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*Morone saxatilis*, and White Perch, *M. americana***

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## Effects of Shear on Eggs and Larvae of Striped Bass, *Morone saxatilis*, and White Perch, *M. americana*<sup>1</sup>

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### ABSTRACT

Shear stress, generated by water movement, can kill fish eggs and larvae by causing rotation or deformation. Through the use of an experimental apparatus, a series of shear (as dynes/cm<sup>2</sup>) mortality equations for fixed time exposures were generated for striped bass and white perch eggs and larvae. Exposure of striped bass eggs to a shear level of 350 dynes/cm<sup>2</sup> kills 36% of the eggs in 1 min; 69% in 2 min, and 88% in 4 min; exposure of larvae to 350 dynes/cm<sup>2</sup> kills 9.3% in 1 min, 30.0% in 2 min, and 68.1% in 4 min. A shear level of 350 dynes/cm<sup>2</sup> kills 38% of the white perch eggs in 1 min, 41% in 2 min, 89% in 5 min, 96% in 10 min, and 98% in 20 min. A shear level of 350 dynes/cm<sup>2</sup> applied to white perch larvae destroys 38% of the larvae in 1 min, 52% in 2 min, and 75% in 4 min. Results are experimentally used in conjunction with the determination of shear levels in the Chesapeake and Delaware Canal and ship movement for the estimation of fish egg and larval mortalities in the field.

Water velocity may affect striped bass, *Morone saxatilis*, or white perch, *M. americana*, eggs and larvae in two ways. First, water velocity actively transports pelagic eggs of striped bass and larvae of both striped bass and white perch to either a suitable or unsuitable habitat. Second, variation of velocity with position gives rise to shear fields which, with respect to time, can produce accelerative or decelerative stress. We have no information from the literature on the effect of shear fields on any fish eggs.

If one imagines a body of fluid flowing parallel past a stationary boundary, there is a region where velocity is increasing with distance from the wall. If an object, such as a spherical fish egg is present in this region, the velocity to which the outboard side of the egg is subject is greater in magnitude than that experienced by the side closer to the stationary surface. The resultant effect upon the egg can be resolved into a rotational component and a deformational component.

The intensity of the shear field is measured in units of force per unit area (dynes/cm<sup>2</sup>) which would be exerted tangentially on the surface of the egg. There is, however, the

probability that damage to the egg is caused by the centrifugal effects of rapid spinning. Here one may use the vorticity equation to estimate the rate of spinning induced by the shear field. For water at 20 C, the approximation is  $f = \tau/0.02\pi$ , where  $f$  is the angular spin in revolutions per second and  $\tau$  is the magnitude of the shear field in dynes/cm<sup>2</sup>. Thus, an egg subject to 0.2 dynes/cm<sup>2</sup> shear stress spins at 3 rps. It should always be remembered, nonetheless, that damage may be effected by both deformation and rotation.

### METHODS

The apparatus used for studying effects of shear fields on eggs and larvae is shown in Figure 1. Each exposure chamber consists of two concentric plexiglas cylinders, one of 20.3 cm and one of 30.5 cm diameter mounted in a constant temperature bath. Both of these cylinders were fixed to a plexiglas base with epoxy cement. An inner rotating cylinder of 25.4 cm diameter attached by a pulley system to Dayton fixed-speed gear motors was mounted to a wooden rack. The 25.4-cm cylinder was placed between the 20.3-cm and 30.5-cm cylinders such that the 25.4-cm cylinder rotated in a concentric path between the 20.3-cm and 30.5-cm cylinders. A similar unit was constructed with a variable speed 1,725 rpm motor and was used for time-shear field

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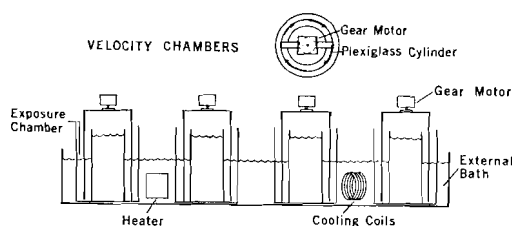


FIGURE 1.—Velocity chambers used in testing effects of shear on white perch and striped bass eggs and larvae. Temperature was controlled with an external bath system. Each gear motor is mounted on a wooden rack to ensure stability and to maintain a concentric path for the inner moving cylinder.

exposure experiments. The Dayton fixed-speed gear motors have rpms of 14, 61, 158, and 231.

The shear stress experienced by a fish egg or larva in the experimental apparatus is a function of the speed of rotation of the middle cylinder. The ensuing flows in the two annuli are markedly different, however. In the inner annulus the centrifugal force is in the direction of increasing radial velocity, thereby stabilizing the flow into a circularly laminar pattern (Covette flow). In the outer annulus, the faster moving fluid near the wall of the middle cylinder tends to be hurled radially outward, resulting in turbulent mixing (Taylor instability).

A full analytical treatment of the Covette flow can be found in almost any book on fluid mechanics or transport phenomena (e.g., Bird et al. 1960, p. 94). The shear stress at the moving boundary is given by the formula

$$\tau_0 = \frac{2\mu\Omega R_3^2}{(R_1^2 - R_3^2)}$$

where:  $\tau_0$  = shear stress at the wall in dynes/cm<sup>2</sup>,  $\Omega$  = angular velocity of moving cylinder in radians/s,  $\mu$  = viscosity of water in g/cm-s,  $R_1$  = radius of moving cylinder in cm, and  $R_3$  = radius of inner cylinder in cm. Accordingly, the shear stress at the lowest experimental speed (14 rpm or  $\Omega = 1.47$ ) works out to be  $\tau_0 = 0.052$  dynes/cm<sup>2</sup>.

No corresponding analytical treatment is possible for the flow in the outer cylinder. However, the shear stress at the moving wall has been empirically observed as a function of the dimensionless Reynolds number of the

flow (see Donnelly and Simon 1959, Fig. 4). For the given geometry and rotational rate the Reynolds number is approximately 4,748. Graphical interpolation yields a value of approximately 0.64 dynes/cm<sup>2</sup>. While shear values in the bulk of the fluid are probably lower,  $\tau_0$  may, nevertheless, be regarded as a "characteristic" stress in the sense of dimensional analysis.

Thus, the characteristic shear in the outer cylinder is an order-of-magnitude greater than that of the inner cylinder at low rpm. The discrepancy grows with higher rpm, increasing the probability that mortality is incurred predominantly in the outer flow. It should be noted that the middle cylinder does not reach to the very bottom of the tank where ichthyoplankton may exchange between the two annular chambers. It is possible, then, that mortalities during short exposures are slightly underestimated, but that assessment rapidly becomes more accurate as exposure time lengthens. Generally, eggs and larvae are placed in the outer cylinder. Exchanges of eggs and larvae between the inner and outer cylinders is minimal (less than 10%) for striped bass eggs and larvae and white perch larvae. Exchange is slightly greater for white perch eggs.

During the remainder of this paper all quoted shear stresses are understood to be the characteristic value of the shear at the rotating wall of the outer annulus.

During the spring of 1971 and 1972, white perch were collected from the Patuxent River estuary, Maryland, and held in laboratory tanks at the Chesapeake Biological Laboratory for artificial spawning. Females were injected intramuscularly with 500 IU of chorionic gonadotrophin per 250 g immediately after capture in order to prevent yolk reabsorption and to maintain ovarian development.

Eggs were stripped from the fish and fertilized. After eggs were water-hardened for 5 minutes in tap water, they were placed in the selected test chamber. A sample from each artificial spawning was retained as a reference.

Striped bass eggs from the Chesapeake and Delaware Canal were collected by towing a

TABLE 1.—Regression equations for percent mortality ( $Y$ ) of white perch eggs and larvae and striped bass eggs exposed to long-term shear ( $X$  in dynes/cm<sup>2</sup>). White perch exposures were for three days, striped bass for two days.

Stage	Regression equation	$r$	$LS_{50}$ (dynes/cm <sup>2</sup> )
White perch eggs	$\log Y = 0.849 + 0.015 X$	0.879	56.5
White perch larvae	$\log Y = 0.275 + 0.016 X$	0.949	87.5
Striped bass eggs	$\log Y = 0.710 + 0.014 X$	0.866	70.3

0.5-m net. Corrections were made in the final analysis for the age of the egg as collected in the field. Again, a reference set of eggs was retained for each experiment. Eggs were also obtained from Mr. Joseph Boone of the Department of Natural Resources from fish being artificially spawned for fry production and subsequent stocking out of Maryland.

All test solutions were approximately 1 part per thousand in salinity. At predetermined times, eggs and larvae were removed from the exposure chamber and preserved in our modification of Stockard's solution (10 parts pure formalin, 4 parts glacial acetic acid, 6 parts glycerine, and 80 parts filtered seawater). This preservative prevents the chorion from becoming opaque.

Information from several sets of experiments is the basis for a series of regression equations describing effects of low intensity long-term shear (0.00, 0.64, 8.6, 44.5 and 86 dynes/cm<sup>2</sup>) on white perch eggs and larvae and striped bass eggs. Although the information derived from these experiments is of value, shorter exposures to high shear forces are of more immediate importance to understanding shear effects. Therefore, time exposures of 1 to 20 min and shear levels of 76 to 404 dynes/cm<sup>2</sup> are used to develop further regression equations relating shear intensity and mortality. Controls consist of eggs or larvae placed in an identical shear apparatus with the same handling procedures and time exposures as test organisms, except the control tank motor was not turned on during the assay.

Mortality criteria for eggs are disruption of the yolk-protein material and total egg disintegration. Larval mortalities are judged on the basis of lack of mobility and acute tissue destruction.

For each time exposure of a given developmental stage to a defined shear level, a minimum of two and as many as ten replicates were used in developing the regression equations. Statistical procedures follow Sokal and Rohlf (1969).

#### RESULTS

We were careful in making observations on mortality of white perch eggs since we were concerned with possible damage from impact on the wall of exposure chambers. Any eggs that even had a small indentation of the chorion were discarded from our sample. To check on the path that the eggs followed in the exposure chamber, we used dyed eggs. Generally, eggs did not strike walls of the tank but stayed suspended and moved in a circular path. Eggs tended to stratify, which may be indicative of their specific gravity. The pattern of egg movement was similar for the larvae of white perch and striped bass eggs and larvae.

Damage to white perch and striped bass eggs was observed to be due to either a breakup of the yolk droplet or a separation of the developing embryo from the yolk. There did not seem to be any one stage that was particularly vulnerable to the shear force.

Information from several sets of experiments is the basis for a series of regression equations (Table 1) relating low intensity long-term shear and mortality. From these regression equations, a set of  $LS_{50}$  (median lethal shear that would kill 50% of test animals within a given time period) values can be calculated (Table 1). Given the amount of shear (which in some cases can be calculated from hydrodynamic formulas) mortality can be estimated. Given mortality of white perch eggs and larvae or striped bass eggs observed in the field or laboratory, an estimate

TABLE 2.—Regression equations for time-shear experiments on fish eggs and larvae.  $Y$  = percent mortality,  $X$  = shear level in dynes/cm<sup>2</sup>,  $r$  = regression coefficient.

Stage	Time (min)	Equation	$r$
Striped bass eggs	1	$\log Y = -0.278 + 0.723 \log X$	0.96
	2	$\log Y = -0.721 + 1.006 \log X$	0.96
	4	$\log Y = -0.431 + 0.933 \log X$	0.997
Striped bass larvae	1	$\log Y = -4.361 + 2.094 \log X$	0.90
	2	$\log Y = -2.008 + 1.370 \log X$	0.89
	4	$\log Y = -3.357 + 2.040 \log X$	0.99
White perch eggs	1	$\log Y = -1.806 + 1.333 \log X$	0.91
	2	$\log Y = -1.430 + 1.194 \log X$	0.91
	5	$\log Y = -0.220 + 0.852 \log X$	0.95
	10	$\log Y = -0.226 + 0.868 \log X$	0.97
	20	$\log Y = 0.410 + 0.621 \log X$	0.99
White perch larvae	1	$\log Y = -2.681 + 1.675 \log X$	0.93
	2	$\log Y = -2.277 + 1.571 \log X$	0.95
	4	$\log Y = 0.852 + 0.402 \log X$	0.90

of shear can be made if precautions discussed by Sokal and Rohlf (1969, p. 446) are followed.

Information from an extensive set of experiments employing white perch and striped bass eggs and larvae is the basis for another group of equations (Table 2) expressing mortality (of a given stage for a specified time exposure) as a function of shear. In addition,  $LS_{50}$  (or  $LS_{75}$ ) values can be calculated for each stage for specified time exposures from the equations listed in Table 2. These values are shown in Table 3 and are expressed as the amount of shear (in dynes/cm<sup>2</sup>) required to kill 50% of a specified life stage of striped bass or white perch within a given time inter-

val. The estimated  $LS_{50}$  or  $LS_{75}$  values can also be used to generate a final series of regression equations that express median lethal shear as a function of time exposure in minutes (Table 3).

#### DISCUSSION

Having estimated the characteristic  $LS_{50}$  values of shear stress on striped bass and white perch eggs and larvae, we now turn our attention to some characteristic shear values in the Chesapeake and Delaware Canal which connects the Upper Chesapeake Bay with the Delaware River. Due to increased shipping traffic and larger vessels, Congress authorized a reconstruction program in 1954 that will

TABLE 3.—Estimated (using equations from Table 2)  $LS_{50}$  values for time-shear exposure experiments on white perch and striped bass eggs and larvae. The regression equation developed for each stage considers median lethal shear ( $Y$ , in dynes/cm<sup>2</sup>) as a function of time ( $X$ , in minutes).

Stage	Exposure (min)	$LS_{50}$ (dynes/cm <sup>2</sup> )	Regression equation	$r$
Striped bass eggs	1	542		
	2	255	$\log Y = 2.798 - 0.139 X$	-0.906
	4	190		
Striped bass larvae	1	785	$\log Y = 3.010 - 0.136 X$	-0.991
	2	510		
	4	300		
White perch eggs	1	425	$\log Y = 2.569 - 0.028 X$	-0.865
	2	415		
	5	175		
	10	165		
	20	120		
White perch larvae	1	415	$\log Y = 2.835 - 0.180 X$	-0.984
	2	340		
	4	125		

soon result in a canal 10.7 m in depth with a channel width of 137.2 m. (Details concerning the hydrology, physical and biological characteristics of the Canal plus the research program authorized by Congress can be found in Pritchard and Cronin 1971). Our studies on shear are a result of water movement investigations in the Chesapeake and Delaware Canal system.

To make some estimates on the amount of shear generated by the Canal, we begin with the assumption that water flows through the Canal under an extreme head of 0.46 m. This head difference between the two ends of the Canal results in an approximate pressure difference across the Canal of  $4.5 \times 10^4$  dynes/cm<sup>2</sup> acting on a cross sectional area of 1,788.4 m<sup>2</sup>. At steady state, it would be opposed by a shear force on the Canal sides. However, this shear force acts over an effective area of  $582.7 \times 10^4$  m<sup>2</sup> through a 29-km stretch of the Canal. Consequently, the average shear force ( $\tau_0$ ) on the wall is 13.8 dynes/cm<sup>2</sup> with a head of 0.46 m. Shear force of this magnitude is operative only over a thin boundary layer ( $\sim 0.2$  cm). Hence, the volume of water wherein shear is potentially damaging is an insignificant fraction of the total volume and actually decreases with the new geometry after dredging. In addition, the shear force of 13.8 dynes/cm<sup>2</sup> is far below the  $LS_{50}$  values given in Tables 1 and 3. Eggs and larvae also would not be entrained in the boundary layer for periods long enough to cause shear damage.

Shipping traffic, especially during the spawning season, is also of concern. Shear generated by a ship, except for the propeller, in passage through the canal can easily be calculated. For example, an ocean-going ship with a length of 135 m, a mean draft of 8.5 m, and a molded breadth of 17.4 m traveling at 5.6 km/h against a tidal flow of 5.2 km/h generates a shear of 78.9 dynes/cm<sup>2</sup>. Again, referring to Table 3, the shear generated by the cargo ship is below the  $LS_{50}$  values for 1 minute of exposure and it is doubtful that eggs or larvae could remain in the boundary layer for periods over one minute.

Some of the shear information may apply to power generation. Marcy (1971, 1973)

found some evidence of mechanical damage at the Connecticut Yankee Nuclear Power Plant. During a plant operation mode of just water passing through (no biocides or thermal elevation), 80% of the entrained organisms were killed. Water flow, during peak operation, is approximately 25 m<sup>3</sup>/s through twin, single-pass, divided water boxes where velocities are about 2.4 m/s. Depending on the smoothness of the conduit walls, shears of 72 to 230 dynes/cm<sup>2</sup> would be present at the water box. Even though these values are still lower than the  $LS_{50}$  values for 1 minute exposures, they are approaching the damaging range. Additional shear, from pumps and other parts of the cooling water system could increase shear damage.

Some allied work by fish culturists indicated that mechanical damage can affect the survival of hatchery fish (Hayes 1949; Davis 1953; Leitritz 1963). The damage is not acute, but sublethal and appears as deformed juveniles. Emadi (1973) observed yolk sac deformation in salmon alevins raised in smooth bottomed trays. Water flow acting concurrently with abrasion may have induced the abnormalities.

One important point remains to be pointed out in relation to the Chesapeake and Delaware Canal. The water velocity and the turbulence in the canal area serves to keep striped bass eggs suspended. Albrecht (1964) and Fisk (1959) have determined the vertical water movement required to keep striped bass eggs in suspension. If these eggs are not suspended, increased mortality of the egg occurs (Bayliss 1968; Albrecht 1964). Data from the temperature-salinity runs by the Chesapeake Bay Institute, Johns Hopkins University, in the Canal indicated that stratification does not occur in the spring, indicating good vertical mixing in the canal area for keeping the striped bass eggs suspended. Indeed, one may think of the canal as a gigantic incubation chamber.

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