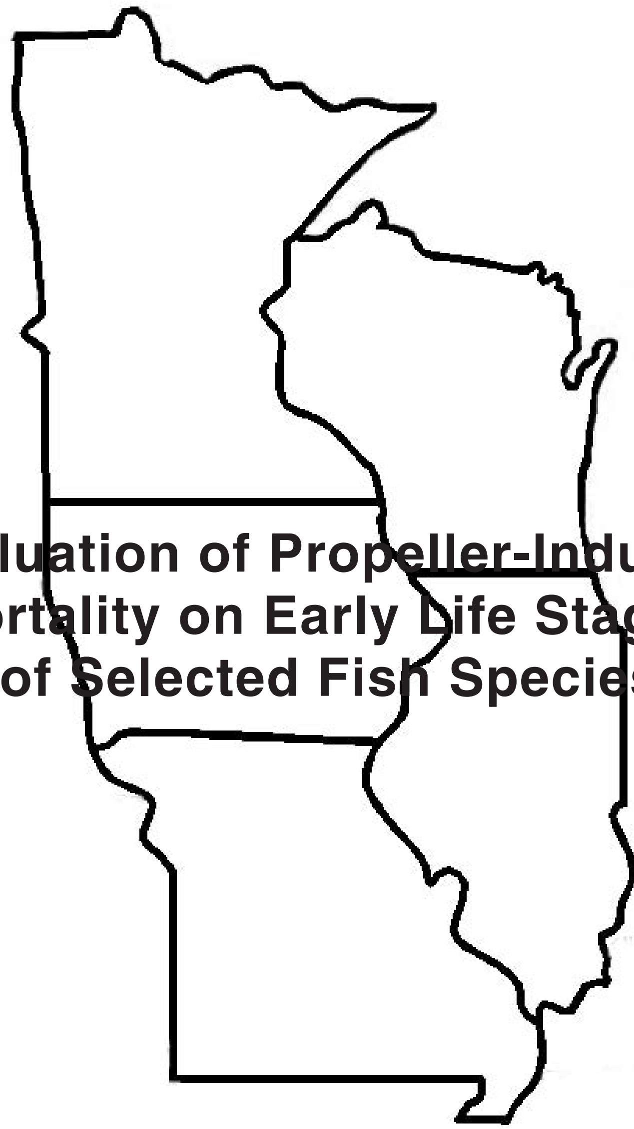
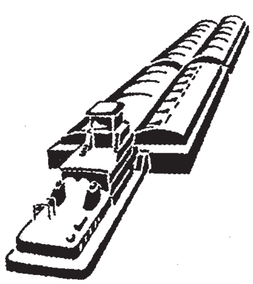
ENV Report 30

Interim Report For The Upper Mississippi River - Illinois Waterway System Navigation Study



Evaluation of Propeller-Induced Mortality on Early Life Stages of Selected Fish Species



March 2000

Rock Island District
St. Louis District
St. Paul District

US Army Corps of Engineers

Upper Mississippi River - Illinois Waterway System Navigation Study

ENV Report 30
March 2000

Evaluation of Propeller-Induced Mortality on Early Life Stages of Selected Fish Species

by K. Jack Killgore

U.S. Army Engineer Research and Development Center
Environmental Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Steve T. Maynord

U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Matthew D. Chan

Virginia Polytechnic Institute and State University
Department of Fisheries and Wildlife Sciences
Blacksburg, VA 24061

Raymond P. Morgan II

University of Maryland
Appalachian Environmental Laboratory
Frostburg, MD 21532

Interim report

Prepared for U.S. Army Engineer District, Rock Island
Rock Island, IL 61204-2004
U.S. Army Engineer District, St. Louis
St. Louis, MO 63103-2833
U.S. Army Engineer District, St. Paul
St. Paul, MN 55101-1638

Engineer Research and Development Center Cataloging-in-Publication Data

Contents

Preface

The work reported herein was conducted as part of the Upper Mississippi River - Illinois Waterway (UMR-IWW) System Navigation Study. The information generated for this interim effort will be considered as part of the plan formulation process for the System Navigation Study.

The UMR-IWW System Navigation Study is being conducted by the U.S. Army Engineer Districts, Rock Island, St. Louis, and St. Paul, under the authority of Section 216 of the Flood Control Act of 1970. Commercial navigation traffic is increasing and, in consideration of existing system lock constraints, will result in traffic delays that will continue to grow in the future. The system navigation study scope is to examine the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic. The study will determine the location and appropriate sequencing of potential navigation improvements on the system, prioritizing the improvements for the 50-year planning horizon from 2000 through 2050. The final product of the System Navigation Study is a Feasibility Report which is the decision document for processing to Congress.

This report was written by Mr. K. Jack Killgore, U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL), Vicksburg, MS; Dr. Steve T. Maynord, Coastal and Hydraulics Laboratory, ERDC; Mr. Matthew D. Chan, Virginia Polytechnic Institute and State University, Department of Fisheries and Wildlife Sciences, Blacksburg, VA; and Mr. Raymond P. Morgan II, University of Maryland, Appalachian Environmental Laboratory, Frostburg, MD.

Mr. William Merryman, Naval Surface Warfare Center Carderock Division, set up the propeller boat and operated the system. Mrs. Tracy Robinson and Sherry Harrel assisted with data collection. Drs. Glenn Cada, Tom Keevin, Webb Van Winkle, and Alexander Zale were reviewers.

Mr. Robert C. Gunkel, Jr., EL, ERDC, was responsible for coordinating the necessary activities leading to publication. Dr. John W. Keeley was Acting Director, EL, ERDC.

At the time of publication of this report, Dr. Lewis E. Link, Jr. was Acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

This report should be cited as follows:

> Killgore, K. Jack, Maynord, Steve T., Chan, Matthew D., and Morgan, Raymond P., II. (2000). "Evaluation of propeller-inducted mortality on early life stages of selected fish species," ENV Report 30, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

1 Introduction

Propellers of towboats can cause abrupt changes in hydraulic patterns, including increased turbulence and water velocities (Maynord 1990; Hyun and Patel 1991). Fish eggs and larvae that pass through water currents induced by a propeller may come in contact with the blade and can experience stresses from pressure changes and shear forces (Cada 1990). Early life stages of fish are most vulnerable to propeller impacts because they are fragile and cannot avoid turbulent conditions (Hickey 1979; Pearson et al. 1989). High mortality of eggs and larvae may result in a subsequent decrease in adult recruitment, particularly for pelagic species that occur in main channel habitats (Holland and Sylvester 1983).

Ichthyoplankton mortality related to propeller-type turbine passage may be no more than 5 percent (Cada 1990), although higher mortalities have been reported for juvenile clupeids (Stokesbury and Dadswell 1991) and alosines (DuBois and Gloss 1993). Low mortalities have also been reported for controlled studies of ichthyoplankton subjected to pressure changes (Tsvetkov, Pavlov, and Nezdoliy 1972; Beck, Poje, and Waller 1975; Blaxter and Hoss 1979; Hoss and Blaxter 1979) and rapid acceleration (Killgore, Miller, and Conley 1987; Payne, Killgore, and Miller 1990). Conversely, shear forces created along the hull of a barge are sufficiently high to kill larval fishes (Morgan et al. 1976), and since propeller-induced shear can be substantially greater than hull shear (Kotb and Schetz 1984), ichthyoplankton passing through towboat propellers may experience high mortalities. However, field investigations of direct ichthyoplankton mortality from towboat propellers are inconclusive (e.g., Odom, Orth, and Nielsen 1992) because organisms are difficult to sample in turbulent waters behind large vessels, and mortality has never been measured for fish directly placed through an operating towboat propeller.

2 Mortality Evaluation Study

We conducted a controlled study to evaluate mortality of ichthyoplankton entrained through water currents induced by a scale model of a towboat propeller placed into a large circulating water channel (CWC). This study was part of a larger research effort to evaluate the potential effects of increased commercial navigation in the Upper Mississippi River on fish population dynamics. Our objective was to develop empirical relationships between percent mortality of ichthyoplankton and shear stress. We also considered the probability of blade contact as a source of mortality. Five species of fish that occur in the Mississippi River were evaluated: larval shovelnose sturgeon *Scaphirhynchus platorynchus*, larval lake sturgeon *Acipenser fulvescens*, eggs and larvae of paddlefish *Polyodon spathula*, juvenile common carp *Cyprinus carpio*, and larval blue sucker *Cycleptus elongatus*.

3 Methods

Fish were obtained from a commercial hatchery and held in recirculating holding tanks (larvae) or McDonald-type hatching containers (paddlefish eggs) prior to experiments. Some paddlefish eggs hatched while the study was being conducted, so both eggs and larvae were tested separately. Larvae of all species were in the yolk-sac phase or early postyolk-sac phase; maximum age was 4 days posthatch and total lengths ranged from 9 to 16 mm (Table 1). Common carp were obtained as juveniles. Once fish absorbed yolk sac, they were fed brine shrimp three times daily. Temperature and pH of the aquaculture facilities and CWC were 21 to 23 °C and 6.5 to 7.2, respectively. Dissolved oxygen was always greater than 7 mg/l. Photoperiod was approximately 12 hr light, 12 hr dark.

Table 1
Mean and Range of Total Length (mm) by Species

Species	Mean	Length Range, mm
Shovelnose sturgeon larvae	14	13 - 16
Lake sturgeon larvae	11	9 - 13
Paddlefish eggs	14	13 - 16
Paddlefish larvae	14	13 - 16
Carp juveniles	22	16 - 32
Blue sucker larvae	8	7 - 9

Note: Paddlefish larvae were in the early yolk-sac stage; all other larvae were in the late yolk-sac or early postyolk-sac stage.

A three-blade, open-wheel propeller (measuring 46 cm in diameter with a 36-cm pitch and 20-cm maximum blade width; surface area of each blade was 303 cm^2) was used in this study. Although towboat propellers are larger (>2 m in diameter), the rotational speed of the experimental propeller could be adjusted to approximate shear stress levels similar to actual conditions.

4 Free Surface Test Section

The CWC was a closed water system on a vertical plane with a free surface test section open to the atmosphere (Merryman 1996). The test section of the CWC was 44.7 m long, 6.7 m wide (except at pumps), 2.7 m deep, and contained 2,539,300 L of filtered water. Two variable-speed, 1,250-HP, impeller motors maintained an ambient flow in the test section of the CWC. Ambient water velocity was measured at 10 equidistant points along a cross-sectional transect in the test section. At each point, measurements were taken at 0.5 and 2.2 m and averaged. The mean (±SD) velocity of the test section was 0.7 ± 0.7 m/s.

The propeller boat hull was fusiform, 3 m long, and 76 cm wide (Figure 1). The shaft and propeller extended out 43 cm from the body of the propeller boat hull. The propeller was 1.1 m below the surface. A propeller shroud was mounted 2 to 3 cm above the blade tip to simulate an actual hull above the propeller and prevent aeration into the propeller from the water surface (Merryman 1996). The drive train of the propeller boat consisted of a 15-HP motor, and a dynamometer that measured propeller speed and thrust (Merryman 1996).

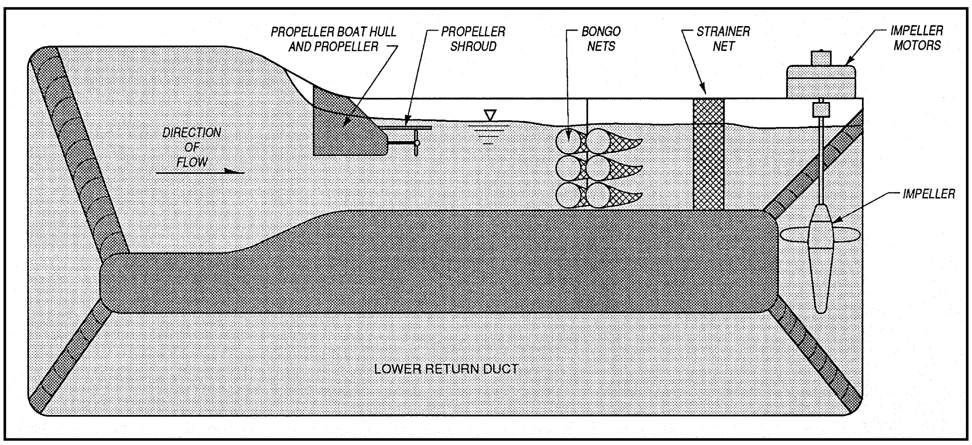


Figure 1. Schematic of the scale model of a towboat propeller placed into a circulating water channel and bongo nets used to collect fish entrained through propeller

Four propeller speeds (RPM) were evaluated: 400, 598, 798, and 969. Depending on species and life stage, three to seven replicate trials were obtained for each propeller speed and controls (propeller not operating). To ensure availability of ichthyoplankton for subsequent replication, an average (± SD) of 24.8 ± 1.3 individuals were used per trial. A total of 109 trials were obtained during the study.

To inject fish through the propeller, a copper tube was positioned at a point 38 cm upstream and directly behind the propeller hub. A tygon tube (15-mm inside diameter) was inserted through the copper tube with one end extending above the water surface to use for siphoning fish. All species and life stages were injected at this point. In addition, carp juveniles were injected on the same plane but 5 cm from the starboard side of the propeller to evaluate mortality of fish entrained in water currents at the edge of the blade.

Fish were removed from their holding tanks using a roasting baster and placed in a 19-L bucket. Gravity fed suction was created through the tygon tube. The propeller was then brought to the desired speed and individuals were siphoned out of the bucket through the propeller. This process took 10 to 30 sec depending on the species, and air was blown through the tube to ensure that all individuals were injected. The propeller was immediately turned off after siphoning was completed.

Fish were collected downstream with bongo nets; each net was 60 cm in diameter and constructed of 505-µm nylon mesh. A cod end bucket, 10 cm in diameter, was attached to each net. Six bongo nets were placed 7 m downstream of the propeller (Figure 1) prior to each test and filtered water during propeller operation. The mean number of individuals recovered in the bongo nets, out of an average of 25 individuals injected per trial, was 14.4 ± 3.1 for treatments (n=72) and 10.2 ± 5.1 for controls (n=37). Fish were removed from cod end buckets into a 15-cm-diam petri dish using a roasting baster, and number of dead, moribund, and live specimens were enumerated. Dead specimens had no heart beat. Moribund specimens had heart beats but exhibited erratic movements (e.g., swimming in tight circles) or were immobile. Observations of delayed mortality, up to 180 min after entrainment, were made for treatment and control groups; moribund individuals were assumed dead at the last count. All individuals were preserved in 5 percent buffered formalin and total lengths were obtained later.

Control and treatment groups were handled the same except that the propeller was not operating during control runs. Control fish were removed from the holding tanks using the baster, placed in the 19-L bucket, and individuals were siphoned out of the bucket into the CWC. Fish were collected with bongo nets that had been moved to approximately 2 m downstream of the propeller; this increased the likelihood of catching fish at the lower ambient velocity.

When the propeller is operating, through-mesh velocities of the bongo nets will increase and may cause impingement mortality unrelated to propeller entrainment. We measured water velocity directly in front of the nets at ambient velocity and for each propeller speed (Table 2). Although velocities measured in front of the bongos were less than propeller jet velocities except at 400 RPM, through-mesh velocity in the bongo nets may have contributed to some mortality.

Table 2
Water Velocities and Shear Stress Created by Propeller Operating at Four Different RPMs

RPM	Mean Velocity in Front of Bongo Nets, m/sec	V_1, m/sec	V_2, m/sec	V_{avg}, m/sec	Shear Stress, dynes/cm^2
0	0.7 ± 0.7	0	0	0	0
400	1.1 ± 0.6	1.7	1.9	1.8	634
598	1.4 ± 0.8	2.4	3.3	2.8	1,613
798	1.7 ± 0.8	3.1	4.7	3.9	3,058
969	2.7 ± 1.0	3.8	6.0	4.9	4,743

Note: RPM and velocity in front of bongo nets were measured during trials; remaining variables were derived according to Methods. V_1 is the velocity at the plane of the propeller and V_2 is the maximum velocity change impacted by the propeller; V_{avg} is the mean of V_1 and V_2 and was used in Equation 2 to calculate average shear stress.

A 7.6- by 3.0-m net with 500-μm mesh was deployed at the downstream end of the CWC test section to strain individuals not collected with bongo nets. In addition, bongo nets were fished between trials. These procedures were used to avoid and quantify capture of recirculating fish during subsequent trials. Dead fish, primarily pieces of individuals, were collected in the strainer net, but never in the bongo nets between trials. Retention of dead fish during removal of the strainer net was difficult, but we counted 10 larvae, 2 eggs, and numerous pieces of fish at the end of 1 day. The coloration of these individuals was pale compared with the dark coloration of live individuals used in control and treatment groups; pale individuals or pieces of fish were not observed in control or treatment groups. Fish caught in the strainer net were not used in subsequent analysis.

Propeller-induced velocity was calculated as the velocity at the plane of the propeller (V_1) and the maximum velocity created by the propeller (V_2). Based on Maynord (1999), V_1 is equal to discharge/area of the propeller and V_2 is based on the measured thrust and the momentum theory of propeller design expressed as:

$$V_2 = z(V_1 - V_a) \qquad (1)$$

where

z = 2 for open-wheel propellers, 1 for Kort nozzles

V_a = approach velocity (m/s)

The mean of V_1 and V_2 was used as the velocity to calculate shear stress (dynes/cm^2) from Albertson et al. (1950) who gives the shear stress within a free jet as:

$$\text{Shear stress} = 0.02\rho V^2 \qquad (2)$$

where

ρ = water density (g/cm)

V = average water velocity (cm/sec; V_{avg} in Table 2)

Variation of these derived variables was considered minimal. Coefficients of variation of measured variables (i.e., RPM, thrust, torque) ranged from <1 to 4 percent.

An Analysis of Variance (ANOVA) was used to test the null hypothesis that percent mortality, based on the number of fish collected in the bongo nets that were dead at the end of the final observation period, was equal among propeller speeds. Prior to ANOVA, percent mortality was transformed using the arcsine (square root of X) and shear stress was transformed using $\log_{10}$ +1 to normalize the data. However, means are reported as untransformed values. The Student-Neuman-Keuls multiple range test (SNK) was used to identify shear stress that caused significantly different ($p<0.05$) mortalities (SAS Institute 1993). Bivariate plots of raw data were examined and equations were developed for each species that predicted percent mortality as a function of shear stress. The goal was to select the equation with the highest coefficient of determination (R^2). The following statistical techniques were applied using transformed and untransformed data (SAS Institute1993): linear regression, quadratic regression, and exponential functions.

5 Results

Mean total mortalities (initial plus delayed) of control groups were low (0 to 3 percent) for common carp juveniles and lake sturgeon larvae, moderate (13 to 15 percent) for shovelnose sturgeon larvae and paddlefish eggs and larvae, and relatively high (40 percent) for blue sucker larvae. Consequently, total mortalities of blue sucker larvae were not significantly different ($P = 0.06$) among control and treatment groups (Table 3). There were significant differences between control and at least one treatment group(s) for all other species/life stages.

Table 3
Mean (±SD) Percent Total Mortality (Initial Plus Delayed) of Fish species Entrained Through or Adjacent to Propeller Operating at Different Shear Stress Levels

		Shear Stress (dynes/cm^2)					
Species/Life Stage	**N**	**0**	**634**	**1,613**	**3,058**	**4,743**	**Probability**
Shovelnose sturgeon larvae	4	13.1 ± 5.8[a]	-	-	-	57.6 ± 13.6[b]	0.002
Lake sturgeon larvae	4,5[1]	2.8 ± 5.6[a]	-	23.1 ± 12.1[a]	47.1 ± 23.5[b]	86.0 ± 9.8[c]	<0.001
Paddlefish eggs	5	15.1 ± 12.0[a]	-	-	-	30.4 ± 10.2[a]	0.06
Paddlefish larvae	7,5[2]	14.7 ± 13.1[a]	8.6 ± 10.5[a]	21.3 ± 6.6[a]	37.5 ± 14.5[b]	48.9 ± 7.9[b]	<0.001
Common carp juveniles - through propeller	5	0[a]	-	8.4 ± 6.5[ab]	-	16.8 ± 12.0[b]	0.02
Common carp juveniles - adjacent to propeller	5	0[a]	-	7.0 ± 5.1[a]	-	26.4 ± 12.9[b]	<0.001
Blue sucker larvae	6,3[3]	40.2 ± 17.2[a]	-	74.5 ± 15.9[a]	-	78.8 ± 36.7[a]	0.06

Note: Sample size (N) indicates the number of groups replicated for each control and treatment. Values with different letters along a row are significantly different according to the Student-Neuman-Keuls Multiple Range Test. Probability values represent results of the full ANOVA model.
[1] Sample size was 4 groups of fish for controls, 5 groups of fish for each treatment.
[2] Sample size was 7 groups of fish for control and 4,743 dynes/cm2 trials, 5 groups of fish for remaining treatment.
[3] Sample size was 6 groups of fish for controls, 3 groups of fish for each treatment.

Lake sturgeon and paddlefish larvae were injected at four shear stress levels induced by the propeller. For both taxa, mortalities of the two highest shear stress groups (3,058 and 4,743 dynes/cm^2) were significantly greater than the other treatment and control groups (Table 3). Shovelnose sturgeon larvae and paddlefish eggs were injected only at 4,743 dynes/cm^2. Mortality of shovelnose sturgeon larvae was significantly greater for treatment than control groups. However, paddlefish egg mortality of the treatment group was only marginally greater than controls ($p = 0.06$).

Common carp juveniles were injected through and adjacent to the propeller at intermediate and high shear stress levels. Controls groups had no mortality and mortalities of the high shear stress groups were significantly higher. However, mortalities of the high shear stress groups were lowest among the other taxa. Mortalities were only slightly higher for individuals passed adjacent to the propeller compared to those injected through the propeller. Four individuals that passed adjacent to the propeller had obvious physical injuries that could occur from blade impact; three carp had been sliced in half and another was missing part of its anal fin. However, we could not observe the actual pattern of carp movement through or adjacent to the propeller or the instance of blade impact.

Delayed mortality was observed for all taxa and life stages except for common carp juveniles (Table 4). In addition, there was no delayed mortalities for control groups of paddlefish eggs. The greatest difference in delayed mortality between initial and final observation periods occurred for blue sucker larvae. At 1,613 dynes/cm^2, the initial mortality was 17 percent, whereas 1 hr later the mortality was 75 percent, which corresponds to a 57 percent increase in number of larvae that died between the two time periods. Overall, delayed mortality was greater for treatment than control groups.

Table 4
Initial and Total Mean (±SD) Percent Mortality of Fish Passing Through a Propeller

Species	Shear Stress (dynes/cm^2)	Initial Percent Mortality	Total Percent Mortality (Minutes)
Shovelnose sturgeon larvae	0	9.3 ± 7.6	13.1 ± 5.8 (120)
	4,743	6.6 ± 1.2	57.6 ± 13.6 (120)
Lake sturgeon larvae	0	0	2.8 ± 5.6 (120)
	1,613	5.1 ± 3.0	23.1 ± 12.1 (60)
	3,058	2.9 ± 3.9	47.1 ± 23.5 (120)
	4,743	43.0 ± 24.0	86.0 ± 9.8 (180)
Paddlefish eggs	0	15.1 ± 12.0	15.1 ± 12.0 (60)
	4,743	18.2 ± 6.7	30.4 ± 10.2 (60)
Paddlefish larvae	0	5.6 ± 7.9	14.7 ± 13.1 (60)
	634	2.4 ± 3.2	8.6 ± 10.5 (120)
	1,613	7.6 ± 7.2	21.3 ± 6.6 (180)
	3,058	9.5 ± 10.0	37.5 ± 14.5 (120)
	4,743	7.7 ± 6.3	48.9 ± 7.9 (180)
Blue sucker larvae	0	16.4 ± 15.1	40.2 ± 17.2 (180)
	1,613	17.2 ± 6.9	74.5 ± 15.9 (60)
	4,743	28.7 ± 6.9	78.8 ± 36.7 (60)

Note: Sample size is the same as shown in Table 3. Numbers in parenthesis represent time (minutes) of last observation made for species.

Linear regression using untransformed variables provided predictive equations with the highest R^2 values, and except for paddlefish eggs, models were statistically significant (Table 5). Paddlefish and shovelnose sturgeon larvae had similar coefficients, but the slope for lake sturgeon larvae was steeper. The intercept for blue sucker larvae, which were the smallest larvae used in the study, was 45 percent due to high mortality of control groups. Coefficients for carp juveniles passed through and adjacent to the propeller were almost identical, so these data were pooled prior to linear regression.

Table 5
Output Values for Least-Squares Regression Analysis of Percent Mortality as the Dependent Variable and Shear Stress as the Independent Variable

Taxa	df	F-value	P	Intercept	Slope	R^2
Paddlefish eggs	9	4.7	0.062	15.08	0.003	0.37
Paddlefish larvae	28	52.7	<0.001	10.16	0.008	0.66
Shovelnose sturgeon larvae	7	35.9	0.001	13.12	0.009	0.86
Lake sturgeon larvae	18	81.3	<0.001	-2.12	0.018	0.83
Blue sucker larvae	11	5.3	0.045	45.45	0.008	0.35
Carp juvenile-combined	29	38.4	<0.001	0.14	0.004	0.58

Note: Data were combined for carp juveniles passed through and adjacent to the propeller.

6 Discussion

Entrainment of fish through propellers can result in immediate or delayed mortality, but the magnitude is dependent on species and life stage. Riverine ichthyoplankton, such as paddlefish and sturgeon eggs and larvae, are generally adapted to turbulent conditions. Streamlined bodies of larval fish minimize pressure drag. As larvae are entrained at low velocities, they probably align themselves with the prevailing current resulting in less drag and acceleration. At higher velocities, however, alignment is influenced more by turbulent flow. Since the internal organs of larval fish are not fully developed and the integument is relatively fragile during early development, greater mortality can be expected during periods of high turbulence.

Paddlefish eggs, which are spawned in riffles, appear to tolerate high shear stress levels. The spherical shape and flexible, outer chorion of the egg likely protects the embryo from rotational, deformational, and shear stresses. Paddlefish larvae have also been reported to tolerate rapid acceleration (Payne, Killgore, and Miller 1990), but our study suggests that larvae are susceptible to turbulent flows from towboat propellers.

Both species of sturgeon larvae experienced high mortalities, but lake sturgeon larvae are less tolerant to high shear stress levels than shovelnose sturgeon larvae. Conditional mortality (i.e., subtracting mortalities of control from treatment groups) of shovelnose sturgeon larvae was approximately 44 percent at 4,743 dynes/cm^2 compared to 83 percent for lake sturgeon larvae. Lake sturgeon larvae typically occur in low velocity habitats while shovelnose sturgeon larvae are usually found in the pelagic drift (Wallus, Yeager, and Simon 1990). Thus, adaptation to different habitats may account for different tolerances to shear stress.

Size of larvae may also be a contributing factor. Lake sturgeon larvae were smaller than shovelnose sturgeon larvae (Table 1). Size-dependent mortality is further supported by relatively high mortalities of blue sucker larvae, which were the smallest individuals used in the study. We attempted to evaluate white bass *Morone chrysops* and smallmouth buffalo *Ictiobus cyprinellus* larvae (<5 mm TL), which were smaller than blue sucker larvae, but most individuals died during control trials. Conversely, common carp juveniles, the largest of the individuals used in the study, experienced low mortality. Juvenile carp have fully developed organs and a more rigid integument, which probably promote higher survival in turbulent conditions.

Probability of blade impact is as a function of propeller characteristics (size, number of blades), propeller speed, and size of fish. Using equation reported by

Cada (1990), probability of blade contact in our study was 5.2 × length, which is higher than the probability during turbine passage (Cada 1990) and for most towboat propellers which operate at considerably less RPM. However, only a few juvenile carp had blade-type injuries, and the point of entrainment did not affect mortalities. Fish eggs and larval fish closely follow the water motion because of their small size and near neutral buoyancy which may minimize blade impact. Downstream of the leading edge of the blade, primary water currents become relatively parallel to the blade surface, and if the fish's momentum does not carry it into the blade, the chance of blade impact would be further reduced. Thus, blade impact is probably a minor component of mortality during entrainment.

Shear is highest in areas where velocity is rapidly changing with distance and can cause mortality by exposing the organism to a differential force (shear stress) across its body. In and downstream of a propeller jet, high shear occurs at the zone between the propeller blades, the zone downstream of individual blades, near the hub, and within and around the perimeter of the jet. The magnitude of shear is dependent on towboat characteristics and speed of the vessel. A large tow going at a typical speed in the Upper Mississippi River might have the following characteristics: three-barge wide by five-barge long tow; loaded with a draft of 2.74 m; pushed by a towboat having two, 2.74-m-diam open-wheel propellers; and travelling at 9.7 km/h. Calculating V_1 (velocity at the plane of the propeller) and V_2 (maximum velocity change created by the propeller) for this tow configuration results in 0.4 and 7.2 m/s, respectively. Inserting the average (V_{avg}) of these two variables into Equation 2 results in a shear stress of 6,270 dynes/cm^2, which probably represents the upper range of most towboats. The maximum shear stress created in the CWC was 4,743 dynes/cm^2, which resulted in conditional fish mortalities of up to 83 percent, and there was a positive relationship between shear stress and mortality. Consequently, shear created from propellers can be a major source of mortality for larval fishes.

The linear relationships between mortality and shear stress suggests that mortality can be predicted for different towboat configurations and extrapolated to approximate impacts of increased navigation traffic. Based on our study, mortality of eggs will be low or nonexistent and juveniles will experience relatively minor mortality. Larval losses will depend on species and size, but mortality may be substantial for smaller individuals entrained at higher shear stress levels.

References

Albertson, M. L., Dai, Y. B., Jensen, R. A., and Rouse, H. (1950). "Diffusion of submerged jets." *Transactions of the American Society of Civil Engineers* 115 (2409), 639-697.

Beck, A. P., Poje, G. V., and Waller, W. T. (1975). "A laboratory study on the effects of exposure of some entrainable Hudson River biota to hydrostatic pressure regimens calculated for the proposed Cornwall pump-storage plant." *Fisheries and Energy Production, a Symposium.* S. B. Saila, ed., Lexington Books, Lexington, MA, 23-32.

Blaxter, J. H. S., and Hoss, D. E. (1979). "The effect of rapid changes of hydrostatic pressure on the Atlantic herring *Clupea harengus* L. II. The response of the auditory bulla system in larvae and juveniles," *Journal of Experimental Marine Biology and Ecology* 41, 87-100.

Cada, G. F. (1990). "A review of studies relating to the effects of propeller-type turbine passage on fish early life stages," *North American Journal of Fisheries Management* 10, 418-426.

DuBois, R. B., and Gloss, S. P. (1993). "Mortality of juvenile American shad and striped bass passed through Ossberger crossflow turbines at a small-scale hydroelectric site," *North American Journal of Fisheries Management* 13, 178-175.

Hickey, G. M. (1979). "Survival of fish larvae after injury," *Journal of Experimental Marine Biology and Ecology* 37, 1-7.

Holland, L. E., and Sylvester, J. R. (1983). "Distribution of larval fishes related to potential navigation impacts on the upper Mississippi River, Pool 7," *Transactions of the American Fisheries Society* 112, 293-301.

Hoss, D. E., and Blaxter, J. H. S. (1979). "The effect of rapid changes in hydrostatic pressure on the Atlantic herring *Clupea harengus* L. I. Larval survival and behavior," *Journal of Experimental Marine Biology and Ecology* 41, 75-85.

Hyun, B. S., and Patel, V. C. (1991). "Measurements in the flow around a marine propeller at the stern of an axisymmetric body," *Experiments in Fluids* 11, 33-44.

Killgore, K. J., Miller, A. C., and Conley, K. C. (1987). "Effects of turbulence on yolk-sac larvae of paddlefish," *Transactions of the American Fisheries Society* 116, 670-673.

Kotb, M. A., and Schetz, J. A. (1984). "Measurement of three-dimensional turbulent flow behind a propeller in a shear flow," *American Institute of Aeronautics and Astronautics Journal* 24, 570-577.

Maynord, S. T. (1990). "Velocities induced by commercial navigation," Technical Report HL-90-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

______ . (1999). "Inflow zone and discharge through propeller jets," ENV Report 25, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Merryman, W. J. (1996). "Fish larvae mortality test," Marine Systems Department, Naval Surface Warfare Center Carderock Division, Bethesda, MD.

Morgan R. P., II, Ulanowicz, R. E., Rasin, V. J., Jr., Noe, A., and Gray, G. B. (1976). "Effects of shear on eggs and larvae of striped bass *Morone saxatilis*, and white perch *M. americana*." *Transactions of the American Fisheries Society* 105, 149-154.

Odom, M. C., Orth, D. J., and Nielsen, L. A. (1992). "Investigation of barge-associated mortality of larval fishes in the Kanawha River," *Virginia Journal of Science* 43, 41-45.

Payne, B. S., Killgore, K. J., and Miller, A. C. (1990). "Mortality of yolk-sac larvae of paddlefish entrained in high-velocity water currents," *Journal of Mississippi Academy of Sciences* 35, 7-9.

Pearson, W. D., Killgore, K. J., Payne, B. S., and Miller, A. C. (1989). "Environmental effects of navigation traffic: Studies on fish eggs and larvae," Technical Report EL-89-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

SAS Institute. (1993). "SAS Companion for Microsoft Windows Environment. Version 6," 1st ed., Cary, NC.

Stokesbury, K. D. E., and Dadswell, M. J. (1991). "Mortality of juvenile clupeids during passage through a tidal, low-head hydroelectric turbine at Annapolis Royal, Nova Scotia," *North American Journal of Fisheries Management* 11, 149-154.

Tsvetkov, V. I., Pavlov, D. S., and Nezdoliy, V. K. (1972). "Changes of hydrostatic pressure lethal to young of some freshwater fish," *Journal of Ichthyology* 12, 307-318.

Wallus, R., Yeager, B. L., and Simon, T. P. (1990). “Reproductive biology and early life history of fishes in the Ohio river drainage. Volume 1: Acipenseridae through Esocidae,” Tennessee Valley Authority, Chattanooga, TN.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
March 2000

3. REPORT TYPE AND DATES COVERED
Interim report

4. TITLE AND SUBTITLE
Evaluation of Propeller-Induced Mortality on Early Life Stages of Selected Fish Species

5. FUNDING NUMBERS

6. AUTHOR(S)
K. Jack Killgore, Stephen T. Maynord, Matthew D. Chan, Raymond P. Morgan II

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
See reverse.

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
See reverse.

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ENV Report 30

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Mortality of ichthyoplankton entrained through a scale model of a towboat propeller was evaluated in a large (>2 million L) circulating water channel. Five species of fish (larval shovelnose sturgeon *Scaphirhynchus platorynchus*, larval lake sturgeon *Acipenser fulvescens*, larvae and eggs of paddlefish *Polyodon spathula*, larval blue sucker *Cycleptus elongatus*, and juvenile common carp *Cyprinus carpio.*) were subjected to one or more shear stress levels (634, 1,613, 3,058, 4,743 dynes/cm^2). Mortality was a linear function of shear stress for all species and life stages. However, conditional mortalities (i.e., subtracting control from treatment mortality) were relatively low (<30 percent) for paddlefish eggs and common carp juveniles. Smaller larvae (lake sturgeon and blue sucker) experienced higher mortalities than larger larvae. However, conditional mortality of blue suckers was less than 50 percent due to high mortality of control groups. Delayed mortality was observed for all larval species, particularly at higher shear stress levels, but none for common carp juveniles and paddelfish eggs. Shear stress created from propeller jet velocities in navigable rivers can exceed 5,000 dynes/cm^2 and is probably the primary force contributing to mortality of ichthyoplankton entrained during vessel passage.

14. SUBJECT TERMS
Impacts
Larval fish
Navigation

15. NUMBER OF PAGES
22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED		

7. (Concluded).

U.S. Army Engineer Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199
U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199
Virginia Polytechnic Institute and State University, Department of Fisheries and Wildlife Sciences, Blacksburg, VA 24061
University of Maryland, Appalachian Environmental Laboratory, Frostburg, MD 21532

9. (Concluded).

U.S. Army Engineer District, Rock Island, Clock Tower Building, P.O. Box 2004, Rock Island, IL 61204-2004
U.S. Army Engineer District, St. Louis, 1222 Spruce Street, St. Louis, MO 63103-2833
U.S. Army Engineer District, St. Paul, Army Corps of Engineers Centre, 190 5th Street East, St. Paul, MN 55101-1638