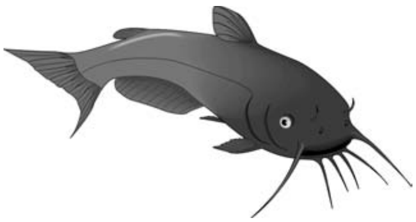
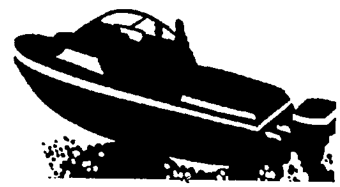
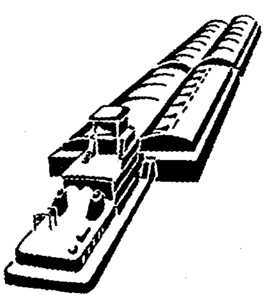
ENV Report 35

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





Mortality of Fish Early Life Stages Resulting from Hull Shear Stress Associated with Passage of Commercial Navigation Traffic



September 2002

Rock Island District
St. Louis District
St. Paul District

US Army Corps of Engineers

Upper Mississippi River - Illinois Waterway System Navigation Study

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Mortality of Fish Early Life Stages Resulting from Hull Shear Stress Associated with Passage of Commercial Navigation Traffic

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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 report 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 in 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 study was conducted in the Coastal and Hydraulics Laboratory (CHL), and Environmental Laboratory (EL), U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. The work was conducted under the direction of Mr. Thomas A. Richardson, Acting Director, CHL, and Dr. Edwin A. Theriot, Director, EL.

This report was written by Dr. Thomas M. Keevin, Environmental Analysis Branch, U.S. Army Engineer District, St. Louis; Dr. Stephen T. Maynord, CHL, ERDC; Messrs. S. Reid Adams, Southern Illinois University, Carbondale, IL, and Dr. K. Jack Killgore, EL, ERDC.

The Couette cell was built by Messrs. Larry Purvis and Mickey Blackmon, Machine Shop, ERDC. Dr. David Schaeffer, University of Illinois, Urbana, IL, provided statistical assistance. Drs. Glenn Cada and Webb Van Winkle, Oak Ridge National Laboratory, Oak Ridge, TN, and Schaeffer reviewed a draft of this paper. This study was funded by the U.S. Army Engineer District, St. Louis, through the Upper Mississippi River–Illinois Waterway System Navigation Study. Permission was granted by the Chief of Engineers to publish this document.

At the time of publication of this report, Director of ERDC was Dr. James R. Houston, and Commander and Executive Director was COL John W. Morris III, EN.

1 Introduction

The Upper Mississippi River-Illinois Waterway System (UMR-IWWS) Navigation (Feasibility) Study (U.S. Army Corps of Engineers 1994) is currently evaluating capital investment planning for the UMR-IWWS for the years 2000-2050. The study is evaluating the justification for providing additional lockage capacity on the UMR-IWWS. If lockage capacity is increased, frequency of tow passage is expected to increase on the UMR-IWWS. Increased commercial navigation traffic subjects organisms using the waterway to an increased frequency of potentially damaging physical forces caused by tow traffic.

It has been suggested that the physical forces caused by commercial navigation traffic may kill larval fish (Holland and Sylvester 1983; Nielsen, Sheehan, and Orth 1986). Field evidence of direct mortality of larval fish is inconclusive because of difficulties in sampling small organisms in turbulent waters behind tow boats, and also because sampling alone causes mortality (Holland 1986; Odom, Orth, and Nielson 1992). Laboratory studies have evaluated individual physical forces resulting from tow traffic that have the potential to cause mortality. Factors studied were shear stress, turbulence, pressure, and shoreline dewatering (Holland 1987; Killgore, Miller, and Conley 1987; Morgan et al. 1976; Payne, Killgore, and Miller 1990; Adams et al. 1999).

Fluid shear adjacent to the hull of the tow may impact aquatic organisms. Shear stress is the force per unit area that results from differences in velocity from one point in the water to an adjacent point. Shear is defined as the velocity difference between two adjacent points divided by their distance apart. The product of the velocity gradient and the water viscosity (laminar viscosity + eddy viscosity) determine the shear stress. The shear stress on the hull of a vessel forms because water molecules immediately adjacent to the hull are dragged along at the speed of the hull. Some distance away from the hull, the water particles are undisturbed by passage of the vessel. Between the hull and the outer limit of the hull effect, there exists a velocity gradient that results in a zone of shear stress. These concepts are shown in Figure 1, which replaces a vessel moving through still water with water moving past a stationary vessel at a water velocity equal to the vessel speed. The boundary layer is the zone in which the hull affects the velocity and in which shear stress exists. Common practice is to define the edge of the boundary layer as the point where the velocity is 0.99 times the velocity outside the boundary layer (Rouse 1950).

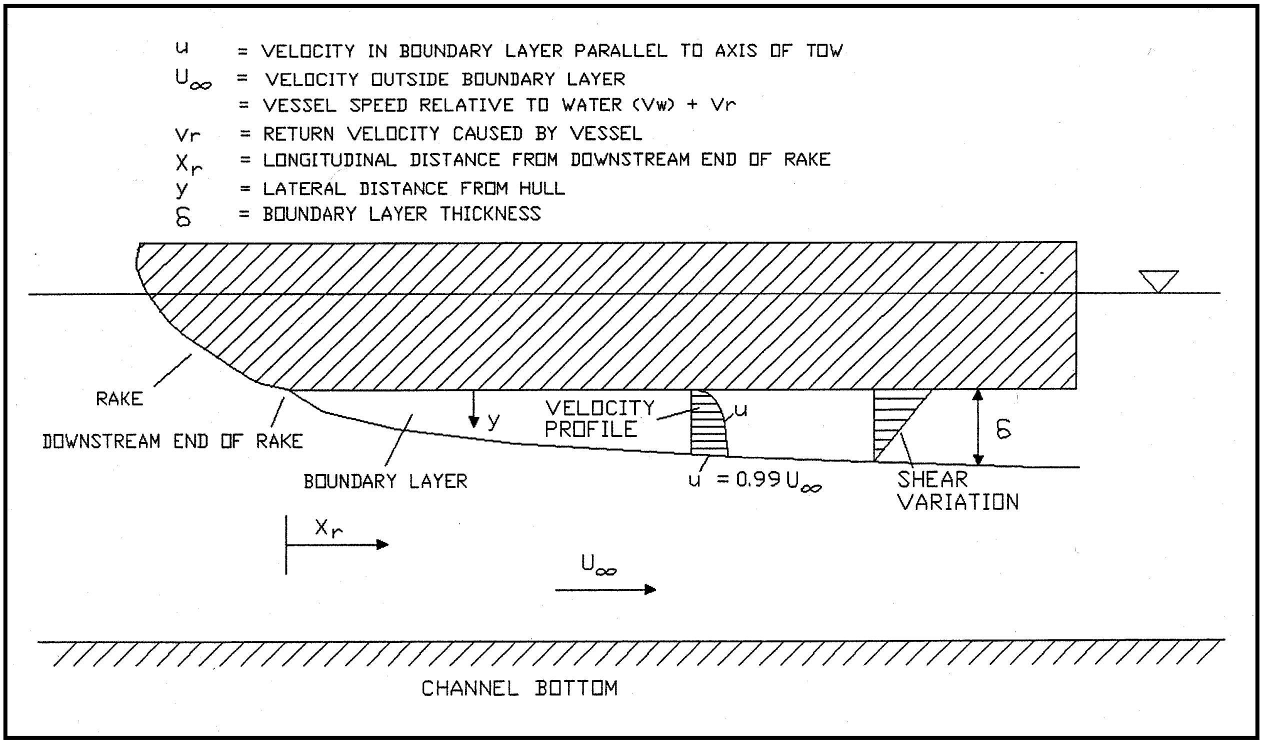

Figure 1. Schematic of boundary layer along hull of vessel

The velocity profile in Figure 1 shows that the velocity is zero at the hull and increases rapidly away from the hull. The velocity gradient is largest near the hull and approaches zero at the edge of the boundary layer. Consequently, the vessel-caused shear and shear stress are largest near the hull and approach zero at the edge of the boundary layer. This is shown as the shear variation on Figure 1. A linear variation of shear from the hull to the edge of the boundary layer is typical. The boundary layer thickness varies from zero at the bow of the tow to a maximum at the stern of the tow, which results in the velocity gradient being largest at the bow and least at the stern. Consequently, the shear stress distribution is complex; the peak is at the bow nearest the hull and decreases both toward the stern and away from the hull. The amount of flow within the boundary layer is zero at the bow and increases toward the stern. In a significant number of UMR–IWWS tows, the clearance between the bottom of the barges and the channel bottom is as low as 0.6 m, and the boundary layer thickness grows until it reaches the channel bottom.

Early life stages of fish have poor swimming capability and are fragile, making them vulnerable to shear stress from moving tows (Hickey 1979; Pearson et al. 1989). A controlled laboratory study was conducted to evaluate mortality of young fish resulting from simulated shear stress caused by passage of a barge hull through the water column. Mortality of five fish species, larval shovelnose sturgeon *Scaphirhynchus platorynchus*, larval bigmouth buffalo *Ictiobus cyprinellus*, larval blue catfish *Ictalurus furcatus*, juvenile bluegill *Lepomis macrochirus*, and juvenile largemouth bass *Micropterus salmoides*, was measured in a Couette cell. Mortality was measured for shear levels of 0, 100, 300, and 500 dynes/cm^2 at exposure times of 30, 60, and 120 sec. Mortality values were compared with calculations of barge hull shear levels provided by Maynord (2000) to determine the potential for mortality of fish early life stages in view of commercial navigation traffic.

2 Methods

Effects of Shear Stress on Fish

Early life stages of fish were subjected to shear stress by placing them in the well-defined velocity gradient, and thusly well defined shear, of Couette-Taylor flow. Couette flow was formed between a rotating inner cylinder and a stationary outer cylinder, shown in Figure 2, and is identical to the geometry of the cylinders used by Lathrop, Fineberg, and Swinney (1992). The inner and outer cylinders were constructed of smooth nylon, and the upper and lower end plates were constructed of aluminum. The gap between the inner cylinder and the upper and lower end plates was small enough to prevent small fishes from entering the cavity at the ends. Lathrop, Fineberg, and Swinney (1992) conducted detailed torque and wall shear stress measurements and developed an equation for the dimensionless torque G for Reynolds number $R > 1.3 \times 10^4$.

$$\log_{10} G = 1.190 + 0.0555\,(\log_{10} R)^2 + 1.203\,(\log_{10} R) \tag{1}$$

where

$G = T/(\rho v^2 L)$

T = measured torque

ρ = water density

v = kinematic viscosity

L = cylinder length

$R = \Omega\, a\,(b - a)/v$

Ω = rotation rate of inner cylinder in rad/sec

a = radius of inner cylinder

b = radius of outer cylinder

Shear stress in the region between the cylinders is equal to the wall shear stress (τ_w) and is defined by Lathrop, Fineberg, and Swinney (1992) as

$$\tau_w = \frac{\rho\, G\, \nu^2}{2\,\pi\, b^2} \tag{2}$$

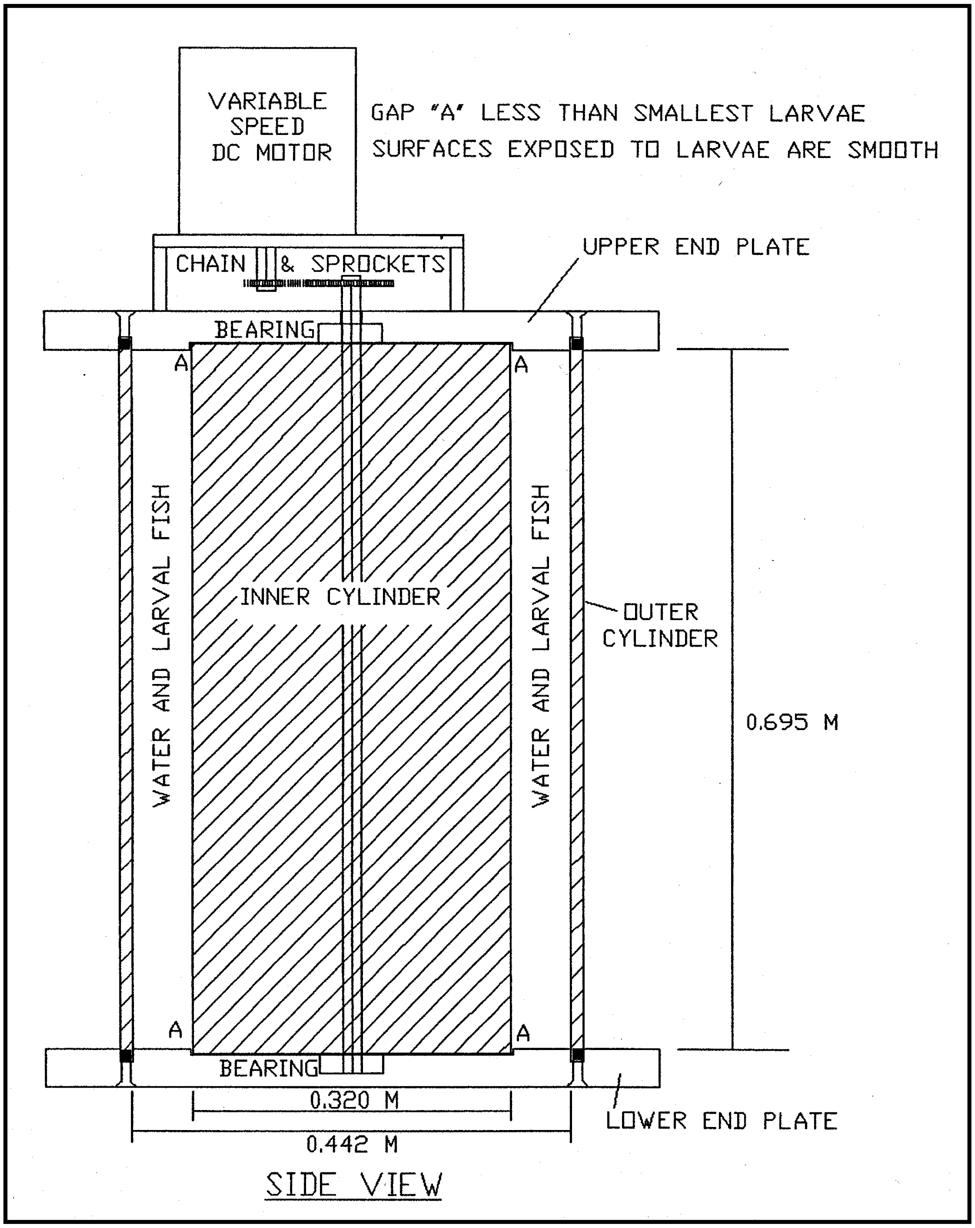

Figure 2. Schematic of rotating inner cylinder and stationary outer cylinder

Equations 1 and 2 were solved for shear stress as a function of inner cylinder speed at a water temperature of 21.1 °C (Figure 3). The 3 hp DC motor powering the inner cylinder was capable of producing a maximum shear stress of about 570 dynes/cm^2. The minimum R used in these experiments was 3.0×10^5. According to Lathrop, Fineberg, and Swinney (1992), flow between the cylinders in our experiments at $R > 1.3 \times 10^4$ is similar to flow in a wall-bounded shear flow, which is what occurs beneath the hull of a vessel. Couette cells, such as the one designed for our study, have been used to evaluate the effects of shear stress conditions on mortality and biological processes for a variety of aquatic organisms (Latz, Case, and Gran 1994; Mead and Denny 1995; Morgan et al. 1976; Thomas and Gibson 1990, 1992).

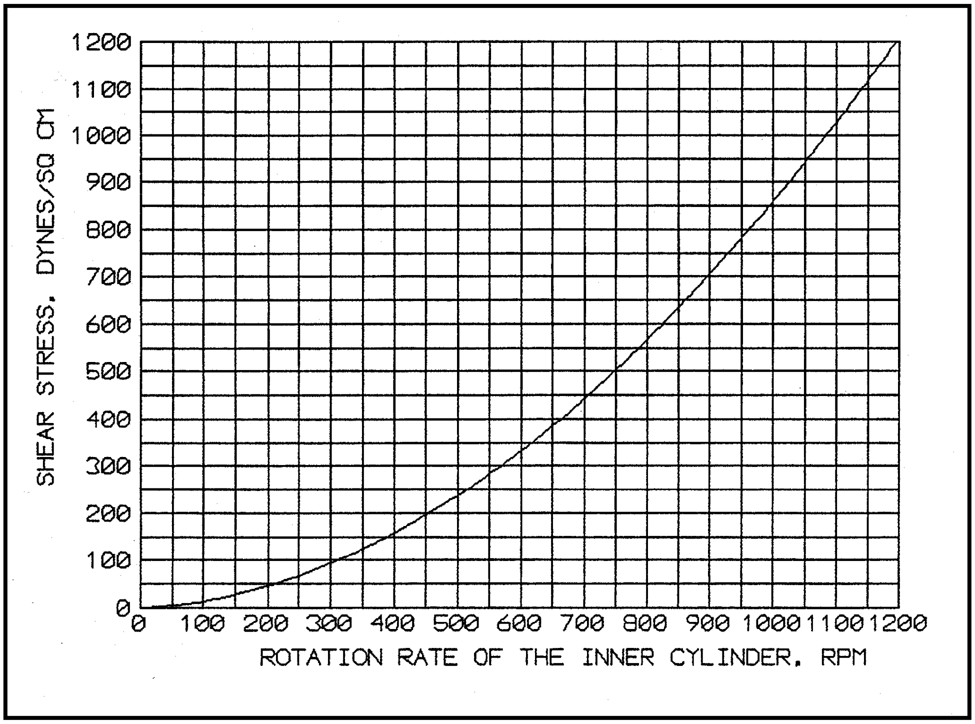

Figure 3. Shear stress between cylinders versus rotation rate of the inner cylinder

Commercial Hatchery Fish

Fish were obtained from a commercial hatchery (Osage Catfisheries, Osage Beach, Missouri) and held in circulating holding tanks prior to experiment. Shovelnose sturgeon, bigmouth buffalo, and blue catfish were obtained as larvae in the early postyolk sac phase; largemouth bass were juveniles, and bluegills ranged from late larvae to early juveniles (Table 1). Fish were fed Nutrafin Fry Food, *ad libitum*. Temperature of the aquaculture facilities was 19 to 22 °C. Photoperiod was approximately 12 hr light, 12 hr dark.

Table 1
Mean and Range of Total Length (mm) for Species Tested (N = 20)

Species	Mean	Range	S.D.
Shovelnose Sturgeon	16.08	15.0 – 16.8	0.43
Bigmouth buffalo	11.26	9.4 – 13.0	0.95
Blue catfish	15.27	14.4 – 15.8	0.33
Largemouth bass	28.52	27.2 – 30.8	0.93
Bluegill	17.29	13.6 – 25.7	2.67

Fish were removed from holding tanks with a roasting baster and placed in the Couette cell. Except for largemouth bass, three replicates of 10 fish each were used for each shear level (0, 100, 300, 500 dynes/cm^2) for a total sample size of 30 fish per treatment. Largemouth bass were replicated twice for a total of 20 fish per treatment. With the exception of applying shear stress, handling and time in the Couette cell were identical for control and experimental fishes. When applying shear stress, the rheostat control was rapidly (2-3 sec) set to the desired shear stress level; following the desired duration (30, 60, or 120 sec), the rheostat was immediately turned off and shear stress decayed to zero over a period of 15 to 25 sec. After each treatment, larval fish were removed from the Couette cell using a 500 µ nylon mesh net, placed in 15-cm-diam petri dishes or in aerated 4-L buckets, and observed throughout a 24-hr time period. Mortality was determined at 24 hr, except that bluegill were examined at 6 hr. Death was defined as the absence of a heart beat. All individuals were preserved in 5-percent buffered formalin and total lengths of 50 individuals were obtained later.

A Fisher exact test (Agressti 1990; Mehta and Patel 1995) was used for testing the equality of two binomial proportions (control dead versus experimental dead) for each exposure time and shear stress level combination. Failure to reject the null hypothesis (control = exposed) was accepted at $P \geq 0.05$.

Shear Stress Induced by Commercial Navigation Traffic

The representative shear stress for vessel passage was determined in the zone beneath the tow where the shear stress decreases significantly with both longitudinal distance from the bow and lateral distance from the hull. The representative value considered the influence of the channel bottom on shear stress because many UMR-IWWS tows have low underkeel clearance.

Figure 4 plots the time-history of bed shear stress measured in the physical model reported in Maynord (2000). Shear stress on the river bottom peaks near the bow but duration is low (4 sec) and results in minimal boundary layer thickness. Therefore, bed shear stress near the bow need not be considered when defining a representative shear stress, because only a small water volume will be impacted. Following the peak near the bow, the bed shear stress for the duration of the barge hull passage is less than 50 dynes/cm^2 (Maynord 2000). Consequently, the bed shear stress beneath the hull, even for low underkeel clearance, is small compared to the hull shear stress over the length of the tow (Figure 5).

Figure 5 defines the hull shear stress variation for a low depth/draft ratio (1.2) for two speeds representing average (2.9 m/sec) to high (4.0 m/sec) vessel speeds through the water (Maynord 2000). A depth/draft ratio of 2.0 has hull shear stress about 8 percent less than hull shear stress for depth/draft = 1.2. The steep rise near the rake is likely exaggerated, and the actual shape is similar to the profile of bed shear stress (Figure 4). The exaggerated shear near the rake is a result of the boundary layer equations predicting an infinite shear at the beginning of the boundary layer development. The infinite shear does not occur because the velocity change at the rake is not instantaneous as assumed in boundary layer equations. Figure 6 provides the distribution of shear stress beneath the tow which is based on the hull shear stress variation curves, a bed shear stress of 50 dynes/cm^2, boundary layer thickness equal to the lesser of

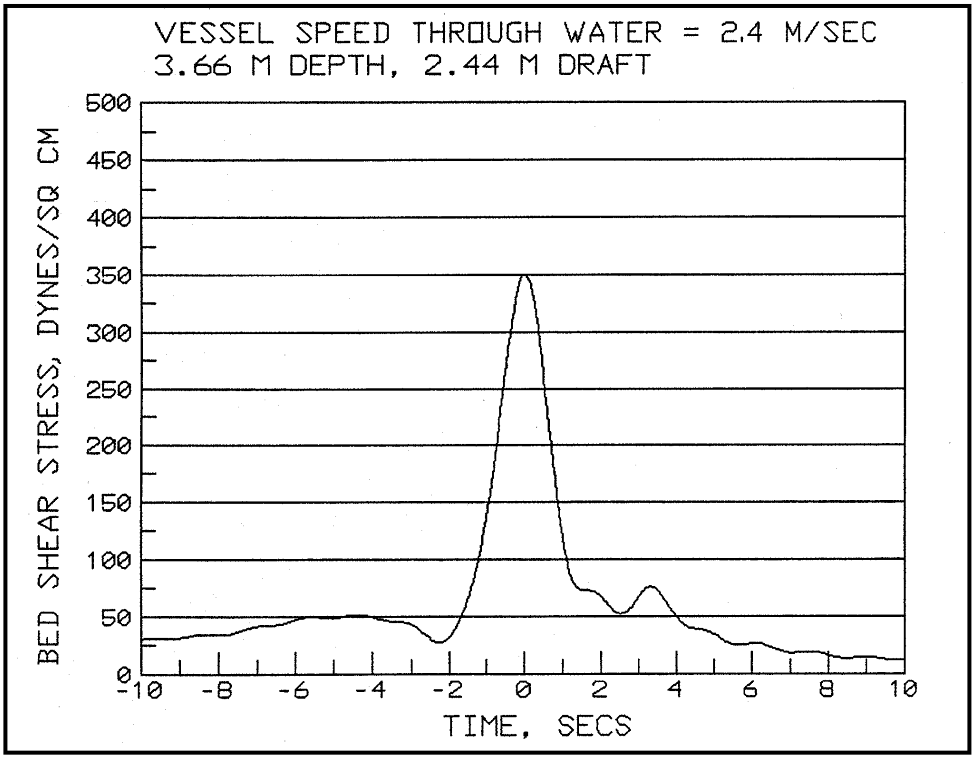

Figure 4. Typical trace of channel bottom shear stress measures in physical model. Quantities shown are scaled to their full-size equivalent

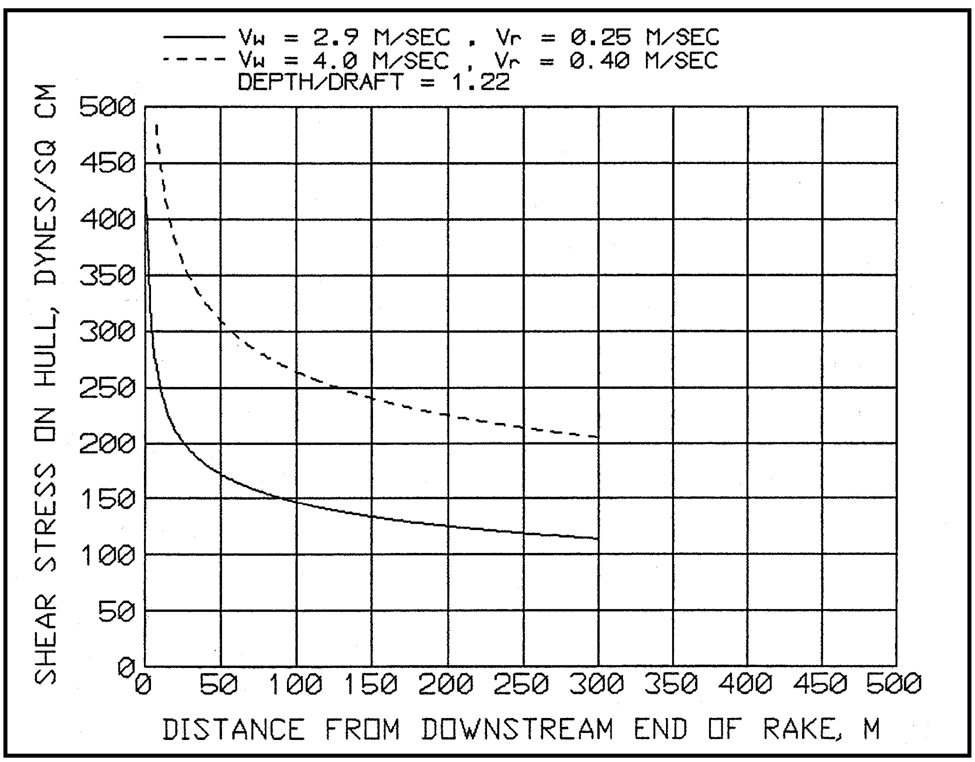

Figure 5. Shear stress on hyull versus distance from downstream end of rake. Based on rough hull in Maynord (2000). Depth/draft = 1.22

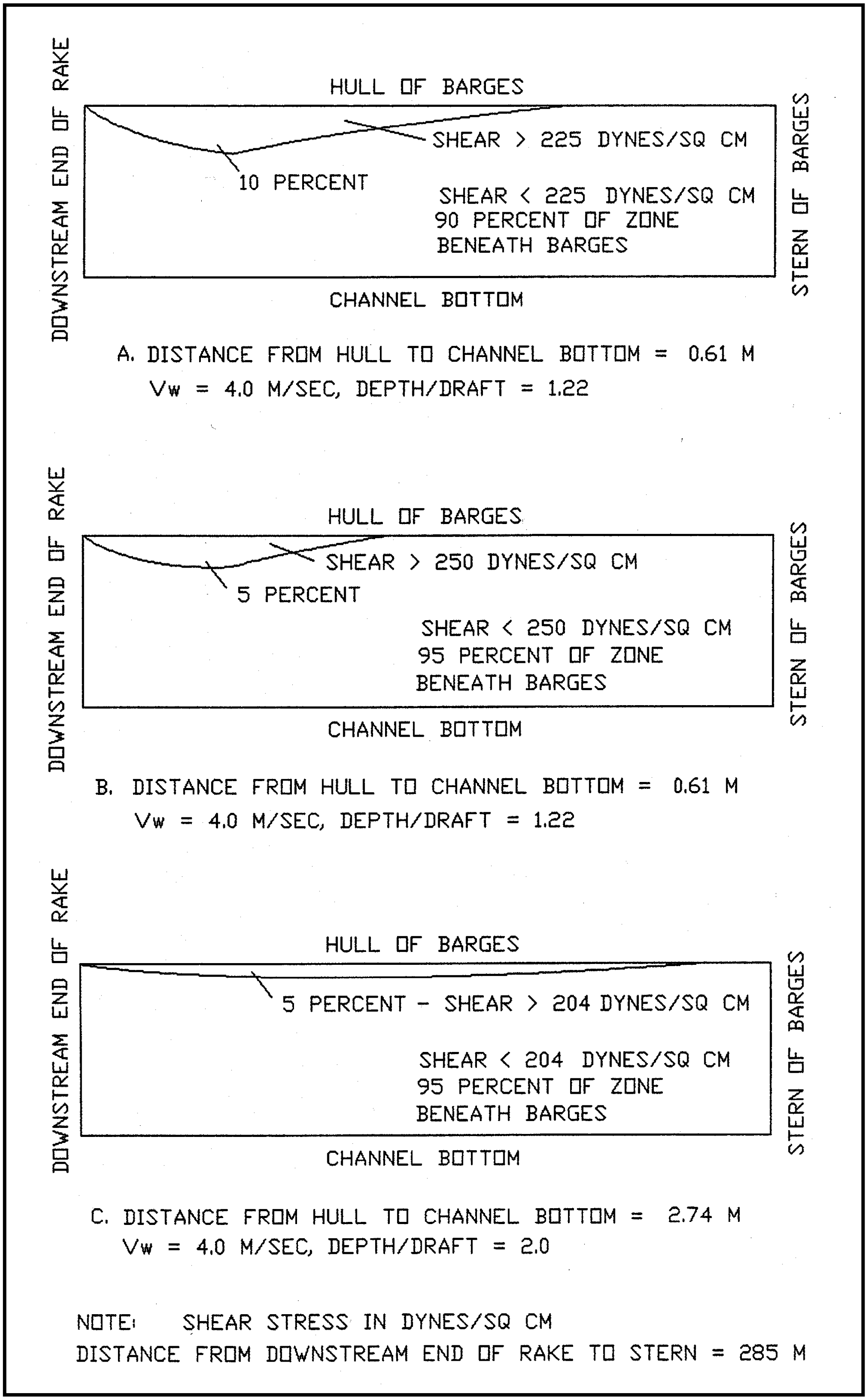

Figure 6. Distribution of shear stress beneath tow for 0.61- and 2.74-m distances from hull to channel bottom

either the computed boundary layer thickness (BLT) or the bottom clearance, and a linear variation of shear stress between the edge of the boundary layer and the hull. The BLT was computed for a rough boundary using Granville (1987) for an unlimited water depth. The resulting BLT for the hull surface and speeds used herein, is approximately BLT = $0.01X_r$, where X_r is distance from the downstream end of rake. For example, at a distance of 50 m from the downstream end of the rake, the boundary layer is 0.5 m thick.

3 Results

Mortality rates for shovelnose sturgeon, blue catfish, and largemouth bass, exposed to shear stresses of 100, 300, or 500 dynes/cm^2 for 30, 60, or 120 sec, did not exceed control mortality (Table 2). Shovelnose sturgeon experienced no experimental mortality, and the 3.3-percent mortality for the 30- and 60-sec control groups was assumed to be handling mortality. There was no mortality in blue catfish experimental or control groups. Largemouth bass experienced 5 percent mortality when exposed to shear stress of 100 dynes/cm^2 for 60 sec and 500 dynes/cm^2 for 60 sec and 120 sec. There was no mortality in the other largemouth bass experimental or control group.

Table 2
Percent Mortality of Shovelnose Sturgeon *Scaphirhynchus platorynchus*, Bigmouth Buffalo *Ictiobus cyprinellus*, Blue Catfish *Ictalurus furcatus*, and Largemouth Bass *Micropterus salmoides* at 24 hr and Bluegill *Lepomis macrochirus* at 6 hr Exposed to Shear Stress Levels of 0 (control), 100, 300, or 500 Dynes/cm^2 for Three Exposure Durations, 30, 60, or 120 sec

Exposure Duration, sec	Control, 0	Stear Stress Level, 100	Dynes/cm^2 300	500
Shovelnose Sturgeon				
30	3.3	0	0	0
60	3.3	0	0	0
120	0	0	0	0
Bigmouth Buffalo – Most pelagic compared to other species tested				
30	7	0	10	33[1]
60	3	0	23[1]	20
120	3	7	27[1]	67[2]
Blue Catfish				
30	0	0	0	0
60	0	0	0	0
120	0	0	0	0
Largemouth Bass				
30	0	0	0	0
60	0	5	0	5
120	0	0	0	5
Bluegill				
30	0	0	0	3
60	3	7	0	10
120	10	0	0	57[2]

Note: Numbers were rounded to the nearest whole number.
[1] $P < 0.05$.
[2] $P < 0.01$.

Bluegill experienced significant ($P < 0.01$) mortality (56.6 percent) when exposed to shear stress of 500 dynes/cm^2 for 120 sec, the highest shear stress level and duration tested. There were no significant differences ($P < 0.5$) between experimental and controls for any other bluegill group tested (Table 2).

Bigmouth buffalo experimental groups experienced the highest species-specific mortality compared to controls (Table 2). Significant mortality was observed at shear stresses of 500 dynes/cm^2 for 30 sec (33.3 percent, $P < 0.05$), 300 dynes/cm^2 for 60 sec (23.3 percent, $P < 0.05$), 300 dynes/cm^2 for 120 sec (26.7 percent, $P < 0.05$), and 500 dynes/cm^2 for 120 sec (66.7 percent, $P < 0.01$).

Median shear stress for the region beneath the tow is shown in Table 3. While a median value best defines conditions over the zone beneath the tow, exceedance values of 5 and 10 percent account for the higher magnitudes near the bow (Table 3). Shear stress greater than 5 to 10 percent exceedance values occurs over a small region and has a short duration; therefore, their use as a representative value overstates the tow effect.

Table 3
Representative Shear[1] Stress Values (dynes/cm^2) for Two Vessel Speeds and Two Depth/Draft Ratios

Vessel Speed	Depth/Draft Ratio, m/sec	Exposure Duration, sec	Representative Shear Stress (dynes/cm^2) for Percent Exceedance		
			50	10	5
2.9	1.22	102	87	129	142
4.0	1.22	74	135	225	250
2.9	2.0	102	53	107	115
4.0	2.0	74	57	187	204

[1] Representative shear is the magnitude of shear stress that is exceeded in 50, 10, and 5 percent of the volume beneath the tow. For example, at the vessel speed of 4.0 m/sec and a depth/draft of 1.22, the shear stress is greater than 225 dynes/cm^2 in 10 percent of the volume beneath the tow and less than 225 dynes/cm^2 in 90 percent of the volume beneath the tow.

High-speed tows will have high shear stress but low duration whereas lower-speed tows will have a lower shear stress but a longer duration. The duration of exposure to shear stress can be estimated as L/V_w, where L is the vessel length and V_w is the vessel speed relative to water. For a tow traveling at a typical speed of 2.9 m/sec V_w on the UMR-IWWS with a five-barge length of 297 m, the duration will be 102 sec. For a tow traveling at a high speed of 4.0 m/sec V_w on the UMR-IWWS with a five-barge length of 297 m, the duration will be 74 sec.

4 Discussion

Comparison of the Couette cell data (Table 2) with calculated hull shear stress values (Table 3) indicates that among the species tested, only bigmouth buffalo larvae are susceptible to shear stress effects and only in approximately 5 percent of the water column adjacent to the hull of a fast moving barge (4.0 m/sec). The representative shear stress in Table 3 for a 5-percent exceedance vessel speed of 2.9 m/sec and depth/draft of 1.22 means that in the region beneath the tow, 5 percent of the volume will have shear stress greater than 142 dynes/cm^2 and 95 percent will have less than 142 dynes/cm^2. Exposure of larvae to shear stress of 300 dynes/cm^2 for 60 sec caused 23.3-percent mortality ($P < 0.05$), while 300 dynes/cm^2 for 120 sec resulted in 26.7-percent mortality ($P < 0.05$) (Table 2).

The minimum combination of shear and time that would result in predicting mortality significantly greater than zero (i.e., 95-percent confidence interval around the prediction does not include 0-percent mortality) provides a reassuring perspective concerning the likely risk of mortality because of hull stress in the field. A linear regression was fitted between the logarithm of mortality adjusted for control mortality and the logarithm of the product of shear stress and time for $n = 9$ values for shear stress > 0. Specifically,

$$\ln(\text{corrected mortality} + 1) = b_0 + b_1\, x \tag{3}$$

where

$$x = \ln[\text{shear stress} \times \text{time (min)}]$$

corrected mortality = percent treatment mortality - percent control mortality

If corrected mortality < 0, then corrected mortality is assigned a value of zero. The best fit linear regression yielded a $b_0 = -6.009$ and $b_1 = 1.485$ ($R = 0.922$, $F = 39.7$). The maximum shear stress value for which the 95-percent confidence interval included zero, x, was calculated from the standard expression for the interval around a predicted value:

$$0 = -\,(b_0 + b_1 x) \pm t\,[1 + 1/9 + (x + 5.508)^2/6.941]^{1/2} \tag{4}$$

where Student's $t = 2.365$ (two-sided 95-percent critical value, 7 df).

The -*t* factor gave shear estimates < 0. The +*t* factor gave $x = 5.731$, therefore, shear stress = exp (5.731)/(74/60) = 250 dynes/cm^2 at 74 sec and exp (5.731)/(102/60) = 181 dynes/cm^2 at 102 sec.

A high-speed tow hull produces shear stress levels of 225 dynes/cm^2 under a 1.22-depth/draft ratio and 187 dynes/cm^2 under a 2.0-depth/draft ratio condition in 10 percent of the zone beneath the tow. These shear stress values do not exceed the calculated value of 250 dynes/cm^2, at which bigmouth buffalo mortality would be statistically greater than control mortality. A high-speed tow would produce a shear stress of 250 dynes/cm^2 under a 1.22-depth/draft ratio in only 5 percent of zone beneath the tow. This is the only experimental factor combination where hull shear stress values approach levels causing significant ($P < 0.05$) mortality in bigmouth buffalo.

An average tow hull speed would produce shear stress of about 129 dynes/cm^2 under a 1.22-depth/draft ratio and 107 dynes/cm^2 under a 2.0-depth/draft ratio in 10 percent of the zone beneath a tow (Table 3). These shear stress values do not exceed the calculated value of 180 dynes/cm^2 that would cause significant ($P < 0.05$) bigmouth buffalo mortality.

Hull shear stress levels that would result in early life stage mortality are not exceeded by commercial navigation for shovelnose sturgeon, blue catfish, largemouth bass, and bluegill.

Morgan et al. (1976) generated a series of shear stress-mortality equations for fixed time exposures for striped bass *Morone saxatilis* and white perch *Morone americana* eggs and larvae. These values were used in empirical equations of shear stress levels resulting from ship movement in the Chesapeake and Delaware Canal to estimate egg and larval mortalities. The conclusions of this study agree with those of Morgan et al. (1976). They found a 60-sec exposure LS_{50} value of 542 dynes/cm^2 for striped bass eggs and 785 dynes/cm^2 for larvae. The 60-sec exposure LS_{50} value was 425 dynes/cm^2 for white perch eggs and 415 dynes/cm^2 for larvae. Morgan et al. (1976) indicated that shear stress generated by a cargo ship was below the LS_{50} values for 60 sec of exposure. They concluded that it was doubtful that eggs or larvae could remain in the boundary layer for periods over 60 sec.

5 Conclusion

Based on the results of this study and published studies, it appears that the range of hull shear stress experienced by early life stages during tow passage will not result in significant mortality.

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14. ABSTRACT
Mortality of fish early life stages was measured in a Couette cell to simulate fluid shear stress resulting from passage of a barge hull in the water column. Mortality was measured for three shear stress levels at three exposure times for five fish species: larval shovelnose sturgeon *Scaphirhynchus platorynchus*, larval bigmouth buffalo *Ictiobus cyprinellus*, larval blue catfish *Ictalurus furcatus*, juvenile bluegill *Lepomis macrochirus*, and juvenile largemouth bass *Micropterus salmoides*.

Mortality values were compared with calculated barge hull shear stress levels to determine the potential for mortality of fish early life stages in relation to commercial navigation traffic. There was no significant mortality of shovelnose sturgeon, blue catfish, bluegill, and largemouth bass at shear stress levels produced by barges in the upper Mississippi River. However, the hull of a high-speed tow (4.0 m/sec) with a 1.22-depth/draft ratio will produce a shear stress of 250 dynes/cm^2 in 5 percent of the zone beneath the tow. This is the only area in the water column where hull shear stress values approach levels causing significant ($P < 0.05$) mortality of bigmouth buffalo larvae. Therefore, it is unlikely that barge hull shear stress will result in substantial mortality of larval and juvenile fishes.

15. SUBJECT TERMS

Barges	Hull shear	Shear mortality
Fish mortality	Juvenile fish	Towboats
	Larval fish	Upper Mississippi River

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