RIVER RESEARCH AND APPLICATIONS
*River Res. Applic.* **30**: 1056–1064 (2014)
Published online 2 August 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.2696

SHORT COMMUNICATION

# PATTERNS OF FISH PASSAGE IN THE UPPER MISSISSIPPI RIVER

S. TRIPP[a,b,c*], R. BROOKS[b], D. HERZOG[c] AND J. GARVEY[a]
[a] *Fisheries and Illinois Aquaculture Center, Department of Zoology, Center for Ecology, Southern Illinois University, Carbondale, Illinois, USA*
[b] *Kentucky Department of Fish and Wildlife Resources, Frankfort, Kentucky, USA*
[c] *Missouri Department of Conservation, Big Rivers and Wetlands Field Station, Jackson, Montana, USA*

## ABSTRACT

Dams have been implicated in the alteration of natural river processes. Quantifying spatial and temporal movement and passage patterns of large river fishes are critical for determining the extent of restricted passage and the needs for fish passage improvements. However, limited information regarding this topic exists because of the inherent difficulties associated with large river systems and assumptions associated with movement studies. Because of this lack of information, we investigated broad scale passage patterns of several riverine fish species through seven locks and dams complexes of the Upper Mississippi River using telemetry. Over the course of our 5-year evaluation, we observed species-specific movement and passage patterns, and how these trends were affected by factors such as water level and lock and dam management. Stationary receivers placed in a monitoring array detected a total of 1036 passage events. Eighty-four percent of the passage occurred through all but one of the lock and dam structures during both open and closed river conditions. While 70% of the passage occurred during open river conditions, further investigation of passages that occurred during closed river conditions (when gates are extended into the water column at some level) revealed that the majority of passage occurred when the average opening for all gates ranged from 0.6 to 1.2 m. Lock usage was also quantified, and most species were not routinely using the lock chambers for passage. Ultimately, these data have shown that individuals of each study species were able to negotiate most of the locks and dams during open and closed river conditions in both directions. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: fish passage; lock and dams; Upper Mississippi River; discharge

*Received 18 September 2012; Revised 03 June 2013; Accepted 26 June 2013*

## INTRODUCTION

The majority of large rivers and their tributaries are regulated with dams for many reasons (i.e. flood control, navigation or hydropower). Although regulation may be necessary, this process can transform free-flowing rivers into a series of reservoirs or impoundments, ultimately altering the natural flow regime (Poff *et al*., 1997; Nilsson and Berggren, 2000; Garvey *et al*., 2010). Many riverine fish species rely on the duration, timing, frequency and magnitude of seasonal flooding provided by the natural flow regime. While these processes are crucial for many riverine organisms, dams have altered flow and available habitat (Junk *et al*., 1989; Poff *et al*., 1997; Graf, 2006) and modified migration cues and timing of spawning (Junk *et al*., 1989; DiStefano *et al*., 1997; Humphries and Lake, 2000; King *et al*., 2009) by impairing the natural course of these large rivers. Dams also restrict movement by blocking the migration pathways to spawning, overwintering and feeding areas (Ligon *et al*., 1995; Cowx and Welcomme, 1998; Northcote, 1998; Bunt *et al*., 2001; Lucas and Baras, 2001). The potential negative effects of dams and river regulation have been implicated in the decline in abundance and distribution of many native species (Kanehl *et al*., 1997; Jungwirth *et al*., 1998; Northcote, 1998) and are causing increased concern world-wide.

Increasingly, more attention has been paid to the effects of dams on aquatic ecosystems and the fisheries within them (Wunderlich *et al*., 1994; Ligon *et al*., 1995; Cheng *et al*., 2006). The ability of fish to navigate dams has become a concern; thus, more consideration has been given to dam removal and fish passage improvement projects (Kanehl *et al*., 1997; Beasley and Hightower, 2000; Schmetterling, 2003; Cheng *et al*., 2006). In many cases (e.g. navigation dams on large rivers), dam removal is not a viable option; therefore, the potential impacts of dams on fish migration must be assessed (Cheng *et al*., 2006). Some studies have attempted to quantify fish passage through the navigation dams of the Upper Mississippi River ([UMR]; Coker, 1929; Holland *et al*., 1984; Southall and Hubert, 1984; Moen and Scarnecchia, 1992; Ickes *et al*., 2001; Wlosinski

*Correspondence to: S. Tripp, Missouri Department of Conservation, Big Rivers and Wetlands Field Station, 3815 East Jackson Blvd, Jackson, Montana 63755, USA.
E-mail: sara.tripp@mdc.mo.gov

and Surprenant, 2001; Zigler *et al*., 2004). However, fish passage and the factors influencing passage continue to remain relatively unknown because of the underlying caveats associated with these data (e.g. low recapture rates and extended periods between mark and recapture; Wlosinski and Surprenant, 2001). Despite the lack of definitive data, most agree that improving passage of native fishes in the UMR is necessary for managing and maintaining the ecological integrity and sustainability of the river ecosystem (Holland *et al*., 1984; UMRCC, 2001; Wilcox *et al*., 2004; Garvey *et al*., 2010).

Before fish passage improvements (i.e. modified management of locks and dams or construction of passage facilities) can be implemented in the UMR, an understanding of current passage opportunities and environmental influences is necessary. Therefore, the goal of this study was to describe patterns in fish passage, for several native and invasive species, through navigation dams in the lower reaches of the UMR. Specific objectives included the following: (i) determine the effects of navigation dams (lock and dam complexes) on fish movement; (ii) investigate environmental factors and operational aspects of the dams themselves that influence movement and behaviour; and (iii) establish a baseline of information that can be used to assess the efficacy of proposed fish passage measures in the future.

## STUDY AREA

In the UMR, 29 navigation locks and dams are thought to be at least partial barriers to fish movement (Fremling *et al*., 1989). St. Anthony Falls and Locks and Dams 1 and 19 are high-head dams that control water levels at all flows, creating permanent barriers, except for potential movement through the navigation lock chambers (Wilcox *et al*., 2004). The dam located furthest downstream is the Chain of Rocks Weir that crosses the river channel with notches, so it is not suspected to hinder fish movement (Wlosinski and Surprenant, 2001). The UMR dams are composed of either a combination of tainter and roller gates or a series of tainter gates. The gates are operated to control water levels or pool elevation, that is gates can lower to the sill of the river bottom during low flow and are entirely raised out of the water during extremely high flows, so that the navigation channel will be maintained (Wlosinski and Surprenant, 2001; Wilcox *et al*., 2004; Zigler *et al*., 2004). These dams may create a potential for fish movement and passage during open river (when gates are completely raised entirely out of the water during periods of high discharge), but the possibility of passage during closed river conditions (at low discharge, gates are completely or partially closed to restrict flow and maintain the navigation channel) has not been quantified (Zigler *et al*., 2004).

## METHODS

Fish movement and passage was monitored in the UMR from above Lock and Dam 19 (Keokuk, IA; River Kilometer [RKM] 591) downstream to below the Chain of Rocks Weir (St. Louis, MO; RKM 305) from the spring of 2006 through the winter of 2010 (Figure 1). The monitoring array consisted of a minimum of 22 stationary receivers (Vemco VR2W) that were focused above and below Locks and Dams 22 and 26 (three receivers each above and below both dams); however, the remaining receivers were scattered throughout the study area. The stationary receivers were affixed to navigation buoys, submerged on rebar stands or mounted to bridge piers. Data collected from the stationary receivers were used to quantify interpool movement within Pools 20 through 26 of the UMR. To investigate movement through lock chambers, we mounted additional receivers in the lock chambers at Lock and Dam 26.

After the monitoring array was deployed, selected fish species were sampled using a variety of gears including electrofishing, gill nets, trammel nets and trotlines. Fish were captured and tagged during spring 2006 through fall 2010. Ultrasonic transmitters were implanted in fish following the 2% rule (Jepsen *et al*., 2002; see Table I for mean lengths and weights of fish). Fish were anesthetized with a carbon dioxide and oxygen mixture, and river water was circulated over the fish's gills during surgery. The incision was made ventrally, and anterior to the anal opening and the transmitter was inserted. The incision was closed with simple interrupted sutures (Summerfelt and Smith, 1990) and sealed with cyanoacrylate resin to hold the wound and suture knots together securely. Tagged fish were then placed in a recovery tank and released after normal swimming occurred (Tripp and Garvey, 2010).

Fish collection and surgical implantation of ultrasonic transmitters occurred at Locks and Dams 22 and 26, because these sites were chosen to begin fish passage improvements by the Army Corps of Engineers. Because we expected that fish moving upstream would be more restricted by dams than those moving downstream, 25% of the fish were tagged and released above the structure, and the rest (i.e. 75%) were tagged in the pool downriver of the dam. This increased our power to detect upstream movement by increasing our sample size of fish at the downstream location. Our goal was to have 200 fish (approximately 40 fish of each target species) with active transmitters at large in the river at each study site. Target fish species initially included silver carp *Hypophthalmichthys molitrix*, paddlefish *Polyodon spathula*, shovelnose sturgeon *Scaphirhynchus platorynchus* and white bass *Morone chrysops* at both locations, with the addition of blue catfish *Ictalurus furcatus* at Lock and Dam 26. However, over the course of the study, other species (i.e. sauger *Sander*



DOI: 10.1002/rra

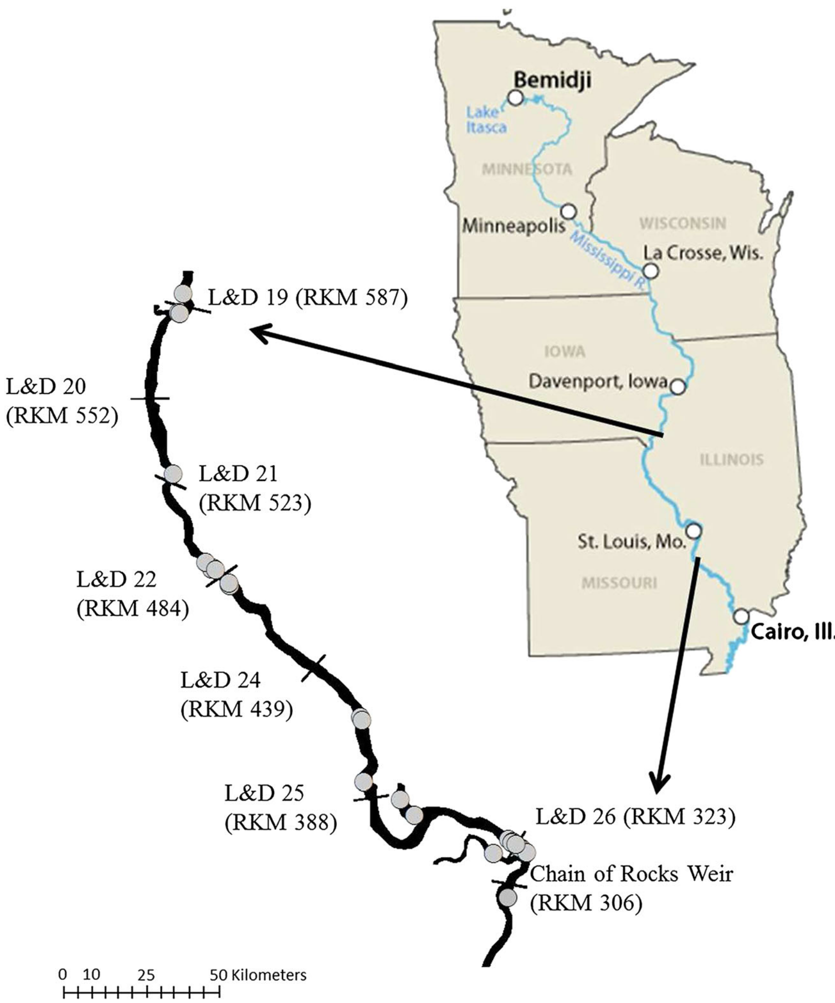


Figure 1. Map showing location of lock and dam structures in the Upper Mississippi River with stationary receivers illustrated with grey circles

*canadensis*, walleye *Sander vitreus*, hybrid striped bass *Morone chrysops x Morone saxatilis*, lake sturgeon *Acipenser fulvescens*, bighead carp *Hypophthalmichthys nobilis* and American eel *Anguilla rostrata*) were also implanted with transmitters to incorporate other riverine species.

Data from the stationary receivers were downloaded monthly and summarized to quantify fish passage. For the purposes of this study, we considered passage to have occurred when a fish was detected on one side of the structure and then later detected on a receiver on the opposite side. Due to noise interference from water flowing through the dams and excessive barge activity in some areas, stationary receivers were placed about 0.8 km above or below the structure, so fish were required to move beyond the structure to be detected. Thus, it is possible that fishes only moving a short distance through structures were not detected, underestimating passage potential. Passages at all locks and dams were combined for analyses, but because Locks and Dams 22 and 26 were slated for the initial fish passage improvements, we also included individual data from these dams as means to support or refute overall patterns. Chi-square tests were used to determine if the proportion of upstream and downstream passage at Locks and Dams 22 and 26 were different. Simple linear regression was used to determine if the location of the dam (i.e. number of dams upstream or downstream of the dam) in the river was related to the upstream–downstream trends in the direction of passage.

Both hydraulic and hydrologic conditions at dams within the study area were estimated from river stage data compiled by the US Geological Survey and total gate openness provided by the US Army Corps of Engineers (USACE). From this data, we determined date ranges when locks and dams were essentially set for open river conditions (when water levels approached or exceeded flood stage), and then whether or not passages



DOI: 10.1002/rra

Table I. Mean lengths and weights of species collected, tagged with ultrasonic transmitters and released above and below Locks and Dams 22 and 26 of the upper Mississippi River during 2006 through 2010

| Species | *N* | Mean length (mm) | Std | Mean weight (g) | Std |
|---|---|---|---|---|---|
| Bighead carp[a] | 10 | 916 | 78 | 10 030 | 2709 |
| Blue catfish[a] | 107 | 661 | 109 | 3878 | 3009 |
| American eel[a] | 3 | 502 | 18 | 334 | 61 |
| Hybrid striped bass[a] | 16 | 529 | 77 | 2329 | 1319 |
| Lake sturgeon[b] | 86 | 708 | 274 | 3414 | 3934 |
| Paddlefish[b] | 105 | 1033 | 142 | 5261 | 2609 |
| Sauger[a] | 33 | 415 | 45 | 712 | 282 |
| Shovelnose sturgeon[b] | 311 | 634 | 99 | 1057 | 230 |
| Silver carp[a] | 362 | 690 | 100 | 4060 | 2120 |
| Walleye[a] | 17 | 445 | 66 | 944 | 495 |
| White bass[a] | 165 | 332 | 37 | 514 | 202 |

[a]Total length (mm).
[b]Fork length (mm).

occurred at open or closed river (gates were in the water) conditions. Passages during closed conditions may be underestimated because, for any period between detections when the fish could have passed during either closed or open conditions, passage was assumed to have occurred during the period of open conditions. More specific, the total gate openness value provided by the USACE was the total depth of the dam open (the opening in meters from sill at the river bottom to the bottom of the gate), combined across all gates at each dam. We then assumed that the average depth open at each gate for fish to pass through was the total openness divided by the number of gates. An analysis of variance was used to determine if study species passed through the locks and dams at different average gate openings. A two-sample *t*-test was used to compare gate openness during upriver and downriver passages.

## RESULTS

From March 2006 through December 2010, 1215 fish were implanted with transmitters and 5.5 million fish identifications were recorded by the monitoring array. Of the tagged fish, 913 (75%) were detected multiple times by the stationary receivers on more than one date. Detection rates for each species ranged from 33% (American eel) to 86% (bighead carp; Table II). The relocated fish were identified from RKM 584 of the UMR in upper Pool 20 down to beyond RKM 305 below the weir at Chain of Rocks.

The monitoring array detected a total of 1036 passage events. The majority (868 passages or 84%) of the passage occurred through one of the lock and dam structures (Locks and Dams 20, 21, 22, 24, 25 or 26); however, no fish were detected passing above Lock and Dam 19. Of the fish relocated, 304 (36%) passed through at least one dam, and 199 passed through multiple structures. Overall, the direction (upriver versus downriver) of passage was comparable, with upriver passages accounting for 49% of the total passages. The frequency of both upstream and downstream passage events depended on the location in the UMR (Table III; Figure 2; $r^2 = 0.90$, $p < 0.001$). Passages at Lock and Dam 22 comprised 21% of the total number of passages, and 62% were upstream into Pool 21. Similarly, the number of passages through Lock and Dam 26 represented 20% of the total passages, but in contrast to Lock and Dam 22, only 38% of passages were upriver (Table III; Figure 2). Both the proportion of upstream ($X^2 = 15.16$, $p < 0.01$) and downstream ($X^2 = 9.29$, $p < 0.01$) passage were significantly different between Locks and Dams 22 and 26. The remaining 168 passages (16%) were fish detected passing over the weir at Chain of Rocks, and of those, 74% were downriver into the Middle Mississippi River.

Water levels and discharge influenced when fish passed through the lock and dam complexes. The positions of the tainter and roller gates are used to manage discharge and water levels. Thus, when water levels in pools approached or exceeded flood stage, gates were raised out of the water creating open river conditions (Figure 3). When passages at all lock and dam complexes were combined, 70% of the passage occurred when the gates were raised out of the water. Downriver passage (65%) was more common than upriver passage (35%) when the dam gates were lowered in the water, and the river was being regulated (Table IV). Lake sturgeon and paddlefish upriver passage appeared to be more impeded (4% and 9%) during closed versus open conditions; when compared with 75% of sauger /walleye, 50% of blue catfish and 41% silver carp upriver passages were recorded during closed conditions (Table IV). Despite the number of blue catfish tagged (107) in the Lock and Dam 26 area, blue catfish rarely passed upriver through the lock and dam; however, blue catfish appeared to have



DOI: 10.1002/rra

Table II. Species and number of fish surgically implanted with sonic transmitters during 2006–2010 in the upper Mississippi River for the purpose of passage detection through Locks and Dams 19–26. Percent detected represents the ratio of tagged fish detected for each year in which they were tagged

| Year | Number of fish tagged per year | Number detected | Percent detected | Year | Number of fish tagged per year | Number detected | Percent detected |
|---|---|---|---|---|---|---|---|
| | Lake sturgeon | | | | Blue catfish | | |
| 2006 | 16 | 16 | 100 | 2006 | 39 | 37 | 95 |
| 2007 | 32 | 24 | 75 | 2007 | 27 | 22 | 81 |
| 2008 | 33 | 10 | 30 | 2008 | 13 | 8 | 62 |
| 2009 | 3 | 3 | 100 | 2009 | 13 | 9 | 69 |
| 2010 | 2 | 1 | 50 | 2010 | 15 | 13 | 87 |
| All years | 86 | 54 | 63 | All years | 107 | 89 | 83 |
| | Shovelnose sturgeon | | | | Paddlefish | | |
| 2006 | 69 | 50 | 72 | | | | |
| 2007 | 48 | 26 | 54 | 2006 | 5 | 4 | 80 |
| 2008 | 72 | 62 | 86 | 2007 | 55 | 42 | 76 |
| 2009 | 42 | 24 | 57 | 2008 | 27 | 24 | 89 |
| 2010 | 80 | 41 | 51 | 2009 | 12 | 10 | 83 |
| All years | 311 | 203 | 65 | 2010 | 6 | 2 | 33 |
| | Silver carp | | | All years | 105 | 82 | 78 |
| 2006 | 64 | 58 | 91 | | White bass and hybrid striped bass | | |
| 2007 | 57 | 54 | 95 | 2006 | 38 | 30 | 79 |
| 2008 | 120 | 109 | 91 | 2007 | 6 | 3 | 50 |
| 2009 | 41 | 33 | 80 | 2008 | 56 | 46 | 82 |
| 2010 | 80 | 57 | 71 | 2009 | 35 | 30 | 86 |
| All years | 362 | 311 | 86 | 2010 | 46 | 23 | 50 |
| | | | | All years | 181 | 132 | 73 |
| | Bighead carp | | | | | | |
| 2006 | 10 | 9 | 90 | | Sauger/walleye | | |
| | | | | 2009 | 19 | 12 | 63 |
| | American eel | | | 2010 | 31 | 20 | 65 |
| 2010 | 3 | 1 | 33 | All years | 50 | 32 | 64 |

Table III. Fish passage through Mississippi River Locks and Dams 20–26 and the Chain of Rocks Weir. Passage was detected by stationary receivers placed above and below the dams

| Lock and dam | Number of passages | Percent of total passages | Percent upriver | Percent downriver |
|---|---|---|---|---|
| 20 | 76 | 7 | 75 | 25 |
| 21 | 96 | 9 | 75 | 25 |
| 22 | 216 | 21 | 62 | 38 |
| 24 | 145 | 14 | 42 | 58 |
| 25 | 134 | 13 | 45 | 55 |
| 26 | 201 | 20 | 38 | 62 |
| Chain of Rocks Weir | 168 | 16 | 26 | 74 |
| | 1036 | 100 | 49 | 51 |

no trouble traversing the Chain of Rocks Weir with 50 upstream passages. Silver carp also appear to be more successful in passing under closed river conditions than the native species. Upriver passage during closed conditions accounted for 21% of the 134 upriver passages through Lock and Dam 22. Upriver passage through Lock and Dam 26 during closed conditions represented 48% of the 77 passages.

The majority (58%) of fish passage during closed river conditions occurred when the average opening for all gates ranged from 0.6 to 1.2 m (Figure 4). This trend was observed in passages that occurred at all locks and



DOI: 10.1002/rra

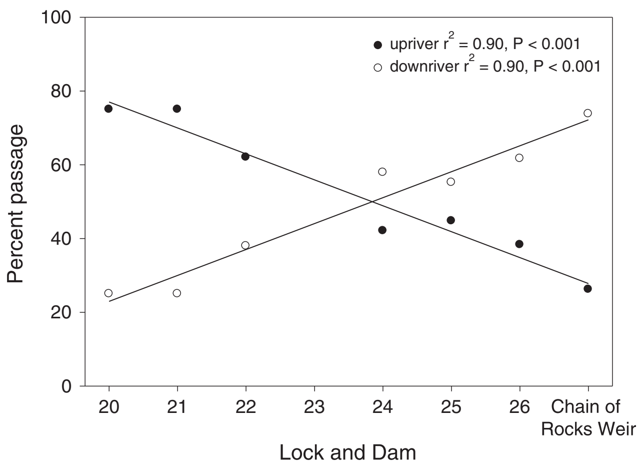


Figure 2. Percent passages of tagged fish either confirmed as upstream or downstream through Locks and Dams 20–26 of the Upper Mississippi River during 2006 through 2010. The Chain of Rocks Weir is also included. Note: There is no Lock and Dam 23.

dams.We evaluated how differing gate openings effected passage by the study species, but there was no difference in average gate opening during passage among species ($F = 1.31$, $df = 1262$, $p > 0.05$). When passage was evaluated by direction, there was a difference between the average gate opening during upriver (1.30 m) and downriver (1.8 m) passage ($t = 2.85$, $df = 1261$, $p = 0.005$).

We assumed that some portion of passage would occur through navigation lock chambers. But when lock usage at Lock and Dam 26 was quantified, most species were not routinely using the lock chambers for passage. All species implanted with transmitters, except bighead carp and American eel, had at least one fish enter one of the lock chambers. While 491 (302 silver carp) fish were detected by the receivers inside the lock chambers; only 29 (20 silver carp) fish actually used the locks for passage (Table V).

## DISCUSSION

Based on the results of this study, most of the locks and dams in the UMR do not appear to completely impede migratory fish movements. We have shown that individuals of each study species had the ability to negotiate all of the locks and dams, with the exception of Lock and Dam 19 both during open and closed river conditions. Previous studies documented passage in both directions during open river

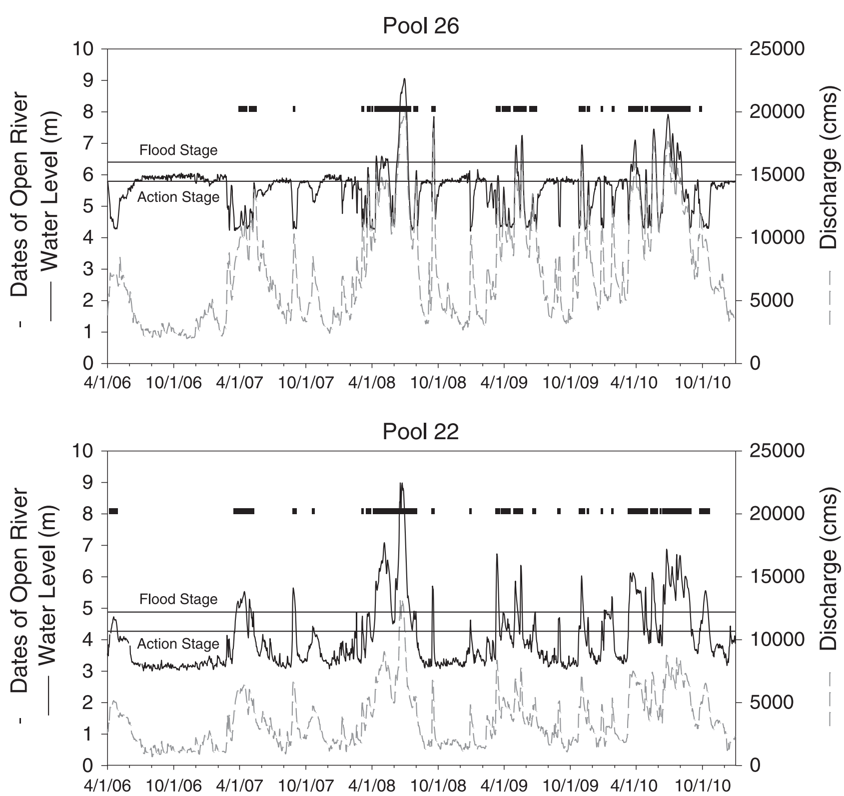


Figure 3. Daily water levels (meters) and discharge (cubic meters per second) at the Alton, IL and Hannibal, MO US Geological Survey gauges during 2006 through 2010. Dates of open river conditions are denoted by black boxes



DOI: 10.1002/rra

Table IV. Fish passage through Upper Mississippi River locks and dams. Passage was detected by stationary receivers placed above and below the dams. Open or closed describes river conditions at the dams. The numbers depict total number of passages

| Species | Downriver | | Upriver | | Total per species |
|---|---|---|---|---|---|
| | Open | Closed | Open | Closed | |
| | | | Locks and Dams 20–26 | | |
| Bighead carp | 0 | 4 | 3 | 0 | 7 |
| Blue catfish | 2 | 22 | 6 | 6 | 36 |
| American eel | 1 | 1 | 0 | 0 | 2 |
| Lake sturgeon | 29 | 13 | 90 | 4 | 136 |
| Paddlefish | 33 | 16 | 80 | 8 | 137 |
| Sauger/walleye | 17 | 2 | 2 | 6 | 27 |
| Shovelnose sturgeon | 93 | 33 | 122 | 34 | 282 |
| Silver carp | 36 | 51 | 43 | 30 | 160 |
| White bass and hybrid striped bass | 26 | 28 | 22 | 5 | 81 |
| Total | 237 | 170 | 368 | 93 | 868 |
| | | | Chain of Rocks Weir | | |
| Bighead carp | 0 | | 0 | | 0 |
| Blue catfish | 11 | | 50 | | 61 |
| American eel | 0 | | 0 | | 0 |
| Lake sturgeon | 11 | | 9 | | 20 |
| Paddlefish | 2 | | 7 | | 9 |
| Sauger/walleye | 0 | | 0 | | 0 |
| Shovelnose sturgeon | 8 | | 19 | | 27 |
| Silver carp | 9 | | 27 | | 36 |
| White bass and hybrid striped bass | 3 | | 12 | | 15 |
| Total | 44 | | 124 | | 168 |

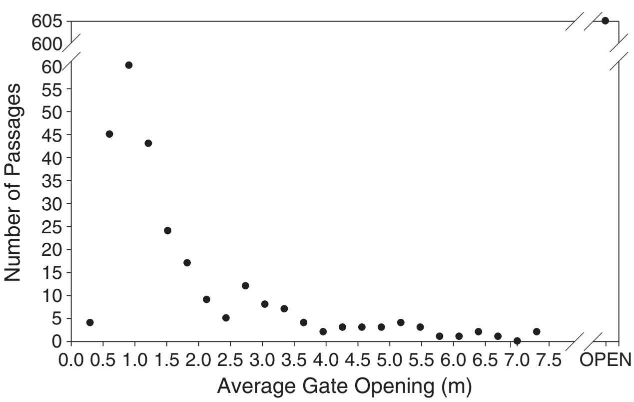


Figure 4. Total number of passages (represented with black circles; for all locks and dams combined) that occurred at a range of average gate openings

conditions and downriver passage during closed river conditions (Southall and Hubert, 1984; Moen and Scarnecchia, 1992), but stated that upriver passage during closed river conditions was impeded by strong current velocities that surround partially submerged gates (Zigler *et al.*, 2004). While the majority of passage was documented during open river conditions similar to other studies, we also observed fish passing upriver through the lock and dam complexes when gates were partially submerged in the river. While hydraulic conditions may restrict upriver passage for some species (i.e. paddlefish and lake sturgeon) more than others, other factors (e.g. fish behaviour and timing of fish movement) also appear to be affecting fish passage. For certain species (i.e. paddlefish), other factors (e.g. electrosensitivity) may cause avoidance of structures such as locks and dams, potentially interfering with passage and migration (Gurgens *et al.*, 2000). Although limited upriver passage was observed by some of the native species, fish passage improvements may curtail some of these other factors that affect fishes ability to pass through dams. On the other hand, silver carp appeared to be more successful than our native species at passing upriver during closed river conditions, and fish passage improvements may only accelerate the spread of these invasive species.

The potential of fish passage is important in regulated rivers to maintain healthy populations of riverine fishes, by ensuring that specific habitats (e.g. nursery, spawning, foraging and overwintering) that are used throughout all life stages remain accessible (Northcote, 1998; Bunt *et al.*, 2001). Some evidence that natural movements throughout the UMR are partially impeded is the greater frequency of downriver movement by study fish closest to the open river and the propensity of upriver movement and upriver passage through Locks and Dams 22, 21 and 20 (Figure 3). This may imply that proximity to the open river may contribute to



DOI: 10.1002/rra

Table V. Fish use of lock chambers to pass through Mississippi River Lock and Dam 26 during 2007 through 2010. Passage was detected by stationary receivers place inside the lock chambers. Numbers depict number of fish entering the locks and passages either upriver or downriver

| Species | Number of entrances | Upriver passage | Downriver passage | Total passage |
|---|---|---|---|---|
| Bighead carp | 0 | 0 | 0 | 0 |
| Blue catfish | 12 | 0 | 1 | 1 |
| American eel | 0 | 0 | 0 | 0 |
| Lake sturgeon | 5 | 2 | 0 | 2 |
| Paddlefish | 2 | 0 | 1 | 1 |
| Sauger/walleye | 61 | 3 | 0 | 3 |
| Shovelnose sturgeon | 75 | 1 | 1 | 2 |
| Silver carp | 302 | 17 | 3 | 20 |
| White Bass and hybrid striped bass | 35 | 0 | 0 | 0 |
| Total | 491 | 23 | 6 | 29 |

increased downriver movement and that downriver movement for upstream fishes may be reduced by successive locks and dams. Thus, locks and dams may have restricted interpool movement enough over time to have altered migratory behaviour of the some of this study's fish species. To test this hypothesis, population-specific markers (i.e. genetics, fatty acids and microchemistry of hard parts) could be compared between individuals that reside in the impoundment of the Upper Mississippi and the open river. These patterns may also suggest that the fish assemblages are showing fidelity to natal or spawning sites and migrate on the basis of location in the UMR. Several nondiadromous species have been shown to return to natal sites or spawning areas (Leggett, 1997; Miller *et al*., 2001). One strategy could be to migrate upstream into the gravel bars in upper Pool 20 for reproduction (Coker, 1929). The other 'downriver' strategy would be to move downstream toward locations such as the bedrock area below the Chain of Rocks Weir. Whether these passage patterns are due to site fidelity or caused by restricted passage, lock and dams are still unknown. We do know that the majority of the fish passages occurred during open river conditions during spring and summer, which encompass the period that riverine fish species are embarking on spawning migrations. It was previously thought that in years when spring flood events do not occur, passage and movement may be prevented (Southall and Hubert, 1984; Zigler *et al*., 2004). However, we have shown that even in these closed river conditions, at least some fish are capable of passing through the dams.

Without estimates for fish movement prior to impoundment, the true impact of lock and dam complexes will be difficult to quantify. The data collected in this study provide a baseline for movement and passage that can later be utilized for comparison after fish passage improvements are completed. We do not know how movements might be enhanced by emplacing fish passage structures (i.e. Will the percentage or frequency of upriver passages increase, facilitating purported spawning?). We are just beginning to determine how gate configuration may affect the ability of these species to pass through dams and potentially may be a viable option for fish passage enhancement. We have also shown that lock chamber usage for passage is likely not practical option for native fish passage improvement; however, the high incidence of silver carp passage via this route suggests that locks may serve as a vector for movement through dams by these invasive species. While the lock and dam complexes in the UMR (except for Lock and Dam 19) appear to function as only partial barriers, the extent of how much movement is restricted cannot be quantified until sufficient post-fish passage improvement data are collected. Although we cannot make definitive conclusions regarding the effects of lock and dam complexes on fish movements or how potential fish passage improvements may enhance interpool movements, we have shown that the series of lock and dam complexes in the UMR are not complete barriers to movement with the exception Lock and Dam 19, at which no fish were detected passing through. We recommend continued monitoring of fish passage and movement across multiple years to increase our understanding about how water-level management at dams affects the passage potential of common UMR fishes.

## ACKNOWLEDGEMENTS

We would like to thank Travis Moore, Dave Ostendorf and Quinton Phelps of the Missouri Department of Conservation; Tim Spier of Western Illinois University and Mike Hill, Heather Calkins and other SIU graduate students and technicians that have helped us implement this project. We also thank USACE's Captain Terry Bequette of the Pathfinder and Gale Howerton of the USCG for their assistance with navigation buoys. We also thank Mark Cornish, Jason Farmer and Donovan Henry of USACE for their assistance in all phases of this project.

REFERENCES


Beasley CA, Hightower JE. 2000. Effects of a low-head dam on the distribution and characteristics of spawning habitat used by striped bass and American shad. *Transactions of the American Fisheries Society* **129**: 1316-1330.

Bunt CM, van Poorten BT, Wong L. 2001. Denil fishway utilization patterns and passage of several warmwater species relative to seasonal, thermal and hydraulic dynamics. *Ecology of Freshwater Fish* **10**: 212–219.

Cheng F, Zika U, Banachowski K, Gillenwater D, Granata T. 2006. Modeling the effects of dam removal on migratory walleye (*Sander vitreus*) early life-history stages. *River Research and Applications* **22**: 837-851.

Coker RE. 1929. Keokuk Dam and the fisheries of the Upper Mississippi River. *Bulletin of the U.S. Bureau of Fisheries* **45**: 87-139.

Cowx IG, Welcomme RL. 1998. Rehabilitation of Rivers for Fish. FAO and Fishing News Books, Blackwell Science Ltd.: Oxford.

DiStefano RJ, Barry TP, Malison JA. 1997. Correlation of blood parameters with reproductive problems in walleye in a Missouri Impoundment. *Journal of Aquatic Animal Health* **9**: 223–229.

Fremling CR, Rasmussen JL, Sparks RE, Cobb SP, Bryan CF, Claflin TO. 1989. Mississippi River fisheries: a case history. *Canadian Special Publication of Fisheries and Aquatic Sciences* **106**: 309-351.

Garvey JE, Ickes B, Zigler S. 2010. Challenges in merging fisheries research and management: the Upper Mississippi River experience. *Hydrobiologia* **640**: 125-144.

Graf WL. 2006. Downstream hydrologic and geomorphic effects of large dams on American Rivers. *Geomorphology* **79**: 336–360.

Gurgens C, Russell DF, Wlikens LA. 2000. Electrosensory avoidance of metal obstacles by the paddlefish. *Journal of Fish Biology* **57**: 277-290.

Holland L, Huff D, Littlejohn S, Jacobson R. 1984. Analysis of existing information on adult fish movements through dams on the Upper Mississippi River. *Report to the St. Paul District, U.S. Army Corps of Engineers*. National Fishery Research Laboratory, U.S. Fish and Wildlife Service, La Crosse, WI; 193 pp.

Humphries P, Lake PS. 2000. Fish larvae and the management of regulated rivers. *Regulated Rivers: Research & Management* **16**: 421–432.

Ickes BS, Wlosinski JH, Knights BC, Zigler SJ. 2001. Fish passage through dams in large temperate floodplain rivers: an annotated bibliography. US 13 Geological Survey, Upper Midwest Environmental Sciences Center, LaCrosse, WI.

Jepsen N, Thorstad EB, Baras E, Koed A. 2002. Surgical implantation of telemetry transmitters in fish: how much have we learned? *Hydrobiologia* **483**: 239–248.

Jungwirth M, Schmutz S, Weiss S. 1998. Fish Migration and Fish Bypasses. Fishing News Books, Oxford; 438.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences* **106**: 110–127.

Kanehl PD, Lyons J, Nelson JE. 1997. Changes in the habitat and fish community of the Milwaukee River,Wisconsin, following removal of the Mills Dam. *North American Journal of Fisheries Management* **17**: 387–400.

King AJ, Tonkin Z, Mahoney J. 2009. Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. *River Research and Applications* **25**: 1205–1218.

Ligon FK, Dietrich WE, Trush WJ. 1995. Downstream ecological effects of dams. *Bioscience* **45**: 183–192.

Leggett WC. 1997. The ecology of fish migrations. *Annual Review of Ecology and Systematics* **8**: 285-308.

Lucas MC, Baras E. 2001. Migration of Freshwater Fishes. Blackwell Science: Malden, MA; 420.

Miller LM, Kallemeyn L, Senanan W. 2001. Spawning site and natal site fidelity by northern pike in a large lake: mark-recapture and genetic evidence. *Transactions of the American Fisheries Society* **125**: 307–316.

Moen CT, Scarnecchia DL. 1992. Paddlefish movement and habitat use in Pool 13 of the Upper Mississippi River during abnormally low river stages and discharges. *North American Journal of Fisheries Management* **12**: 744-751.

Nilsson C, Berggren K. 2000. Alterations of riparian ecosystems caused by river regulation. *BioScience* **50**: 783–792.

Northcote T. 1998. Migratory behaviour of fish and its significance to movement through riverine fish passage facilities. In Migration and Fish Bypasses, Jungwirth M, Schmutz S, Weiss S (eds). Fishing News Books: Cambridge; 3–18.

Poff LN, Allan JD, Bain MB, Karr JR, Prestegaard KL, Ritcher BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience* **47**: 769–784.

Schmetterling DA. 2003. Reconnecting a fragmented river: movements of westslope cutthroat trout and bull trout after transport upstream of Milltown Dam, Montana. *North American Journal of Fisheries Management* **23**: 721-731.

Southall PD, Hubert WA. 1984. Habitat use by adult paddlefish in the Upper Mississippi River. *Transactions of the American Fisheries Society* **113**: 125–131.

Summerfelt RC, Smith LS. 1990. Anesthesia, surgery, and related techniques. In Methods for Fish Biology, Schreck CB, Moyle PB (eds). American Fisheries Society: Bethesda, Maryland; 213-263.

Tripp SJ, Garvey JE. 2010. Fish Passage in the Upper Mississippi River System. 2011. United States Army Corps of Engineers: Rock Island, IL.

Upper Mississippi River Conservation Committee (UMRCC). 2001. A Working River and a River That Works. Upper Mississippi River Conservation Committee: Rock Island, IL.

Wilcox DB, Stefanik EL, Kelner DE, Cornish MA, Johnson DJ, Hodgins IJ, Zigler SJ, Johnson BL. 2004. Improving fish passage through navigation dams on the Upper Mississippi River system. Upper Mississippi River-Illinois Waterway System Navigation Study ENV 54.

Wlosinski JW, Surprenant C. 2001. Fish passage through dams on the Upper Mississippi River. Prepared for the U.S. Fish and Wildlife Service, Rock Island, Illinois.

Wunderlich RC, Winter BD, Meyer JH. 1994. Restoration of the Elwha River Ecosystem. *Fisheries* **19**: 11-20.

Zigler SJ, Dewey MR, Knights BC, Runstrom AL, Steingraeber MT. 2004. Hydrologic and hydraulic factors affecting passage of paddlefish through dams in the Upper Mississippi River. *Transactions of the American Fisheries Society* **133**: 160-172.




DOI: 10.1002/rra