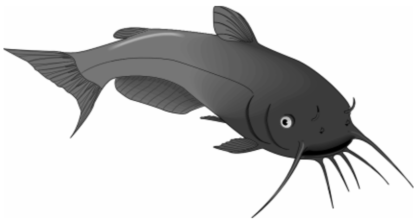
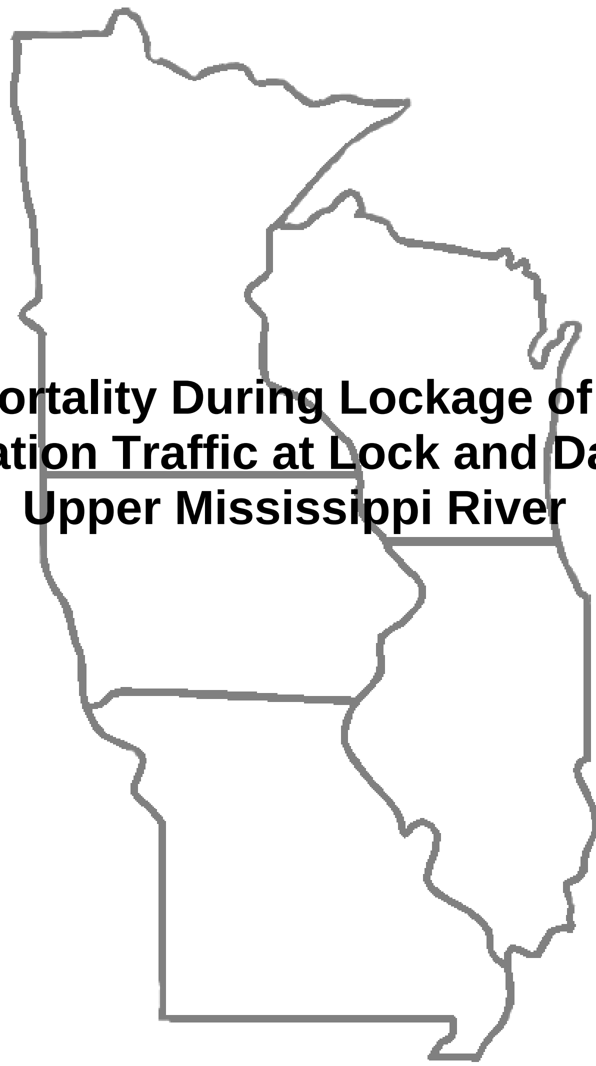
ENV Report 58

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





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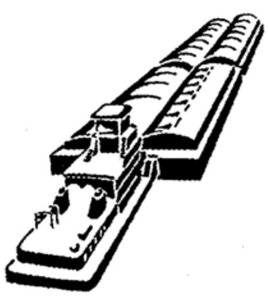

US Army Corps of Engineers®

June 2005

Rock Island District
St. Louis District
St. Paul District

Upper Mississippi River - Illinois Waterway System Navigation Study

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Adult Fish Mortality During Lockage of Commercial Navigation Traffic at Lock and Dam 25, Upper Mississippi River

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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

ABSTRACT: Although lock chambers do not provide suitable aquatic habitat to support resident fish populations, dead fish are sometimes observed in the lock after passage of a towboat. In order to determine the magnitude of fish mortality, locking mortality was monitored during 2002-03 at Lock and Dam 25 on the Mississippi River following 80 lockages during the following months: June - 11 lockages; August - 10 lockages; October - 21 lockages; December -18 lockages; April - 20 lockages.

There were 361 fish killed during the 80 lockages. Gizzard shad (*Dorosoma cepedianum)* (n = 279, 77 percent of total mortality) and freshwater drum (*Aplodinotus grunniens)* (n = 47, 13 percent) accounted for the majority of the observed mortality. The remaining mortality (n = 35, 10 percent) was spread among 10 species. A single towboat lockage was responsible for 17 percent of the total observed mortality; another four towboats accounted for 46 percent of the total mortality. Thirty-two (40 percent) of the lockages resulted in no observed mortality. The highest mortality per lockage (mean = 9.1) occurred in both in August, when the highest density of fish occurred in the lock (2,059 - 20,251), and in December when fish densities were low (0 - 59). High August mortality reflects the large numbers of fish in the lock; high December mortality possibly reflects the inability of the fish in the lock to avoid entrainment because of reduced swimming capabilities. Poisson regression showed that mortality was related to water temperature, depth of water in the lock, horsepower of the tow, number of barges, and time of year. A potential mitigation measure to reduce locking mortality is to close the lock gates between lockages, especially during the spring fish migration.

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 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 that is the decision document for processing to Congress.

This study was conducted by the U.S. Army Engineer District, St. Louis. This report was written by Dr. Thomas M. Keevin, Mr. Brian L. Johnson, Mr. Eric A. Laux, Mr. Thixton B. Miller, and Mr. Kevin P. Slattery of the Environmental Analysis Branch, U.S. Army Engineer District, St. Louis; and Dr. David J. Schaeffer, Department of Veterinary Biosciences, University of Illinois. An early draft of this paper was reviewed by Dr. Jamie Thomerson and Mr. Gordon Farabee. This study was funded by the U.S. Army Engineer District, St. Louis, through the Upper Mississippi River-Illinois Waterway System Navigation Study. We thank Owen Dutt and Teri Allen for assisting with fieldwork.

1 Introduction

On the Upper Mississippi River System (UMRS), there are 37 lock and dam sites (43 locks), consisting of 29 sites on the Mississippi River and 8 sites on the Illinois Waterway. These sites lock commercial navigation traffic during their movements on the navigation system. With the exceptions of Lock 27, Melvin Price Lock, and Lock 19 both of which have usable lengths of 366 m (1,200 ft), locks on the UMRS have a usable length of about 183 m (600 ft).

Most tows on the UMRS have 15 or 16 barges, plus the towboat, and dimensions of about 343 m (1,125 ft) long by 32 m (105 ft) wide. Loaded tows generally have 15 barges in front of the towboat, in a 3 wide by 5 long configuration. Unloaded tows have the same configuration of 15 barges in front of the towboat and frequently have one additional empty barge alongside the towboat. With the exception of non-standard size chemical barges, individual barges are 59.5 m long (195 ft) by 10.7 m (35 ft) wide.

Lockage of a 15-barge tow through a 183 m (600 ft) lock requires that the tow be broken in half and double locked. For example, during an up-bound lockage, the lower gates are opened and the towboat pushes the tow into the lock. The first nine barges are uncoupled, the towboat backs out with the six remaining barges, the lower gates are closed, the water level is raised to match the water elevation of the upper pool, the upper gates are opened, and the barges are mechanically pulled out of the lock. The upper gates are then closed, the lock water elevation is lowered to match the lower pool, the lower gates are opened and the towboat with the remaining six barges enters the lock. The lower gates are closed, the lock pool is again raised, the upper gates are opened, and the towboat moves forward for recoupling. The recoupling process requires approximately 30-minutes, during which the towboat captain maneuvers the towboat to maintain contact between the barges from the first cut and the barges from the second lockage. Once the coupling is complete, the towboat applies power to its propellers to move the 15-barge load up-river, from a dead stop. Tremendous flow fields are generated during maneuvering to re-couple the tow and when the loaded towboat exits the lock.

Towboats entrain large volumes of water through their twin or triple propellers (Maynord 1999), which may exceed 2.5 m in diameter. Maynord (2004) found that the average upbound towboat passed 49 percent of the lock water volume through its propellers, and the average downbound loaded tow passed 228 percent of the lock's water volume through the propellers. Towboat propellers may injure or kill fish via blade strike, shear forces, or pressure changes (Gutreuter et al. 2003). There is a concern that towboats, within the confined area of a lock, may continuously recirculate the lock's water volume, potentially exposing the fish to multiple propeller entrainment events. The confined flow fields within the lock, with high shear stress and pressure changes, may also be responsible for fish injury and mortality. Locks are known to have large numbers of fish that would be susceptible to injury or mortality during locking (Keyes and Klein 1984; Hartman et al. 2000; Johnson et al. 2004). For example, a survey of five 366 m (1,200 ft.) locks on the Ohio River produced fish abundance estimates ranging from 10,340-17,887 fish in a rotenone survey and from 11,543-14,962 fish in hydroacoustic surveys. The two survey methods were highly and positively correlated ($r = 0.938$), and corrected lock rotenone estimates were within –12 percent to +20 percent of those derived from hydroacoustic surveys (Hartman et al. 2000). A hydroacoustic study at Lock and Dam 25 on the Mississippi River found that fish counts varied seasonally (0-14,356) (Johnson et al. 2004).

The objectives of this study were to: (a) determine the magnitude of adult fish mortality during locking at Lock and Dam 25, a representative 183 m (600 ft) lock on the UMRS; and (b) determine the barge-related and lock-related factors contributing to mortality. Lock and Dam 25 is located at river mile 241.4, near Winfield, Missouri. The lock first opened on May 18, 1939, and had approximately 6,000 lockages of both commercial and recreational craft in 2001 (U.S. Army Corps of Engineers 2003).

2 Material and Methods

Counts of dead and alive fish in the lock—and data on several environmental variables thought to potentially affect fish mortality during locking of commercial navigation traffic—were obtained in 2002 and 2003. Water elevations for Pool 25 and the tailwater and water temperatures are continuously recorded at Lock and Dam 25 and were used for this study. Water elevations were used to calculate water depth and water volume in the lock. Towboat statistics (propeller type and number, horsepower) were obtained from The Waterway Journal, Inc. (2003). Hydroacoustic fish surveys were conducted to provide fish abundance estimates for Lock 25 using a BioSonics model DT 6000 with a 200-kHz split beam system transducer. Hydroacoustic surveys were conducted during each day of our fish mortality sampling study and on a monthly basis. The survey was conducted on four equally spaced transects along the length of the lock and was repeated twice. No survey was conducted during January because of low water and ice conditions. Study methodology and results of the hydroacoustic survey are provided in Johnson et al. (2004).

Two sampling methods were employed to determine species mortality in the lock. Immediately after a towboat passed through the lock, dead or injured fish were dip netted from the surface. The lock bottom was then sampled with a 4.9 m (16 ft) long, 3.8 cm (1.5 in.) mesh otter trawl deployed along four equally spaced transects, each approximately 168 m (550 feet) long. Approximately 44 percent of the lock bottom was trawled and a multiplier of 2.4 was applied to the number of dead fish collected in the trawl to account for mortality in the area not sampled. Sampling was conducted in 2002 on June 17-20, August 26-29, October 21-25, December 2-6, and in 2003 on April 14-16, 21-22, and 24.

The numbers of dead fish were modeled using Poisson regression (implemented in the programs Egret and LogXact 5, Cytel Software, Cambridge, MA). In order to compare the contribution of each independent variable to mortality, water temperature, water depth in lock, horsepower (HP), number of barges, and month or season (1 = Jan-Mar; 2 = Apr-Jun; 3 = Jul-Sep, 4 = Oct-Dec) were each standardized to zero mean and unit standard deviation (SD). The denominator was the geometric mean count estimated for the day from hydroacoustic survey data (Johnson et al. 2004). Differences in the spatial distribution of fish in the lock (i.e., transect line) were determined using analysis of variance (ANOVA) on the logarithms of the fish densities. The relationship of mortality to wheel type (open or Kort), direction of travel (up- or down-bound), and extent loaded (15 loaded, 12/3 (loaded/unloaded), 13/2, 14/1, 15/1, 3/13, 4/11, 4/12, 15 unloaded) were determined using exact Kruskal-Wallace analysis of the multinomial table of mortality counts (StatXact 5.0, Cytel Software, Cambridge, MA). Analysis of variance (ANOVA) and other standard statistical analyses were carried out using Systat 10.2 (Systat, Inc., Richmond, CA).

3 Results

As indicated in Table 1, 361 fish were killed during 80 towboat lockages.

Table 1
Seasonal Fish Mortality During Towboat Lockage at Lock and Dam 25, Upper Mississippi River

Towboat	Gizzard Shad	Freshwater Drum	Other Species	Total
June				
Nan	----	----	----	0
Hornet	----	----	----	0
DeSalle	----	----	----	0
Jamie Leigh	1	----	----	1
Ruth D. Jones	----	----	----	0
Washington	----	----	----	0
Greg Mintor	----	----	----	0
Tom Behringer	----	----	----	0
Andrew Cannava	----	----	----	0
Justin Paul Eckstein	----	----	----	0
Philip M. Pheipher	----	----	----	0
August				
Penny Eickstein	----	----	----	0
Prosperity	----	----	1 blue catfish	1
Martha Ingram	9	2	2 blue catfish	13
Cooperative Mariner	----	2	1 bigmouth buffalo	3
Jack D. Wofford	3	1	----	4
Bill Barry	51	2	2 blue catfish, 2 channel catfish	57
James Neal	5	----	----	5
Cooperative Ambassador	2	1	----	3
Prairie Dawn	4	----	----	4
Mary Kay Eickstein	----	1	----	1

(Sheet 1 of 3)

Table 1 (Continued)				
Towboat	**Gizzard Shad**	**Freshwater Drum**	**Other Species**	**Total**
October				
Ruth D. Jones	----	----	----	0
L. J. Sullivan	----	----	----	0
Tom Frazier	----	----	----	0
Jacob Michael Eckstein	7	----	----	7
Thomas Eckstein	----	----	----	0
Gene Herde	----	----	----	0
Daniel Webster	----	----	----	0
Hornet	----	5	----	5
R.W. Naye	3	1	2 sauger	6
Bruce R. Birmingham	----	----	----	0
Andrew Cannava	----	----	----	0
Theresa L. Wood	----	----	----	0
Greg Minton	2	2	----	4
Dell Butcher	----	----	----	0
K.L.S. Erickson	1	----	----	1
Hornet	----	5	----	5
Ardyes Randall	----	----	----	0
Teresa L. Wood	5	2	----	7
Starfire	----	----	----	0
John M. Rivers	1	----	----	1
Cooperative Venture	----	----	----	0
December				
Jack D. Wooford	14	----	----	14
W.A. Kernan	5	----	----	5
Arlie	----	----	----	0
Phylis	2	----	----	2
Senator Sam	19	2	----	21
Kathy Ellen	5	----	----	5
Floyd H. Blaske	28	----	----	28
Tom Behringer	----	----	----	0
Sierra Dawn	5	----	----	5
Richard Baker	12	----	----	12
Milton V. Roth	1	----	----	1
Kevin Michael	2	----	----	2
Cindy L. Erickson	----	----	----	0
Stephen Colby	----	----	----	0
L.W. Hershey	----	----	----	0
				(Sheet 2 of 3)

Table 1 (Concluded)				
Towboat	**Gizzard Shad**	**Freshwater Drum**	**Other Species**	**Total**
December (Conc.)				
Beverly Ann	60	----	----	60
Ruth D. Jones	9	----	----	9
Richard Baker	----	----	----	0
April				
George King	2	1	1 bigmouth buffalo	5
Jeffery G.	----	2	2 smallmouth buffalo	4
Cooperative Ambassador	----	2	----	2
Ruth D. Jones	1	2	----	3
Jeffery G.	----	2	----	2
Mary Kay Eckstein	2	----	----	2
Roberta Tabor	----	----	----	0
James Ermer	2	----	2 smallmouth buffalo	4
Afton	1	----	1 white bass, 2 walleye	4
Arnold Sobel	1	----	----	1
Show Me State	----	3	1 white bass	4
Cooperative Venture	----	----	2 paddlefish	2
Stephen L. Colby	2	2	----	4
Carol P.	----	2	4 common carp	6
Carol Dawn	----	----	----	0
Prairie Dawn	2	----	----	2
Roy E. Claverie	5	----	1 smallmouth buffalo, 2 white bass	9
Carol P.	----	3	2 sauger, 2 shortnose gar	7
Robert Green	2	----	----	2
Marie Hendrick	3	2	1 channel catfish	6
				(Sheet 3 of 3)

The majority of fish mortalities were gizzard shad *Dorosoma cepedianum* (279, 77 percent of total mortality) and freshwater drum (*Aplodinotus grunniens*) (n = 47, 13 percent). The remaining mortality (n = 35, 10 percent) was spread among 10 species:

Paddlefish (*Polyodon spathula*) (2)
Shortnose gar (*Lepisosteus platostomus*) (2)
Common carp (*Cyprinus carpio*) (4)
Smallmouth buffalo (*Ictiobus bubalus*) (6)
Bigmouth buffalo (*Ictiobus cyprinellus*) (3)
Blue catfish (*Ictalurus furcatus*) (5)
Channel catfish (*Ictalurus punctatus*) (3)
White bass (*Morone chrysops*) (4)

Sauger (*Stizostedion canadense*) (4)
Walleye (*Stizostedion vitreum*) (2) (Table 1)

The lockage of the *Beverly Ann* was responsible for 17 percent of the total observed mortality and four towboats (*Beverly Ann*, *Bill Barry*, *Floyd H. Blaske*, and *Senator Sam*) were responsible for 46 percent of the mortality. Thirty-two (40 percent) lockages resulted in no observed mortality.

Eleven towboat lockages were sampled during the early summer (June) survey period, resulting in only one dead fish. A single live, but distressed, gizzard shad was captured from the water surface and counted as dead because of its susceptibility to predation.

Ten towboat lockages in late summer (August) resulted in 91 (74 gizzard shad, 9 freshwater drum, 5 blue catfish, 2 channel catfish, and 1 bigmouth buffalo) mortalities. No mortality was observed in one of the lockages and minor mortality (1-5 fish) was observed in seven additional lockages. Two towboat lockages were responsible for 77 percent of the observed mortality. The *Bill Barry* resulted in 57 dead fish (63 percent mortality) and the *Martha Ingram* was responsible for an additional 13 dead fish (14 percent mortality).

During the fall (October) survey, 21 towboat lockages resulted in 36 (19 gizzard shad, 15 freshwater drum, and 2 sauger) mortalities. No mortality was observed during 13 (62 percent) of the lockages.

During the winter (December) sampling period, a total of 164 fish (162 gizzard shad and 2 freshwater drum) were killed by the 18 locking tows sampled. No mortality was observed during six (33.3 percent) of the lockages. Six lockages resulted in mortality of between one and five gizzard shad. The *Beverly Ann* was responsible for 37 percent of the observed December mortality. Three towboats (*Beverly Ann*, 60 gizzard shad; *Floyd H. Blaske*, 28 gizzard shad; and *Senator Sam*, 19 gizzard shad and 2 freshwater drum) accounted for 67 percent of the locking related mortality. The remaining three lockages resulted in mortality of 14, 12, and 9 (21 percent).

Twenty lockages were sampled during the spring (April) resulting in 69 dead fish. Twenty-three gizzard shad (33 percent of recorded mortality) and 21 (30 percent) freshwater drum were killed. In addition, a number of additional species were killed including: 2 paddlefish, 2 shortnose gar, 4 common carp, 2 bigmouth buffalo, 6 smallmouth buffalo, 1 channel catfish, 4 white bass, 2 sauger, and 2 walleye. No mortality occurred during 2 (10 percent) lockages in April. In June, 10 of 11 lockages (91 percent) had no mortality. In August, October, and December there were no deaths in 10 percent (1/10), 62 percent (13/21) and 33 percent (6/18) of lockages, respectively. Overall, there was no mortality in 40 percent (32) of the lockages.

Poisson regression showed the number of dead fish to be significantly related to water temperature, water depth in the lock, horsepower, number of barges and month (or season). The mean and standard deviation (SD) for each retained covariate is given in Table 2. These values were used to standardize the covariates.

Table 2 Mean and Standard Deviation of Each Parameter Used in the Poisson Regression		
Parameter	**Mean**	**Standard Deviation**
Water temperature	56.62	14.51
Water depth in lock	19.07	3.99
Horsepower	5362.6	1134.1
Number of barges	14.6	2.28
Month	8.15	3.05

The regression coefficients in Table 3 show that increasing the water temperature or the depth in the lock, or decreasing the horsepower or number of barges, decreases the number of dead fish. Poisson analyses with and without a term for month or season suggested that time of year was a predictive variable, independent of correlations with water temperature and water depth in lock. Analysis of variance of the fish densities by transect line showed annual geometric average densities were about twice as high near the walls as in the center. An exact Kruskal-Wallace test of the multinomial tables of dead/alive fish showed comparable mortality distributions for Kort and open nozzles, for up- and down-bound tows, and for various loading configurations. The mean proportions of dead fish (relative to total from the hydroacoustic survey) did not differ significantly (ANOVA) for up-and down-bound tows (N = 7 and 10, respectively), but the proportion for upbound tows (0.62) was three times greater than for downbound tows (0.20).

Table 3 Coefficients for Poisson Regression of Number of Dead Fish						
Parameter[1]	**Coefficient**	**Std. Error**	**P**	**Rate Ratio**	**Lower (C.I.)**	**Upper (C.I.)**
Intercept	-5.119	0.082	<0.001	0.006	0.005	0.007
Water temperature	-0.485	0.094	<0.001	0.6155	0.512	0.739
Water depth in lock	-2.601	0.141	<0.001	0.0742	0.056	0.098
Horsepower	0.176	0.064	0.006	1.192	1.052	1.35
Number of barges	0.377	0.109	<0.001	1.458	1.177	1.806
Month	0.724	0.075	<0.001	2.063	1.781	2.389

[1] Parameters were standardized to zero mean and unit standard deviation.

4 Discussion

Many environmental and tow-related factors have been proposed as contributing to fish mortality during lockages. This is the first study that evaluated fish mortality resulting from towboats passing through locks over a 12-month period. Combined with data from a companion study on fish densities and total counts in the lock following selected tows (Johnson et al. 2004), it was possible to quantify the contribution of individual factors to the total mortality. Some factors, including wheel type (open wheel vs. Korte nozzle), direction of travel, and loading, did not significantly affect mortality.

The major factor affecting mortality was time of year (month or season). This factor is correlated with water temperature and depth of water in the lock, both of which significantly affect the extent of mortality. Time of year will also affect the number of fish using the lock chamber, but this relationship should be accounted for in the Poisson regression by using the number of fish as a weighting factor (rate multiplier). However, the high significance of time of year suggests that this factor affects mortality independent of these relationships. It is likely that differences in species composition over the months or seasons determine the primary relationship that is surrogated by “time of year.”

During the June sampling, only 1 gizzard shad was killed by locking towboats. The water in the lock, with the lower gates open to the tailwaters, ranged from 9.5 to 9.7 m (28 to 31.2 ft) deep and the river was at open river conditions (the dam gates were out of the water). During August, when 91 fish were killed, the water depth in the lock ranged from 6.5 to 8.2 m (21.3 to 26.9 ft) deep. A comparison of summer lock mortality between June (0.1 killed per lockage) and August (9.1 killed per lockage) samples suggests that water level in the lock may be an important mortality factor.

The largest number of fish (14,356, 95 percent confidence interval 10,177-20,251) in the lock occurred on August 29th, when the water levels in the lock were low, mean water temperatures were high (27.2 °C, 81 °F) and a number of large schools of gizzard shad were observed that blackened the water column (Johnson et al. 2004). August also had a high mortality rate (mean = 9.1 fish per lockage). Gizzard shad accounted for 81 percent of the mortality, which undoubtedly reflects their high abundance in the lock. It is interesting that 8 of the 10 August lockages resulted in minor mortality (0-5 fish, mean = 2.6), and two towboats, the *Bill Barry* and *Martha Ingram* accounted for the 77 percent of the mortality, predominantly gizzard shad. This suggests that normally the fish avoid propeller entrainment, but these two towboats entrained portions of the gizzard shad schools in the lock through their propellers.

Fall sampling resulted in only minor mortality (1.7 killed per lockage) of gizzard shad and freshwater drum. The estimated number of fish in the lock ranged from 470 (275-805, 95 percent confidence interval) to 938 (868-1,012) during October 21^{st}-24^{th}, when water temperatures were moderate, 11.1-12.2 °C (52-5 °F) (Johnson et al. 2004).

Based on hydroacoustic surveys, the lowest estimated fish densities occurred during the winter months, when there were very few fish observed in the lock, and extended through mid-April. A drop in fish density began in December as water temperatures dropped, and on December 5^{th} only 4 (0-59, 95 percent confidence interval) fish were in the lock when water temperatures reached 2.2 °C (36 °F) (Johnson et al. 2004). Conversely, high fish mortality was observed during December sampling. Gizzard shad accounted for 99 percent of the fish killed, which reflected their abundance in the lock (Johnson et al. 2004). Thirteen of the eighteen lockages resulted in minor mortality (0-9 fish, mean = 2.2), with no mortality in six of those lockages. Five lockages resulted in 82 percent of the mortality. Although the numbers of gizzard shad in the lock were low, their ability to avoid propeller entrainment was impaired by cold-water temperatures. Gizzard shad must be capable of sustained swimming abilities in order to avoid being entrained into the inflow zone of the propeller, which can have a wide area of effect with high inflow velocities at the propellers (Maynord 1999). However, sustained swimming speed decreases as temperature decreases (Beamish 1978), so during the winter months gizzard shad have minimal swimming abilities. Gizzard shad incapable of swimming are often part of the drift during winter (Bodensteiner and Lewis 1994), and have high rates of entrainment at power plants because of their reduced swimming abilities (Bodensteiner and Lewis 1992).

The largest number of species killed (11) was observed during the April sampling period when fish were presumably making spawning movements or were moving from over-wintering habitat. In addition to the typical mortality of gizzard shad and freshwater drum observed during the other sampling seasons, sport fish (walleye, sauger, and white bass), commercial species (bigmouth buffalo, small mouth buffalo, common carp, and channel catfish), and species of special concern (paddlefish) were also killed (Table 1). The spring appears to be a critical period, when attempts to ameliorate locking mortality should be conducted. The low water stages (normal pool) during the spring sample period were atypical and may have contributed to the observed mortality. Normal spring high flow conditions may have resulted in less mortality, as was observed between summer samples, had they occurred. Poisson regression showed an inverse relationship between mortality and water depth in the lock.

Gizzard shad and freshwater drum accounted for 90 percent of the total observed mortality. These results are not surprising in light of the fact that Dettmers et al. (2001) found freshwater drum and gizzard shad to be the two most abundant fish species in the main channel of Pool 26, the pool immediately downstream of Lock and Dam 25. Johnson et al. (2004) found gizzard shad to be the most abundant species in Lock and Dam 25 and freshwater drum to be the third most abundant. The second most abundant species, channel catfish, was represented by predominantly young-of-the year individuals captured in bottom trawls that may have avoided towboat entrainment and mortality by remaining on the bottom below the propeller entrainment zone.

Interactions possibly exist between some of the variables examined in this study. For example, Poisson regression showed significant interactions between depth of water in the lock or number of barges and horsepower. However, as there were no a priori hypotheses concerning specific interactions, interaction terms were not included in the Poisson regression analysis.

Johnson et al. (2004) suggested that locks do not provide suitable habitat for the development of resident fish populations. Water levels are constantly raised and lowered with the lockage of commercial navigation traffic, and towboats entrain high volumes of water and create major turbulent hydraulic forces within the lock (Maynord 1999). The results of this study also suggest that towboats would continuously crop the resident population. However, Johnson et al. (2004) suggested that locks might be attractive to fish because they provide slackwater refugia from the harsh environmental conditions that occur in the adjacent tailwaters (Bodensteiner and Lewis 1992).

Various studies have demonstrated that fish use navigation locks for inter-pool movements to varying degrees, possibly depending on the fish species, hydraulic conditions adjacent to the lock, and the physical conditions of the lock and dam site (Coker 1929; Carter 1954; Scott and Hevel 1991; Klinge 1994; Zigler et al. 2004). Zigler et al. (2004) suggested that studies should be conducted to address the use of locks for passing fish on the Upper Mississippi River. They suggested that the studies should include modeling flow patterns in tailwaters and evaluating alternatives in gate operation to enhance fish passage. Our study results suggest that making locks more attractive for fish passage would also subject the fish to potential mortality from locking towboats. This would be especially true during spring spawning movements.

It is currently a common practice of the lock masters to leave the downstream lock gates open while waiting for up-bound tows to arrive at the lock, thus facilitating fish access to the lock chamber from the adjacent tailwater. At present, it is not possible to reduce the horsepower or number of barges, to raise the water temperature during colder months, or to increase the depth during drier months to reduce fish usage of the locks. However, a potential mitigation measure to be explored to reduce locking mortality is to simply close the locks gates between lockages, thus keeping fish out of the lock. Studies can be carried out to determine if closing the lock gates between lockages is an effective mitigation measure to reduce locking mortality.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2005

2. REPORT TYPE
Interim report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Adult Fish Mortality During Lockage of Commercial Navigation Traffic at Lock and Dam 25, Upper Mississippi River

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer District, St. Louis
Environmental Analysis Branch
1222 Spruce Street, St. Louis, MO 63103-2833;
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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
190 5th Street East, St. Paul, MN 55101-1638

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ENV Report 58

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Although lock chambers do not provide suitable aquatic habitat to support resident fish populations, dead fish are sometimes observed in the lock after passage of a towboat. In order to determine the magnitude of fish mortality, locking mortality was monitored during 2002-03 at Lock and Dam 25 on the Mississippi River following 80 lockages during the following months: June - 11 lockages; August - 10 lockages; October - 21 lockages; December -18 lockages; April - 20 lockages.

There were 361 fish killed during the 80 lockages. Gizzard shad (*Dorosoma cepedianum)* (n = 279, 77 percent of total mortality) and freshwater drum (*Aplodinotus grunniens)* (n = 47, 13 percent) accounted for the majority of the observed mortality. The remaining mortality (n = 35, 10 percent) was spread among 10 species. A single towboat lockage was responsible for 17 percent of the total observed mortality; another four towboats accounted for 46 percent of the total mortality. Thirty-two (40 percent) of the lockages resulted in no observed mortality. The highest mortality per lockage (mean = 9.1) occurred in both in August, when the highest density of fish occurred in the lock (2,059 - 20,251), and in December when fish densities were low (0 - 59). High August mortality reflects the large numbers of fish in the lock; high December mortality possibly reflects the inability of the fish in the lock to avoid entrainment because of reduced swimming capabilities. Poisson regression showed that mortality was related to water temperature, depth of water in the lock, horsepower of the tow, number of barges, and time of year. A potential mitigation measure to reduce locking mortality is to close the lock gates between lockages, especially during the spring fish migration.

15. SUBJECT TERMS
Fish
Fish mortality
Lock and Dam 25
Lock chamber
Lock chamber fish mortality
Mississippi River
Towboat fish mortality

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	19	