream in time. From the egg distribution data, it could not be determined whether the upstream shifting pattern was due to the upstream movement of the spawning stock itself, or to the upstream propagation of spawning activity through the stock already distributed in a stationary pattern.



'igure 2. Longitudinal-temporal distributions of eggs, larvae, salinity and termperature.

Larvae were found upstream of the egg distributions in spite of the measured downstream transport in the river. The larval distribution also displayed a tendency towards a negative slope, indicating downstream drift of larvae in time. Since all significant larval densities were upstream of the major egg peak in space, no traces of larvae were detected for over 80% of the eggs spawned, indicating an almost complete lack of hatching success of the peak spawn downstream, i.e., the relatively low egg densities observed above transect 8, produced near the end of the spawning process, were responsible for almost all of the larvae that survived.

The egg distribution in Fig. 2 displays unimodal behavior because of the large spawning peak. In contrast, larval distributions are bimodal, with peaks near transects 8 and 10 over an extended period of time. This implies differential survival rates for eggs and larvae in time, and, because of the apparent upstream movement of adults during the process, also in space. The observed phenomenon is probably related to decreased hatching and developmental times for the later spawn as temperature increased over the whole spawning area in time.

Until 30 May 1974, yolk-sac larvae were associated predominantly with salinities of less than 1 ppt. Because of the disappearance of the egg peak and the sharp tapering off of both larval and egg distributions at the salt wedge (in spite of a tendency to be dispersed in the longitudinal direction by turbulent processes), it seems that unidirectional downstream transport of both eggs and larvae into the salt wedge caused the highest mortalities in all early ichthyoplankton stages. The lack of survival of egg and yolk-sac stages in saline waters may have been due to a lack of food organisms required by developing larvae in the saltwedge region as well as to salinity stress. Successful development upstream may have been both a function of temperature (due to more rapid development at later, higher temperatures) and food availability. No definitive conclusions were drawn from food habit and availability studies (10) to resolve this ambiguity.

Subsequent presentation of abundance data will show that egg and yolk-sac distributions were sharply truncated at the salt wedge (transect 6). Flow investigation revealed that longitudinal dispersion processes were important in spreading distributions, with dispersion coefficients attaining values as high as 1.5×10^6 cm^2/sec. Therefore, the truncation of egg and larval distributions implies fairly rapid mortalities as distributions encountered the salt wedge—on a time span much less than the weekly sampling rate.

The acoustic fish density surveys conducted during the ichthyoplankton sampling periods supported the hypothesis of the upstream movement of spawning adults in time. Two acoustic surveys were made in the entire region shaded in Fig. 1. When the analysis of only large acoustic targets was considered, the results displayed the density distributions of adult fish greater than 40 cm in length. These fish were striped bass only, as corroborated by the concurrent, twice-weekly gill net collections of Morgan and Wilson (14). Fig. 3 is taken from

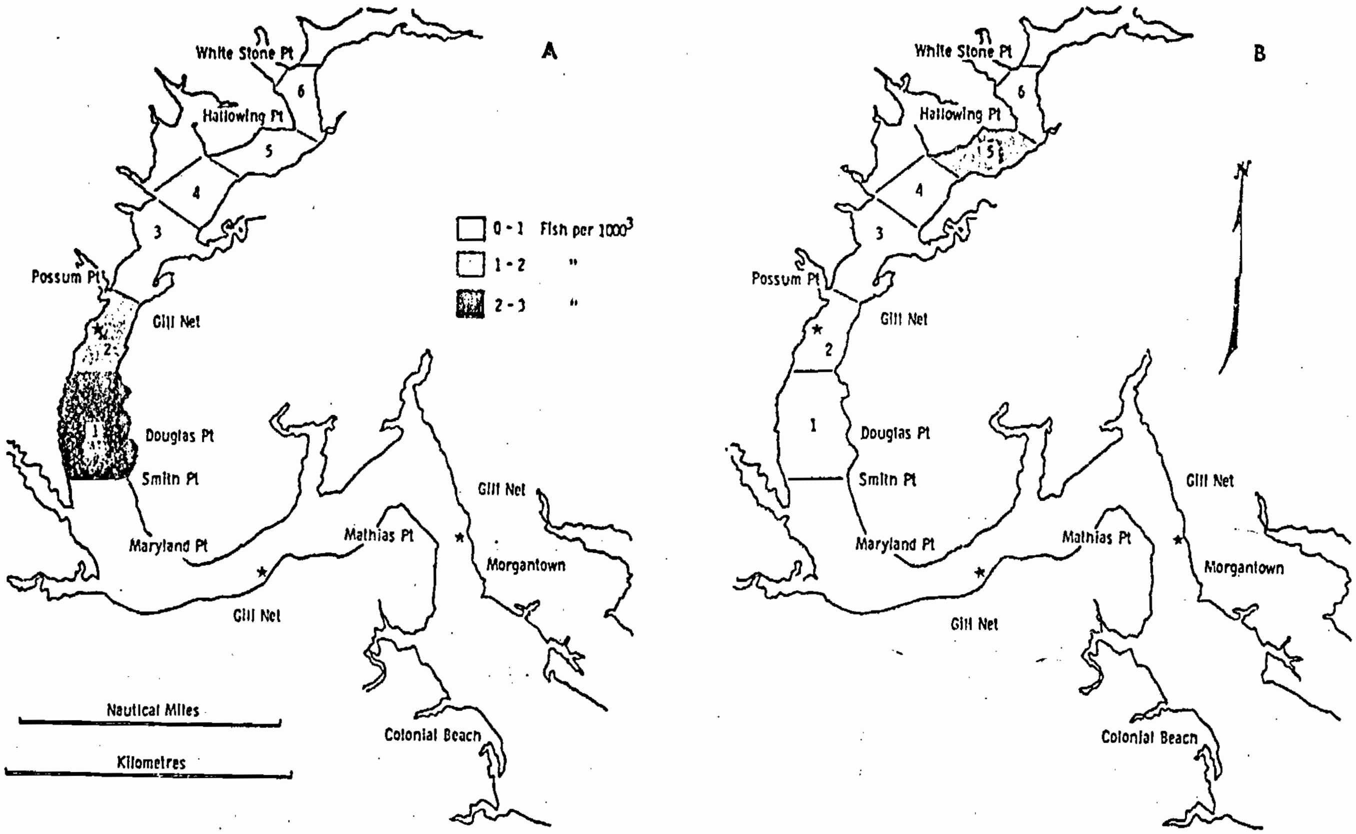


Figure 3. Acoustically determined densities of fish targets greater than 40 cm in length. See text for explanation of parts A and B.

Zankel et al. (25), and indicates the measured densities of large targets in six longitudinal river regions (not corresponding to transect designations). Distribution A(one million adults) was obtained during peak spawning, and the highest concentration of spawning adults corresponds to the time and location of major spawning activity. The second distribution, B (0.5 million adults), was obtained two weeks later, and the highest spawning adult concentrations occurred near transects 9 and 10. The surviving larvae upstream of the location of major spawning can be traced to a reduced adult population spawning upstream. The reason that the bimodal larval peaks were traceable only to adult distribution maxima rather than to eggs is the high mortalities eggs experienced throughout the process, as evidenced by the change in density of egg and larval distributions.

ESTIMATES OF ICHTHYOPLANKTON ABUNDANCES AND MORTALITIES

From weekly sampling of ichthyoplankton distributions, we can calculate densities using tow volumes and counts. These densities may then be extrapolated into river volumes represented by each tow to yield total abundances for the day the sample was taken. However, both the sampling interval of seven days and the hatching and developmental times must be taken into account to interpolate net production between sampling times and obtain abundance estimates over the entire process. Since larval developmental times exceeded the periods between sampling, the calculation between weeks must also take into account only the fraction of the developmental time spent near a particular transect location.

The following general expression was used for abundance estimation of all stages:

$$A_{stage} = 168 \sum_{i=1}^{W} \sum_{j=1}^{N} \sum_{k=1}^{J_k} V_{jk} \times D_{ijk} \, C_{ijk}$$

where

W = number of sampling weeks
N = number of transects
J_k = number of tows at the j^{th} transect
D_{ijk} = density of life stage during i^{th} week at tow location k of the j^{th} transect
168 = the mean time between sampling, in hours
C_{ijk} = the average developmental time of each stage, in hours
$C_{ijk} = -4.69 \times T_{ijk} + 131.6$ for eggs
C_{ijk} = 286 for yolk-sac larvae
C_{ijk} = 264 for finfold larvae
T_{ijk} = temperature during the i^{th} week at section k of the j^{th} transect
V_{jk} = river prism volumes into which tow densities were extrapolated.

The hatching time is a decreasing function of increasing temperature derived from Doroshev (6) and Mansueti (11). There is no temperature-dependent information on other developmental times; however, these are realistic averages from the literature.

The time-integrated absolute abundance estimates centered on each transect location, and the percentage relative abundances are presented in Table 1. The dominance of the singular peak event in spawning on cruise 5 is evident in the abundance of eggs at the transect 7 location over time, as well as in the densities shown previously. However, in the time-integrated abundances of the two larval stages, it is seen that the major egg peak did not contribute to spawning success, or total abundance in those stages. Even though the abundances are integrated over time in the table, both transport downstream and adult movement upstream may be seen. The upstream shift from eggs to yolk-sac larvae is indicative of spawning stock movement. The downstream shift from yolk-sac larvae to finfold larvae is consistent with measured net river flow. The persistence of bimodal distributions from yolk-sac to finfold larvae as the larvae shifted downstream in time (Table 1) indicates that mortalities became uniform over the populations in time, and that survival increased in time.

Potential egg production of the spawning population was estimated (16) from adult age distribution, sex ratio, maturity, and weight of the spawning stock. The absolute stock abundances of Zankel et al. (25) (about 1-3 adult fish/1000 m^3, or one-million fish during peak spawning and one-half million 2 weeks later) were applied to this information to arrive at a potential egg production of 75 billion eggs. Stage-to-stage mortalities were directly obtainable from the abundance estimates given in Table 1:

Potential to calculated (apparent mortality)	93.84%
Egg to yolk-sac mortality	98.40%
Yolk-sac to finfold mortality	95.34%

Insufficient numbers of post-finfold larvae were collected to calculate finfold to post-finfold mortality.

Table 1. Abundance estimates on striped bass eggs and larvae in Potomac Estuary, 1974.

Centered on Transect	Eggs X 10^5	%	Yolk-Sac X 10^5	%	Finfold X 10^5	%
5	1410	3.10	0	0		0
6	401	.90	2.6	.35	11.4	33.5
7	33885	74.80	149.5	20.5	1.0	3.3
8	3692	8.00	264.0	36.2	11.4	33.5
9	4380	9.70	60.6	8.3	5.4	15.9
10	1402	3.10	239.4	32.8	3.8	11.2
11	229	.5	13.8	1.9	.9	2.7
TOTAL	45290	100.1	730	100.0	34	100.1

The first "mortality" figure above could be a consequence of unfertilized and immature egg production effects, perhaps producing rapid disintegration and less than complete extrusion of all eggs, respectively. More importantly, however, overall efficiency of egg sampling was undetermined, which leads to the possibility of a large difference between the potential and accountable figures from sampling. The latter two estimates for mortalities have been obtained, however, by the same sampling method, with roughly equal efficiencies. The abundance distributions of the three stages and the previous interpretation imply that egg and yolk-sac mortalities were considerably higher through the peaking of the spawning process in the lower part of the spawning grounds than subsequently upstream. Further work is necessary to partition time- and space-dependent mortalities in each stage. The timing and locations of biological events, in combination with net longitudinal river flow, have been shown to be primary determinants of high mortalities, especially in the egg stage.

Considering the high mortalities that may occur within the first year of life, and the 3.4 million finfold larvae estimated, it is safe to speculate that 1974 spawning success was poor and will produce a low yearclass. The spawning stock size (25) and preliminary reports of catch in 1974 indicate that the spawning stock had relatively high abundance. Subsequent juvenile collections at 35 stations, repeated biweekly for three months, obtained only 22 striped bass juveniles (10). Although no quantitative historical comparisons have been made with juvenile data from the Maryland Department of Natural Resources, the juvenile abundances this year were very low compared to other years.

CONCLUSIONS

Almost all egg samples were obtained in fresh waters. The peak of spawning occurred sufficiently near the salt wedge for transport of eggs into higher salinities. The largest apparent mortalities during transition from egg to yolk-sac stage were connected with this transport, and were attributable either to low salinity tolerances of eggs and early yolk-sac larvae or to other indirect effects of higher salinities, such as the absence of food organisms necessary for survival and development in this region. Distributions of both eggs and larvae were sharply truncated near the salt wedge, in spite of large longitudinal turbulent dispersion. This indicates rapid mortality as distributions encountered the salinity gradient.

Surviving larvae were found upstream of major egg densities. This distribution shift was due to the movement of the spawning stock upstream, and the rate of this movement exceeded the downstream drift of water. The upstream location of surviving larvae, representing the tail of the spawning process in time, was favorable for survival because it allowed early development in fresh water with possibly higher abundances of food organisms. In addition, increasing river temperatures in time shortened both hatching and developmental periods.

Large ichthyoplankton mortalities occurred during development. The low abundances of post-finfold and juvenile stages indicate a poor yearclass for 1974.

Although no causal mechanisms have been identified for peak spawning close to the salt wedge, this phenomenon—which promoted transport of most early-spawned eggs and yolk-sac larvae into saline regimes—seems to be responsible for the poor spawning success observed. Work is continuing to resolve some of the questions raised and to refine conclusions reached here.

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