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# Applying a Metapopulation Model to Compare Native and Invasive Fish Passage Scenarios in the Upper Mississippi River



Scientific Investigations Report 2026–5054

U.S. Department of the Interior
U.S. Geological Survey

**Cover:** Photograph of Lock and Dam No. 7 at sunset on the Upper Mississippi River in Wisconsin, by Richard Erickson, U.S. Geological Survey, September 14, 2024.

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## Conversion Factors

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| kilometer (km) | 0.5400 | mile, nautical (nmi) |
| meter (m) | 1.094 | yard (yd) |
| | Mass | |
| kilogram (kg) | 2.205 | pound avoirdupois (lb) |

## Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

## Abbreviations

| | |
|---|---|
| MetaIPM | Metapopulation Integral Projection Model |
| MICRA | Mississippi Interstate Cooperative Resource Association |
| RAFT | Riverine Acoustic Fish Telemetry network |
| USGS | U.S. Geological Survey |
| VBGM | Von Bertalanffy growth models |

# Applying a Metapopulation Model to Compare Native and Invasive Fish Passage Scenarios in the Upper Mississippi River

By Morganne C. Borsh,[1] Charles J. Labuzzetta,[2] Marybeth K. Brey,[2] Mark Cornish,[3] Alison Coulter,[4] Andrea K. Fritts,[2] David Smith,[3] and Richard A. Erickson[2]

## Abstract

The U.S. Geological Survey assessed the ability of metapopulation models to evaluate population-level effects of fish passage projects in the Upper Mississippi River for six native species: *Ictalurus furcatus* (Valenciennes in Cuvier and Valenciennes, 1840; blue catfish), *Ictiobus cyprinellus* (Valenciennes in Cuvier and Valenciennes, 1844; bigmouth buffalo), *Acipenser fulvescens* (Rafinesque, 1817; lake sturgeon), *Polyodon spathula* (Walbaum, 1792; American paddlefish [paddlefish]), *Ictiobus bubalus* (Rafinesque, 1818; smallmouth buffalo), *Scaphirhynchus platorynchus* (Rafinesque, 1818; shovelnose sturgeon), and one invasive species: *Hypophthalmichthys molitrix* (Valenciennes in Cuvier and Valenciennes, 1844; silver carp). The study had four objectives: to (1) compile parameter values and identify gaps, (2) parameterize species-specific models, (3) apply the models to multiple scenarios, and (4) develop a point-and-click interface. The literature review revealed a paucity of data, for all species except silver carp and paddlefish; however, length–weight relations, female length–maturity curves, growth curves, spawning and recruitment estimates, and movement data among pools were identified. These data allowed the parameterization of native species metapopulation models, in addition to the use of an existing silver carp model. The models were applied to scenarios representing increased passage, decreased passage, combined passage and deterrents effects, and increased native passage with decreased invasive passage. Increased passage scenarios (depicting potential passage projects) produced greater movement and larger upriver populations. Decreased passage scenarios (depicting potential deterrent projects) yielded reduced movement. Similar population dynamic patterns were observed across species for each scenario because of a lack of species-specific, empirical movement data. Simulations for longer lived, slow growing species required longer response times, including time to reach equilibria. A point-and-click model was created to allow others to use the model. Data availability for movement limited the ability of the model to be used to understand fish-movement biology and thereby inform management strategies. More fish-movement data could improve model projections of these scenarios.

## Plain Language Summary

Locks and dams on the Upper Mississippi River can block fish from moving to the places they need for spawning and feeding. Invasive fish like silver carp have moved upstream and disrupted native fish populations. The U.S. Geological Survey used models to study whether helping native fish species move past dams or blocking invasive fish from moving upriver might help restore balance. Scientists used available data and reasonable substitutes where data were missing to build a model that lets managers test potential actions. The model showed that improving passage increased native fish numbers upstream, and reducing silver carp passage decreased their movement into upstream pools. When combined, both goals could be achieved. More data, preferably coordinated across agencies, could improve estimates of movement, reproduction, and maturity. Adding seasonal movement and habitat information to future versions could make the model's results more realistic.

## Introduction

Informed fisheries management in large temperate rivers benefits from understanding longitudinal connectivity and population dynamics. Locks and dams cause interruptions in upriver fish movement and can disrupt population dynamics by reducing access to preferred habitats and separating populations of fish over time (Theiling and others, 2000;

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Wilcox and others, 2004; McCain and others, 2018; Bouska and others, 2019; Valentine and others, 2024). The U.S. Army Corps of Engineers manages the Upper Mississippi River (fig. 1), a management area defined in the United States Code (33 U.S.C. §652), for navigation and ecosystems (Sparks, 2010). The Upper Mississippi River includes approximately 1,000 river kilometers of the regulated section of the river from the Upper Saint Anthony Falls Lock and Dam in Saint Paul, Minnesota, to the Chain of Rocks Lock and Dam near Saint Louis, Missouri, and includes 29 dams (Theiling and others, 2015). Many navigation dams, including those on the Upper Mississippi River, have movable water control gates for regulating the depth of the impounded pool (fig. 1) upriver of the dam, allowing for boat navigation. When river discharge exceeds the dam's capacity to impound flow, these gates are lifted out of the river to protect the dam's infrastructure by releasing water pressure and debris buildup. This prevents overtopping, bypass, and erosion that could lead to catastrophic failure of the dam during high water events.

The relation between these open-river conditions (when the dam gates are out of the water and flow is unrestricted) and controlled-river conditions (when the dam gates are in the water and controlling flow) dictates the movement potential and distribution of riverine fishes in the Upper Mississippi River (Knights and others, 2002; Tripp and others, 2014; Anderson and others, 2024; Fritts and others, 2024b). Prior to the construction of the dams, the Upper Mississippi River experienced unrestricted movements of migratory fishes to disparate spawning, foraging, and over-wintering habitats (Forbes and Richardson, 1908; Coker, 1914; Jordan and Evermann, 1923; Coker, 1930). After dam construction, the regulated river limited fish passage to open-river events and occasional passage through the lock with commercial and recreational vessels (Johnson and others, 2005; Tripp and others, 2014; Fritts and others, 2021; Turney and others, 2022). Thus, seasonal and temporal changes in open-river

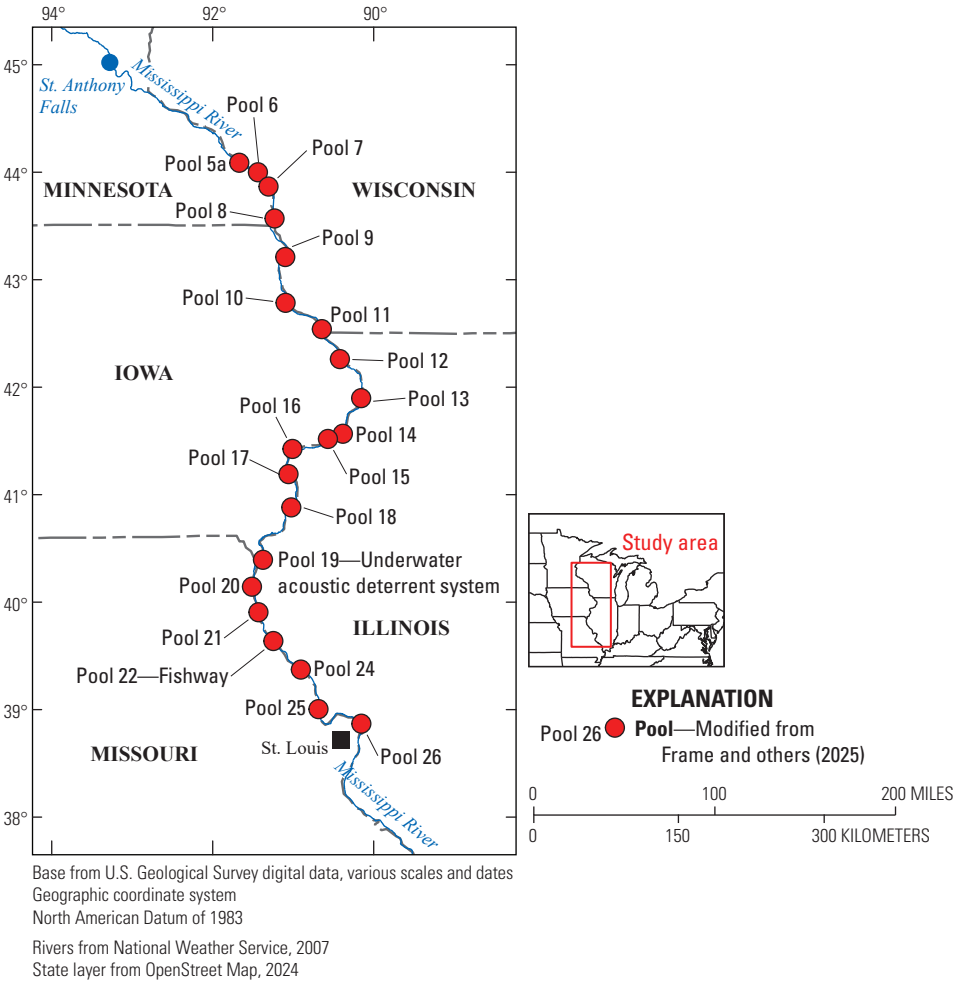



**Figure 1.** Map showing the locations of pools on the upper Mississippi River. Each numbered pool forms upriver of the corresponding lock and dam number.

conditions drive the current metapopulation dynamics for many migratory fish species in the Upper Mississippi River (Cooke and others, 2012; Cooper and others, 2017).

The expanding range of aquatic invasive species in the Upper Mississippi River has changed decision making for the Upper Mississippi River's natural resource managers (Conover and others, 2007; Finger and others, 2020; Brey and others, 2023). Dams, once only considered obstructions to native fish passage, are now recognized as also protecting headwaters from and disrupting the population dynamics of invasive species (Conover and others, 2007; Finger and others, 2020; Brey and others, 2023). Understanding how and when fish move upriver within the Upper Mississippi River can inform management and provide a better understanding of tradeoffs between managing native and invasive species (Sparks, 2010; Fritts and others, 2024a). Changes to lock and dam structures would ideally increase native fish passage and decrease invasive fish passage (Cooper and others, 2021; Fritts and others, 2021). For example, the installation of fishways at dams could expand accessibility to preferred habitats for native species by increasing fish passage across lock and dam structures (Wilcox and others, 2004; Janvrin and others, 2010; Cornish and others, 2013; Harris and others, 2019), but could also unintentionally benefit invasive species. Thus, understanding the spatial population dynamics of native and invasive species concurrently can inform management strategies that simultaneously aid native fish conservation and reduce the spread of invasive species.

Mathematical models and simulations have been applied to fisheries management scenarios to understand the effect of human activity changes to native and invasive fish in the Upper Mississippi River, but could be improved through application to broader native species groups and ease-of-use features such as point-and-click interfaces (Bartell and Campbell, 2000; Wu and others, 2006; Cooper and others, 2021). These models allow the evaluation of different management strategies. For example, fishways exist as a feasible management practice that could help managers restore native fish passage in impounded rivers such as the Upper Mississippi River (Aadland, 2010). Comparing different management strategies would allow resource managers to make science-based decisions and evaluate the tradeoffs regarding how their actions may affect native and invasive species in the Upper Mississippi River. Additionally, parameterizing such models would help identify data gaps and needs for future data-collection efforts. A user interface would also enable end users to independently explore model simulations through point-and-click interfaces—in contrast to previous models that required code interfaces—resulting in an increased ability to evaluate potential management actions.

Since previous fish modeling exercises were completed by Bartell and Campbell (2000), Wu and others (2006), and Cooper and others (2021) in the Upper Mississippi River, ecological knowledge, empirical data, and quantitative tools have advanced. Empirical data now exist for large-scale movement of some fish species, such as the invasive *Hypophthalmichthys molitrix* (Valenciennes in Cuvier and Valenciennes, 1844; silver carp; Coulter and others, 2018; Frame and others, 2025). Additional empirical studies have documented spatial variability in population demographic rates for species in the Upper Mississippi River Basin, such as silver carp (Erickson and others, 2021), *Polyodon spathula* (Walbaum, 1792; American paddlefish [paddlefish]; Sharov and others, 2014; Hupfeld and others, 2016; Wilberg, 2019), *Acipenser fulvescens* (Rafinesque, 1817; lake sturgeon), and *Scaphirhynchus platorynchus* (Rafinesque, 1818; shovelnose sturgeon; Haxton and Findlay, 2008; Bruch and others, 2016; Wilberg, 2019). Metapopulation models have been applied to inland fisheries populations management, such as silver carp in the Illinois River (Erickson and others, 2021; Kallis and others, 2023) and the Upper Mississippi River (Frame and others, 2025). These new data and tools create opportunities to better understand fish passage in the Upper Mississippi River while highlighting critical knowledge gaps.

## Purpose and Scope

The purpose of this report is to evaluate how changes in fish passage at Upper Mississippi lock and dam structures may affect the population dynamics of native and invasive fish. The report synthesizes recent ecological data and advances in metapopulation modeling to inform management decisions that may effectively balance native fish conservation with invasive species management. The scope includes application of a metapopulation modeling framework to multiple management scenarios, assessment of data limitations to fish passage, and demonstration of a tool designed to enable users to explore population responses under alternative passage conditions.

# Methods

This study included four objectives: to (1) compile demographic, movement, and life-history parameters for six native fish species and invasive silver carp to document missing parameter values; (2) parameterize the Metapopulation Integral Projection Model (MetaIPM; Erickson and others, 2023) for each species and apply the model to compare different management strategies based on increased passage of native fish and decreased passage of invasive fish; (3) identify key data gaps and information needs that limit understanding and quantification of fish passage in the Upper Mississippi River; and (4) developed a point-and-click interface that enables users to explore population responses under alternative management scenarios.

The MetaIPM version 2.1 was used to describe the spatial populations dynamics for seven fish species in the Upper Mississippi River. MetaIPM is a Python package that models metapopulation dynamics and continuous growth rates through an integral projection model (Erickson and others, 2023)

for species living in distinct geographic locations. These subpopulations exist because locks and dams fragment the river, and management actions often target specific pools (Bartell and Campbell, 2000; Wu and others, 2006; Cooper and others, 2021). Frame and others (2025) applied the model to compare silver carp control strategies in the Upper Mississippi River (fig. 2). The MetaIPM—consisting of two major components: (1) a spatial movement model based upon movement probabilities among pools of the river, and (2) a population model within each pool of the Upper Mississippi River—was used to represent migratory, large river fish in the Upper Mississippi River. The spatial movement model captures metapopulation dynamics with a Markov process (a projection matrix whose columns all sum to one, and in this case represent all possible movement transitions) to describe the movement of a species among pools within the river on a monthly time step. Individuals may move among multiple pools within a month, creating movements among nonadjacent pools. The population model joins submodels to create the integral projection model to capture the species' population dynamics in the following equation (eq. 1):

$$nz',t+1=\int_{\Omega}(s(z)G(z',z)h(z)n(z,t)+p_b\mathrm{egg}(z')vC_1(z')+1-E)dz, \quad (1)$$

where:

$n(z,t)$ is either the length distribution ($z$) of fish at the current time step ($t$) or the length distribution ($z'$) at the next time step ($t$+1),

$z$ is the length of a fish at the current time step ($t$),

$z'$ is the length of a fish at the next time step ($t$+1),

$t$ is the current time step,

$t+1$ is the next time step,

$s(z)$ is survival as a function of length ($z$),

$G(z',z)$ is the growth kernel from the current length ($z$) to the length ($z'$) at the next time step ($t$+1),

$h(z)$ is the harvest proportion of fish as a function of fish length ($z$),

$p_b$ is the probability of successful female spawning,

egg($z$) is the number of eggs produced per female as a function of length ($z$),

$v$ is the probability that an egg transitions to become an age-1 individual,

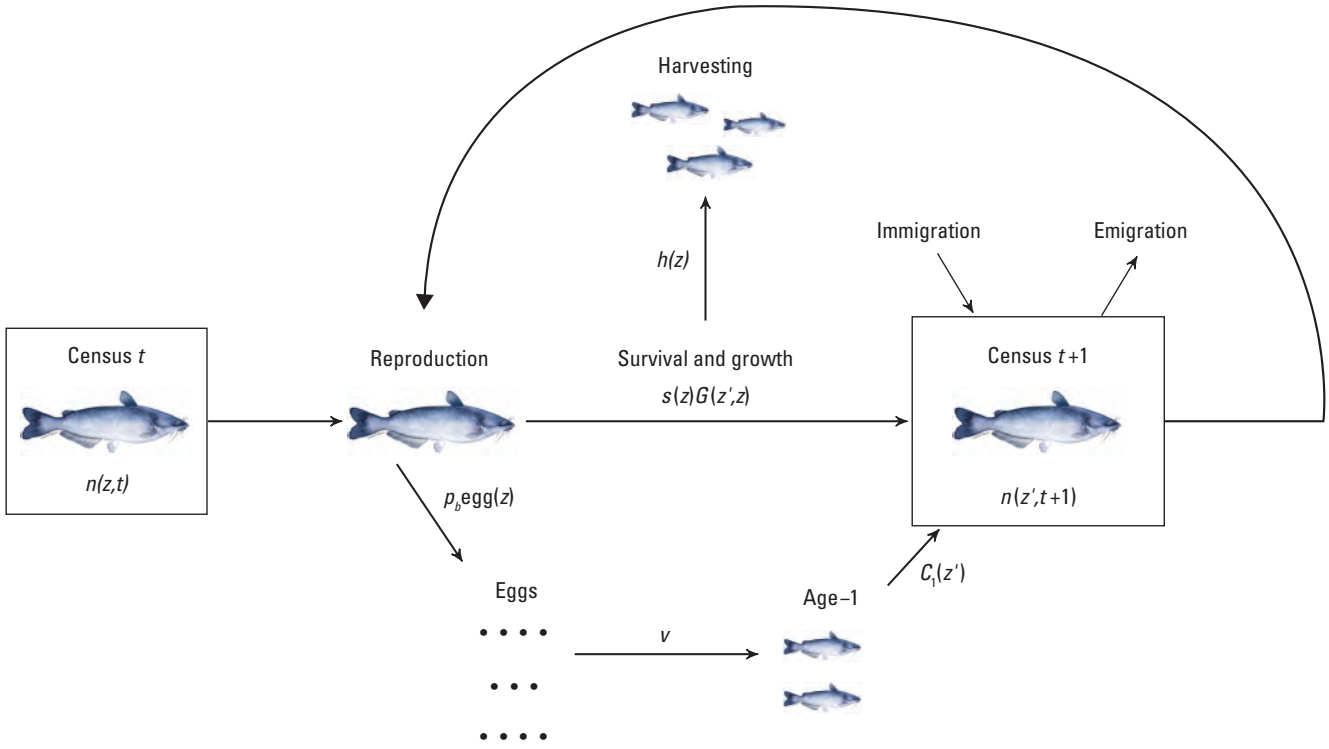
$C_1(z')$ is the length distribution at the next time step ($z'$) for recruits,

$I$ is immigration,

$E$ is emigration, and

$dz$ is the infinitesimal change in the variable $z$.

This model consists of a monthly time step (between time steps $t$ and $t+1$) while keeping track of fish length distributions at the current time step $n(z,t)$ and next time step $n(z',t+1)$ (fig. 2). The model includes a growth function $G(z',z)$, a logistic survival model as a function of length $s(z)$, and a length–weight relation to calculate biomass from the length state variable, $n(z,t)$. Fish lengths are converted to weights and then a Ricker stock function calculates the length distribution of new recruits at the next time step that includes the probability of successful recruitment, $p_b$, the number of eggs, $s$, a function of female size, $p_{b,}$ the probability of successful spawning occurring, egg($z$), the number of eggs produced per female as function of fish length, the probability that an egg transitions to become an age-1 individual, $v$, and the length distribution of age-1 individuals when counted at the next time step in the model, $C_1(z')$: $p_b\mathrm{egg}(z)vC_1(z')$. The model is also capable of including removal, such as through harvest as a function of length ($h(z)$), although we did not highlight this feature for our application; users can change it with the point-and-click model if they want to explore scenarios with removal. Finally, the model includes immigration ($I$) to and emigration ($E$) from each pool, regardless of individual length.




**EXPLANATION**

[Figure adapted from Coles and others (2023); graphic by NOAA Fisheries (2026)]

| | |
|---|---|
| ***n(z,t)*** | **is either the length distribution (*z*) of fish at the current time step (*t*) or the length distribution (*z′*) at the next time step (*t*+1),** |
| ***z*** | **is the length of a fish at the current time step (*t*),** |
| ***z′*,** | **is the length of a fish at the next time step (*t*+1),** |
| ***t*** | **is time step,** |
| ***t*+1** | **is the next time step,** |
| ***s(z)*** | **is the survival as a function of length (*z*),** |
| ***G(z,z′)*** | **is the growth kernel from the current length (*z*) to the length (*z′*) at the next time step (*t*+1),** |
| ***h(z)*** | **is proportion of fish as a function of fish length (*z*),** |
| $p_b$ | **is the probability of successful female spawning,** |
| **egg*(z)*** | **is the number of eggs produced per female as a function of length (*z*),** |
| ***v*** | **is probability that an egg transitions to become an age–1 individual, and** |
| $C_1(z')$ | **is the length distribution at the next time step (*z′*) for recruits.** |

**Figure 2.** Life cycle diagram of the Metapopulation Integral Projection Model (MetaIPM) following the life cycle of *Ictalurus furcatus* (Valenciennes in Cuvier and Valenciennes, 1840; blue catfish). Within the model, a census occurs at time step *t* that keeps track of the distribution of the length of fish *z*. Reproduction then occurs, which includes the product of the probability of reproduction and the number of eggs produced as a function of fish length *z*. A fork in the life cycle diagram occurs. Eggs mature to age-1 fish with probability *v* and then become adults in the model with a length *z*-prime following a distribution *C*. Adults take the other fork in the life cycle model and survive with function *s* of length and grow with function *G* of current length and length at the next time step. Adults may also be harvested as a function of length with function *h* of *z*. The forks then converge for the next census at time step *t*+1. This junction also includes immigration and emigration before repeating to the next time step. Refer to the "Methods" section for detailed parameter explanations.

MetaIPM requires detailed information for each target species, including data on groups, pool- or node-level structure, and network connectivity. The model depends on several demographic data types, such as length–weight regressions, female length–maturity curves, growth curves, spawning and recruitment estimates (stock–recruitment relation), and movement probabilities among pools. Although these data are essential, pool-specific population data for fishes in the Upper Mississippi River is sparse, and sometimes nonexistent for the Mississippi River Basin as a whole. To address these gaps, data from lake and river systems across North America were incorporated to help identify native species locations (in contrast to nonnative or invaded ranges). When raw data were not provided in source materials, the metaDigitise package version 1.0.1 (Pick and others, 2019) in R version 4.4.1 (R Core Team, 2024) was used to extract numerical values from relevant published figures. All data were converted to kilograms and meters. When pool-specific data did not exist, averaged values from across all locations were applied (table 1).

The literature review (app. 1, tables 1.1–1.3) began with searches in Google Scholar and Google for demographic rates and species-specific data and expanded through communication with agency biologists working within the study system (Sara Tripp, Missouri Department of Conservation, written commun., 2024) and others working in the system (Kaitlyn Bearden and Alison Coulter, South Dakota State University, written commun., 2024). Species incorporated into the model include *Ictalurus furcatus* (Valenciennes in Cuvier and Valenciennes, 1840; blue catfish), *Ictiobus cyprinellus* (Valenciennes in Cuvier and Valenciennes, 1844; bigmouth buffalo), lake sturgeon, *Polyodon spathula* (Walbaum, 1792; American paddlefish [paddlefish]), *Ictiobus bubalus* (Rafinesque, 1818; smallmouth buffalo), shovelnose sturgeon, and invasive silver carp. Species selection was guided by dialogue with those involved with Upper Mississippi River management (such as State and Federal agencies) and by the availability of usable data. Silver carp parameter values were extracted from previous modeling applications (Kallis and others, 2023; Frame and others, 2025).

Slope and intercept coefficients were documented for the length–weight regressions and the female length–maturity (binomial) regression coefficients for each species. Gengerke (1978), Koch and others (2009), and Hupfeld and others (2016) provide a minimum of four length–weight regression coefficients per species, although only five coefficients originated directly from Upper Mississippi River populations. Published sources contain few female length–maturity curves, most species having only one available estimate, with paddlefish being the exception. The literature did not report estimates for female smallmouth buffalo length–maturity curves; therefore, bigmouth buffalo estimates served as placeholders, with recognition that these values may not represent true species length–maturity relations. The female bigmouth buffalo length–maturity data derive from smaller-than-average individuals and may not reflect current population size distributions (Johnson, 1963). Blue catfish female length–maturity curves were applied to both sexes, though these estimates may not represent 2026 fish distributions in the Upper Mississippi River (Perry and Carver, 1977). Except for paddlefish, all female length–maturity

**Table 1.** Average Metapopulation Integral Projection Model input parameter estimates for native species' length–weight regressions (L–W slope and intercept), growth (*Cm*, $L_\infty$, *K*, and $T_0$), and female length–maturity curves (maturity slope and intercept).

[All values are averaged from various studies across North America. Refer to the "Methods" section for detailed parameter explanations. L, length; W, weight; *Cm*, conditional natural mortality; $L_\infty$, theoretical maximum length at time=∞; *K*, growth coefficient; $T_0$, theoretical time when length is 0 ; —, no data]

| Species | L–W slope | L–W intercept | *Cm* | $L_\infty$ | *K* | $T_0$ | Maturity slope | Maturity intercept |
|---|---|---|---|---|---|---|---|---|
| *Ictiobus cyprinellus* (Valenciennes in Cuvier and Valenciennes, 1844; bigmouth buffalo) | 3.170 | 1.273 | — | 0.750 | 0.235 | −1.030 | 39.280 | −16.960 |
| *Ictalurus furcatus* (Valenciennes in Cuvier and Valenciennes, 1840; blue catfish) | 3.309 | 1.021 | 0.018 | 1.076 | 0.070 | −0.765 | 9.420 | −4.438 |
| *Acipenser fulvescens* (Rafinesque, 1817; lake sturgeon) | 3.248 | 0.613 | 0.062 | 1.531 | 0.064 | −2.325 | 25.830 | −35.630 |
| *Polyodon spathula* (Walbaum, 1792; American paddlefish [paddlefish]) | 3.195 | 0.997 | 0.128 | 1.114 | 0.170 | −1.683 | 21.108 | −20.150 |
| *Scaphirhynchus platorynchus* (Rafinesque, 1818; shovelnose sturgeon) | 3.323 | −0.025 | 0.067 | 0.745 | 0.186 | −0.830 | 11.237 | −9.117 |
| *Ictiobus bubalus* (Rafinesque, 1818; smallmouth buffalo) | 2.988 | 1.213 | — | 0.226 | 0.538 | −0.534 | — | — |

values originated from populations outside the Mississippi River. Parameter values from the Von Bertalanffy growth models (VBGM) appear more frequently in the literature than other model parameters. The VBGM parameters come from a variety of geographic locations, and most species have at least one Mississippi River-specific value, including two pool-specific growth studies for shovelnose sturgeon and smallmouth buffalo (Koch and others, 2009; Maxson and others, 2024). No natural mortality estimates were reported for bigmouth buffalo or smallmouth buffalo, so an arbitrary placeholder value of 0.01 was applied.

The largest data gaps were in stock-recruitment and movement rates for all species, leading to the use of placeholder parameters for both. These placeholder values were gradated using species- and pool-specific relative abundance estimates from Steuck and others (2010). Smallmouth buffalo and shovelnose sturgeon were categorized as common throughout most of the study area, so the highest spawning–recruitment estimates and movement probabilities were assigned to these species. Bigmouth buffalo were also common across the study area, except in Pool 24 where they were occasional. Paddlefish were occasional throughout the study system. Lake sturgeon were rare in Pools 14–19 and occasional in Pools 20–24. Blue catfish were occasional in Pools 20–24, but only historical records indicate presence in Pools 13–19; therefore, movement and recruitment parameters for these pools were set to zero. Movement values between adjacent pools were assigned higher rates (maximum of 0.5 for species designated as common) than rates between nonadjacent pools (maximum of 0.01 rates for abundant populations). Movement among nonadjacent pools was still permitted because fish can travel across multiple pools within a month, the model's time step, as shown in movements reported by Coulter and others (2018). Stock–recruitment parameters, including average reproductive output ($S_0$), average recruitment ($R_0$), and reproductive steepness ($h$), were scaled from 0 to 5,000 using historical abundance data. For all native species, $R_0$ was set to 10 percent of $S_0$, and reproductive steepness, $h$, was set to one to reflect the generally slow growing and late maturing life histories of species included in this study (table 2).

Deterministic model runs were used because of a paucity of data across most species. Previous applications of MetaIPM and the Spatially Explicit Invasive Carp Population model have used stochastic simulations to explore model uncertainty and variability (Kallis and others, 2023; Erickson and others, 2024). Although stochastic simulations quantify uncertainty and incorporate additional ecological realism, they require more data and longer run times (ranging from hundreds to thousands of times longer, depending on the number of simulations run). Deterministic models have much shorter run times but do not include uncertainty about the system. Given the limited movement and demographic data available, a deterministic model was considered more appropriate and allowed identification of areas with sufficient and insufficient data for each species. Each species was modeled independently, preventing interactions such as competition.

The parameterized models were then used to explore different population-level responses to different upriver passage and upriver deterrent scenarios. Downriver movement probabilities were held constant because the proposed management actions were not expected to influence those rates. Base scenarios did not include management actions. In the absence of formal estimates for increased passage attributable to fishways on the Upper Mississippi River, a conservative placeholder of 25 percent was applied. Preliminary findings from the underwater acoustic deterrent system indicated that 50 percent of silver carp were deterred from moving upriver (Brey and others, 2023). Brey and others (2023) also included bigmouth buffalo and paddlefish, with bigmouth buffalo showing 20-percent deterrence and paddlefish showing no observable deterrence. These findings informed four modeled scenarios:

(1). ***Increase in upriver passage***.—All species experience an increase in upriver passage (25 percent) through Lock and Dam 22;

(2). ***Increase in upriver deterrence***.—Native species experience 20-percent deterrence and invasive carp 50-percent deterrence at Lock and Dam 19;

**Table 2.** Assigned placeholder parameter values for stock–recruitment values ($S_0$, $R_0$, $h$) and movement probabilities based on relative abundance estimates.

[Data are from Steuck and others (2010). Fishes may move between populations in adjacent and nonadjacent (distant) pools in which they are currently established. Refer to "Methods" section for detailed parameter explanations. $S_0$, average reproductive output, $R_0$, average recruitment; $h$, reproductive steepness]

| Relative abundance | $S_0$ | $R_0$ | $h$ | Movement to adjacent pools | Movement to distant pools |
|---|---|---|---|---|---|
| Common | 4,000 | 400 | 1 | 0.050 | 0.010 |
| Occasional | 3,000 | 300 | 1 | 0.030 | 0.005 |
| Uncommon | 2,000 | 200 | 1 | 0.010 | 0.003 |
| Rare | 1,000 | 100 | 1 | 0.005 | 0.001 |
| Historical | 0 | 0 | 0 | 0.000 | 0.000 |

(3). ***Increase in upriver passage and upriver deterrence***.—All species experience increased passage (25 percent) through Lock and Dam 22 and increased deterrence (50-percent invasive, 20-percent native) at Lock and Dam 19; and

(4). ***Idealized management comparison***.—Only native species passage increases to 25 percent through Lock and Dam 22, and only silver carp are deterred by 50 percent at Lock and Dam 19.

Lacking empirical evidence, a conservative deterrence value of 20 percent was applied to represent a possible negative effect across all native species. Simulated changes to passage and deterrence represent total movement upriver from the selected lock and dam, regardless of route. Deterrence rates were held constant throughout the year. These scenarios were selected to illustrate how passage and deterrent strategies may influence metapopulation dynamics of native migrants and invasive carp as a proof-of-concept application.

The model was implemented using Python version 12.0, with version control provided through conda version 2-4.3.0. We used multiple Jupyter Notebooks (version 2.0) to interact with version 2.0.1 of the MetaIPM (Erickson and others, 2023). Each scenario was simulated for a minimum of 100 years to ensure that populations reached equilibrium. R version 4.4.1 (R Core Team, 2024) and the ggplot2 version 3.5.1 (Wickham, 2016) were used to graph deviations of final population sizes for each species and scenario from the base predictions (no increases to passage or deterrence). A Python Shiny based point-and-click interface, designed to operate in the cloud without the need for local installation, has been released as part of the U.S. Geological Survey (USGS) software packaging supporting this study (Labuzzetta and others, 2025). This point-and-click model uses the input parameters described in this report.

# Results

The simulated fishway and deterrent affected metapopulation dynamics across the simulated Upper Mississippi River study system. Long-lived fish, like sturgeon, required longer simulation periods to reach equilibrium than shorter lived species. The passage scenario demonstrated that a functioning fishway at Lock and Dam 22 could increase species populations in all upriver pools. Simulated lake sturgeon metapopulations appeared to be the most affected by increased passage rates; however, all species experienced small (less than 5 percent) increases in upriver populations at the 25-percent rate. Populations in Pool 24 declined for all species when passage at Lock and Dam 22 increased. Under the deterrence scenario (50-percent deterrence for silver carp and 20-percent deterrence for native species at Lock and Dam 19), all species showed population declines in the upriver pools (fig. 3). Lake sturgeon, shovelnose sturgeon, and silver carp had the largest upriver declines in all pools, whereas paddlefish, bigmouth buffalo, and smallmouth buffalo had smaller declines in all upriver populations. The combined passage-and-deterrence scenario indicated that deterrence at Lock and Dam 19 exerted a stronger influence on upriver metapopulation dynamics than increased passage at Lock and Dam 22. Populations increased in Pools 20–22 but then had minor declines in all pools upriver of the deterrent (Pools 14–19). These findings were consistent across species, including silver carp (fig. 3).

The idealized passage-and-deterrence scenario explored the implications of increasing native species passage, while applying deterrence to silver carp simultaneously. Under this scenario, the model indicated consistent increases in native species' population upriver of Lock and Dam 22 for native species, accompanied by declines in source populations in Pool 24 (fig. 4). In contrast, downriver movement probabilities remained unchanged. Silver carp showed a general population increase in downriver pools (20–24) but had larger population decreases in upriver pools (14–19) after the deterrent (fig. 4). Blue catfish metapopulation trends did not include pools upriver of Lock and Dam 19, consistent with the assumption that they no longer move or spawn in Pools 14–19 (Wilcox and others, 2004; Steuck and others, 2010).

# Discussion

Changing simulated connectivity by increasing or decreasing passage affected the metapopulation dynamics of multiple native species and the invasive silver carp in the Upper Mississippi River. Simulations of increased passage rates generally increased populations upriver of the passage site. Increasing passage of native species and decreasing passage of invasive silver carp improved upriver populations of native species and decreased upriver populations of invasive silver carp. These simulations suggest that combined deterrence and fishway efforts may mitigate tradeoffs between native and invasive species management by increasing native species upriver presence while decreasing invasive species upriver presence. Although these simulations demonstrate potential management strategies for increasing upriver populations of established species, they could also be used to explore the reestablishment of upriver populations. For example, blue catfish in the Upper Mississippi River historically made large annual movements upriver in the spring and downriver in the fall (Jordan and Evermann, 1923; Coker, 1930). After dam construction and river regulation, populations upriver of Lock and Dam 19 are now considered uncommon (Wilcox and others, 2004) or historical (Steuck and others, 2010). The model allows management agencies and other stakeholders to explore strategies that could help restore connectivity and reestablish historical populations, such as blue catfish.

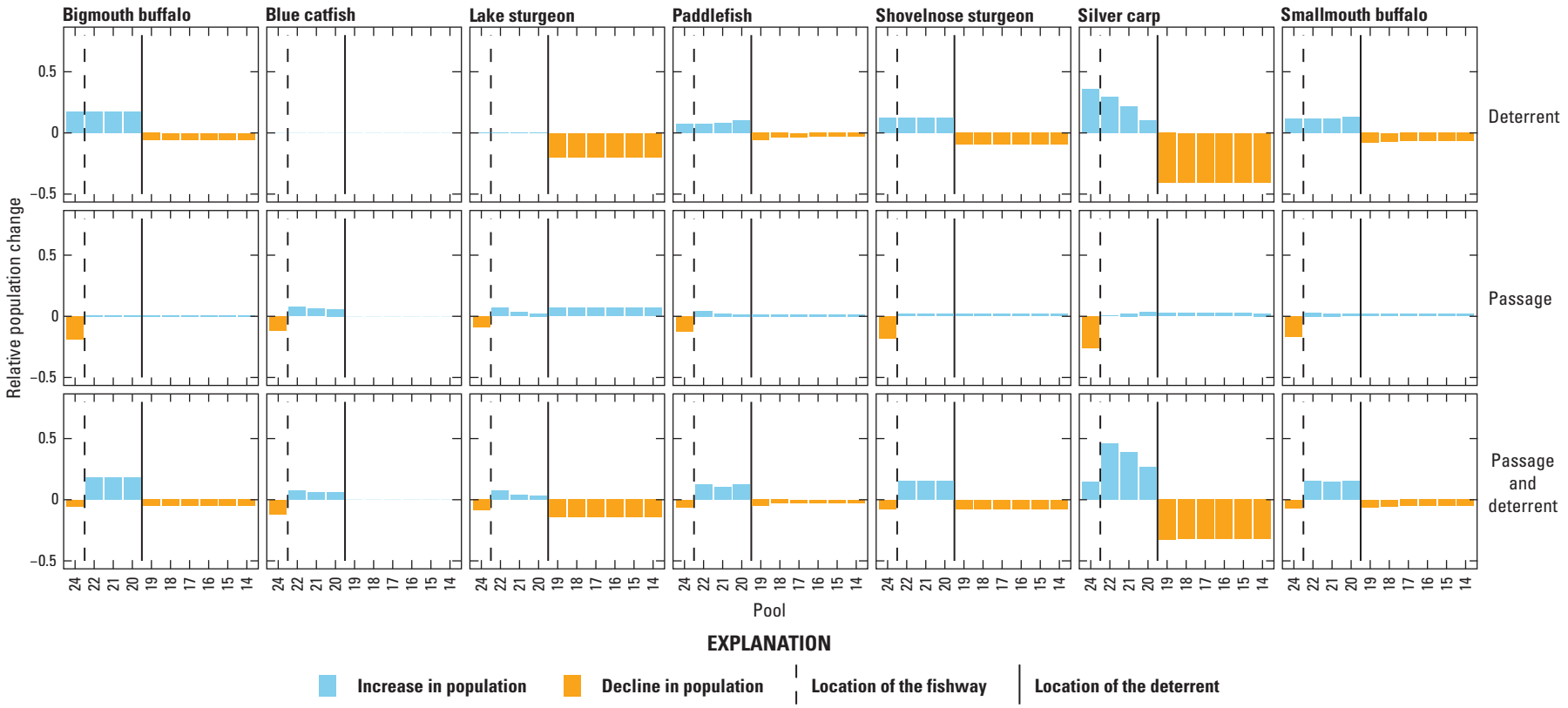



**Figure 3.** Bar graph showing relative population changes by pool under each management scenario for each species. For respective scenarios, deterrence is set at 20 percent for native and 50 percent for *Hypophthalmichthys molitrix* (Valenciennes in Cuvier and Valenciennes, 1844; silver carp; Brey and others, 2023), and passage is set at 25 percent for all species.

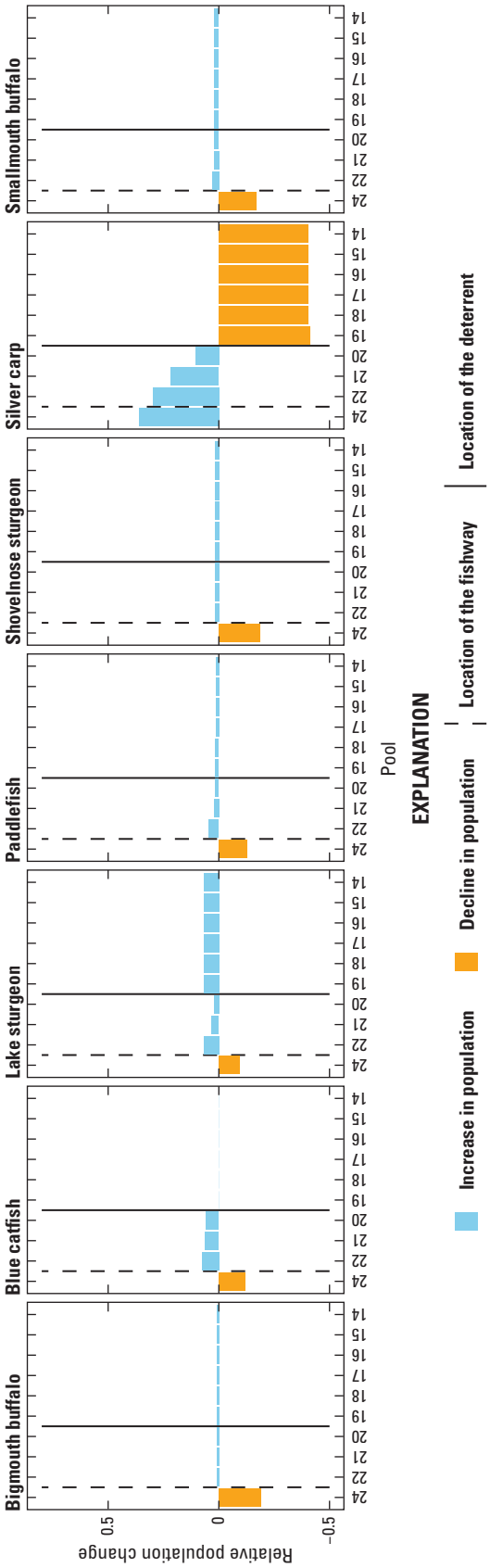



**Figure 4.** Bar graph showing an ideal management scenario in which native passage increases (25 percent) and *Hypophthalmichthys molitrix* (Valenciennes in Cuvier and Valenciennes, 1844; silver carp) passage decreases (50 percent).

These modeling efforts also highlight areas of sufficient and deficient demographic data. Despite the relatively large body of literature across North America, data specific to the Mississippi River system are sparse, with even fewer studies containing pool-specific data for the Upper Mississippi River. As a result, parameter estimates were either unavailable or highly generalized. For all species, sufficient length–weight and Von Bertalanffy growth data existed and generally included populations from the Upper Mississippi River, but only one study (Koch and others, 2009) had pool-specific data. Female length–maturity data were the most deficient across species. No fish population estimates existed specifically from the Upper Mississippi River, and only four of the six native fish had even a single estimate available from other regions of the United States. No estimates existed for smallmouth buffalo. This highlights the need for pool-specific research because these species often show phenotypic plasticity among pools regarding size, age, mortality, growth, and maturation (Koch and others, 2009; Hamel and others, 2015; Devine and others, 2020). Without pool-specific data, only broad-scale population predictions can be made, which may not capture fine-scale metapopulation dynamics.

Understanding and estimating long-term population trends requires additional data on spawning and recruitment rates. Variability in spawning behavior and locations directly influences reproduction estimates, necessitating an understanding of each species' life histories throughout the study system. Several studies suggest that species such as shovelnose sturgeon, lake sturgeon, and paddlefish concentrate in their respective spawning areas (Knights and others, 2002; Tripp and others, 2009; Buszkiewicz and others, 2016). Depending on the locations of spawning sites and downriver drift of eggs, spawning could cause extreme variation in reproductive biomass and recruitment among pools; pools with high spawning or immediately downriver may be more susceptible to harvest during spawning months (Knights and others, 2002). Pool-specific natural mortality estimates were rarely available. Mortality data could help outline source–sink population dynamics that would aid future restoration and recovery efforts (Tripp and others, 2019a). Addressing these demographic knowledge gaps, particularly surrounding female length–maturity and reproduction parameters, at the pool level is necessary for understanding metapopulation dynamics throughout the Upper Mississippi River. These data gaps also highlight the importance of coordinated interstate monitoring and management.

The largest knowledge gap concerns interpool movement parameters, which prior model exploration and sensitivity analyses indicate are more important than other parameters (Erickson and others, 2024). A variety of factors— species, life-history types, river hydrology, and seasonality—affect movement probabilities (Zigler and others, 2004; Tripp and others, 2019b; Turney and others, 2022). For example, a study at Lock and Dam 15 found bigheaded carps present in the lock approach between May and September, whereas paddlefish showed increased residency from April to May

(Turney and others, 2022). At that location, use of a deterrent in midsummer may be effective for managing bigheaded carps while limiting effects on paddlefish. Incorporating seasonal movement patterns into the model could allow managers to explore such scenarios to identify effective approaches for limiting upriver expansion of silver carp and increasing passage for target species. Upriver and downriver movement data provide insight into the source–sink populations dynamics (Pracheil and others, 2015). Under open-river hydrologic conditions, movement probabilities increase among pools, with nearly all passage for lake sturgeon, shovelnose sturgeon, and paddlefish occurring during such conditions (Buszkiewicz and others, 2016; Phelps and others, 2016; Tripp and others, 2019a; Turney and others, 2022; Fritts and others, 2024b). Conversely, during controlled-river conditions, invasive silver carp are more successful than native species at passing upriver (Tripp and others, 2019a).

The structure and location of a lock and dam further affect pool-to-pool movement probabilities and determine how often and when each dam enters open-river condition (Zigler and others, 2004). Lock and Dam 19 and Lock and Dam 14 are the largest barriers to upriver fish movement (Wilcox and others, 2004; Anderson and others, 2024). The dam at Lock and Dam 19 has never gone into open-river conditions, and Lock and Dam 14 averages less than 2 percent of the year in open-river conditions (Wilcox and others, 2004; Bouska, 2021). Because empirical data were scarce, movement probabilities were estimated as monthly averages across the year. A similar data gap exists for long-term population trends for several species (fig. 3). Species-specific movement probabilities would provide clearer insight into population trends, especially as extreme weather events (droughts, floods, and open-river days) change over time (Turney and others, 2022).

Considerable uncertainty also exists regarding deterrence rates because they vary by placement, type, and species. Preliminary reports indicate that silver carp are twice as likely to pass an experimental underwater acoustic deterrent system when it is off compared to on; bigmouth buffalo were 1.2 times more likely to pass when the system was off; and some native species in the study were not meaningfully affected (Brey and others, 2023). Other deterrent types, especially electricity, carbon dioxide, or bubble curtains, may produce different deterrence outcomes (Cupp and others, 2021a, 2021b; Fritts and others, 2023). As species-specific data increases for passage and deterrence, simulations may better reflect these unique long-term population trends. As new deterrent systems and fishways are developed, understanding each system's effects on native and invasive fish populations will be vital.

Available data for species in this study lacked standardization and organization, creating challenges for data-driven interjurisdictional management. MetaIPM requires data for length, weight, sex, maturity, and age to estimate demographic parameters. Many studies reported some of these variables but rarely all. For example, length was often collected but frequently reported without weight or sex, and some studies reported only part of a model function (such as reporting the slope but not the intercept). Movement data were often not reported in formats that support estimating movement probabilities among pools. Although many projects collect movement data (such as those described by Comte and Olden, 2018), the lack of a centralized repository means contacting data collectors and reformatting datasets for analysis. These data collections also span management agencies, each with different objectives and jurisdiction; interjurisdictional movements are therefore often not captured. A lack of coordination may also lead to inconsistent management practices across jurisdictional boundaries (Hupfeld and others, 2016; Porreca and others, 2016; Devine and others, 2020). Standardizing data collection and formatting would assist with interagency collaboration, especially for migratory species with interjurisdictional home ranges.

Efforts to improve data collaboration and coordination exist. Several data-collection and archive projects are ongoing or under development for the Upper Mississippi River, including those led by the Upper Mississippi River Restoration Long Term Resource Monitoring element (Sparks, 2010). For paddlefish, the Mississippi Interstate Cooperative Resource Association (MICRA) began a large-scale, multiagency tag-and-release study in 1995, resulting in a stock-assessment database containing mark–recapture and biometric information for more than 2 million individuals (Grady and others, 2005; Sharov and others, 2014). The Long Term Resource Monitoring element has monitored fish in Upper Mississippi River and Illinois Waterway trend pools since 1986, using standardized scientific methods and a centralized database at the USGS's Upper Midwest Environmental Sciences Center. The USGS has also expanded the interagency telemetry data archive known as the Riverine Acoustic Fish Telemetry (RAFT) network, a node of the Ocean Tracking Network, to archive multiagency fish-movement data from invasive carp and native fish (https://usgs.gov/apps/raft). The RAFT network allows research teams to expand study areas through information sharing and highlights the utility of coordinated fisheries data throughout the system.

The point-and-click interface allows researchers, managers, and other stakeholders to modify scenarios without coding experience. Adaptable functions include changes in passage, deterrence, spawning locations, recruitment rates, initial population sizes, and fish removals. These functions can support exploration of recruitment enhancement, monitoring of commercial and recreational fisheries, and comparison of management alternatives across interjurisdictional units. Additional model expansions could incorporate habitat data and interspecies interactions. Species require specific habitats for different life-history stages (Southall and Hubert, 1984; Zigler and others, 2003; Phelps and others, 2010), and habitat quality influences population dynamics (Maki-Petäys and others, 1997; Stunz and Minello, 2001). The lock-and-dam system also creates habitat differences among pools, driving

differences in fish community structures (Anderson and others, 2024). Integration of the Upper Mississippi River System Environmental Management Program Habitat Needs Assessment (Theiling and others, 2000) and its GIS Query Tool (DeHaan and others, 2000) with this model could help assess long-term population persistence relative to habitat availability. Understanding habitat contributions to successful reproduction and interactions affecting recruitment would further improve model applicability. Identifying limiting factors could help to combat the predicted declines in shovelnose sturgeon and paddlefish (Tripp and others, 2009) and heightened susceptibility of fishes in Pools 20–26 (Hamel and others, 2015).

This study highlights the potential for a fishway at Lock and Dam 22 to support management strategies aimed at increasing upriver populations of native fish. Improving or reestablishing connections among fragmentated populations could improve gene flow and population viability (Bunt and others, 2012; Pracheil and others, 2012). Fishways within navigation dams that currently (2024) act as barriers to upriver movement may provide opportunities to reconnect disjunct movement pathways throughout the river system (Wilcox and others, 2004). As empirical data continues to accumulate, tools such as the MetaIPM point-and-click interface could support planning for deterrent systems and passage structures. Modeling tools may also allow stakeholders to compare tradeoffs between native fish passage and invasive species deterrents.

The MetaIPM point-and-click interface provides a new decision-support management tool by comparing various fish passage scenarios for invasive and native species. Although large data gaps exist around the target species, the model was able to project long-term population trends associated with increased passage (specifically, fishway development) and the implementation of deterrents. This tool could be adapted to other river systems and applied to a wide range of species. As part of this model expansion, additional work could include ground-truthing the model to evaluate how it performs compared to empirical observations. The ease of use of the MetaIPM point-and-click interface enables stakeholders with minimal coding experience to easily explore management scenario outcomes for a wide variety of projects. As knowledge gaps are filled, data can be easily added to model parameters. Additionally, complexity such as stochasticity could be incorporated into point-and-click models if managers and other stakeholders express interest in these model features.

# Conclusions

The U.S. Geological Survey applied a metapopulation modeling framework (MetaIPM) to simulate how changes in fish passage at Upper Mississippi River lock-and-dam structures may affect six native fish species and invasive silver carp. Simulations of increased passage generally produced larger populations upriver of the passage site, whereas deterrence reduced upriver movement and population sizes. The idealized scenario of increasing native passage while deterring silver carp simultaneously increased native populations and decreased invasive silver carp upriver, indicating that combined deterrence and fishway efforts appear to offer the best balance between native fish conservation and invasive species management. These efforts also revealed substantial data gaps, particularly for interpool movement, female length–maturity, and stock–recruitment parameters, along with a lack of standardized, pool-specific data across jurisdictions—limitations that constrain fine-scale projections and underscore the value of coordinated interstate monitoring. As empirical data accumulate and these gaps are filled, the MetaIPM point-and-click interface provides a transferable decision-support tool that enables managers and stakeholders with minimal coding experience to explore scenarios, compare tradeoffs, and refine projections for passage and deterrent planning throughout the Upper Mississippi River and other river systems.

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# Appendix 1. Sources for Model Inputs

These tables contain literature sources used for model inputs.

**Table 1.1.** Generalized linear model parameters for the proportion of mature females at length and the original study citation with the corresponding location.

| Species | Locality | Slope | Intercept | Citation |
|---|---|---|---|---|
| *Ictiobus cyprinellus* (Valenciennes in Cuvier and Valenciennes, 1844; bigmouth buffalo) | Qu'Appelle River, Manitoba | 39.280 | −16.960 | Johnson, 1963 |
| *Ictalurus furcatus* (Valenciennes in Cuvier and Valenciennes, 1840; blue catfish) | Louisiana | 9.420 | −4.438 | Perry and Carver, 1977 |
| *Acipenser fulvescens* (Rafinesque, 1817; lake sturgeon) | Winnebago System, Wisconsin (Female) | 25.830 | −35.630 | Bruch, 2008 |
| *Polyodon spathula* (Walbaum, 1792; American paddlefish [paddlefish]) | Mississippi River Basin | 12.300 | −12.400 | Sharov and others, 2014 |
| | Kentucky Lake, Tennessee and Kentucky | 30.540 | −29.920 | Colvin and others, 2013 |
| | Lower Mississippi River | 22.430 | −20.470 | Risley and others, 2017 |
| | Mississippi and Ohio Rivers | 19.160 | −17.810 | Wilberg, 2019 |
| *Scaphirhynchus platorynchus* (Rafinesque, 1818; shovelnose sturgeon) | Wabash River, Indiana | 11.237 | −9.117 | Kennedy and others, 2006 |

**Table 1.2.** Logistic regression parameters for the length–weight relationship and the originating study citation with the corresponding location.

[—, no data]

| Locality | Slope | Intercept | Citation |
|---|---|---|---|
| *Ictiobus cyprinellus* (Valenciennes in Cuvier and Valenciennes, 1844; bigmouth buffalo) | | | |
| Oahe Lake, North Dakota and South Dakota | 3.132 | 1.128 | Nelson, 1974 |
| Across United States | 3.118 | 1.285 | Bister and others, 2000 |
| Qu'Appelle River, Manitoba, Canada | 3.440 | 1.383 | Bryshun, 2023 |
| Qu'Appelle River, Manitoba, Canada | 2.886 | 1.301 | Johnson, 1963 |
| Clark Lake, Michigan | 3.276 | 1.268 | Walburg and Nelson, 1966 |
| *Ictalurus furcatus* (Valenciennes in Cuvier and Valenciennes, 1840; blue catfish) | | | |
| Mississippi River | 3.454 | 1.105 | Winders and McMullen, 2019 |
| Missouri River | 3.141 | 1.020 | |
| Alabama | 3.354 | 1.062 | Graham, 1999 |
| Kentucky | 3.342 | 1.105 | |
| Missouri | 3.283 | 0.826 | |
| South Carolina | 3.406 | 1.063 | |
| Texas | 3.368 | 0.825 | |
| Lake Wilson, Alabama | 3.452 | 1.106 | Holley and others, 2009 |
| Tennessee | 3.210 | 1.040 | Stewart and others, 2009 |
| Mississippi River | 3.100 | 0.970 | |
| Mississippi River | 3.454 | 1.105 | Winders and McMullen, 2019 |
| Missouri River | 3.141 | — | |
| *Acipenser fulvescens* (Rafinesque, 1817; lake sturgeon) | | | |
| Mississippi River | 3.119 | 0.872 | Buszkiewicz and others, 2016 |
| Manitoba | 3.070 | −0.610 | Nelson and others, 2022 |
| Manistee River, Michigan | 3.170 | 0.990 | Lallaman and others, 2008 |
| Namakan Reservoir, Minnesota and Ontario | 3.448 | 1.199 | Shaw and others, 2012 |
| *Polyodon spathula* (Walbaum, 1792; American paddlefish [paddlefish]) | | | |
| Upper Mississippi River | 2.740 | 1.120 | Hupfeld and others, 2016 |
| Upper Mississippi River | 3.380 | 0.700 | Gengerke, 1978 |
| | 2.540 | 0.900 | |
| | 3.920 | 0.730 | |
| Lower Mississippi River | 3.037 | 0.400 | S.J. Tripp, J.E. Garvey, and A. Asher, Southern Illinois University, unpub. Data, 2012 |
| Lower Mississippi River | 3.258 | 1.149 | Risley and others, 2017 |
| Mississippi River Basin | 3.092 | 1.249 | Grady and others, 2005 |
| Arkansas River, Arkansas | 3.445 | 1.197 | Leone and others, 2012 |
| Mississippi and Ohio Rivers | 3.389 | 1.102 | Wilberg, 2019 |
| Kentucky Lake, Tennessee and Kentucky | 3.149 | 1.419 | Hoffnagle and Timmons, 1989 |
| *Scaphirhynchus platorynchus* (Rafinesque, 1818; shovelnose sturgeon) | | | |
| Wabash River Indiana | 3.424 | −0.360 | Kennedy and others, 2006 |
| Upper Mississippi River, Pools 4–18 | 3.330 | −0.011 | Koch and others, 2009 |

**Table 1.2.** Logistic regression parameters for the length–weight relationship and the originating study citation with the corresponding location.—Continued

[—, no data]

| Locality | Slope | Intercept | Citation |
|---|---|---|---|
| *Scaphirhynchus platorynchus* (Rafinesque, 1818; shovelnose sturgeon)—Continued | | | |
| Missouri River | 3.340 | −0.014 | Quist and others, 2002 |
| | 3.330 | −0.014 | |
| | 3.190 | 0.276 | |
| *Ictiobus bubalus* (Rafinesque, 1818; smallmouth buffalo) | | | |
| Oahe Lake, North Dakota and South Dakota | 3.166 | 1.260 | Nelson, 1974 |
| Across United States | 3.208 | 1.326 | Bister and others, 2000 |
| Clark Lake, South Dakota | 3.020 | 1.117 | Walburg and Nelson, 1966 |
| Clinch River, Virginia | 2.559 | 1.149 | Martin and others, 1964 |

**Table 1.3.** Von Bertalanffy Growth Model parameters with the original study citation and the corresponding study location.

[Parameters include *Cm,* conditional natural mortality; $L_\infty$, theoretical maximum length at time=∞; *K,* growth coefficient, and $T_0$, theoretical time when length is 0 ($T_0$). —, no data]

| Locality | *Cm* | $L_\infty$ | *K* | $T_0$ | Citation |
|---|---|---|---|---|---|
| *Ictiobus cyprinellus* (Valenciennes in Cuvier and Valenciennes, 1844; bigmouth buffalo) | | | | | |
| Iowa | — | 0.607 | 0.398 | 0.402 | Meerbeek, 2022 |
| | — | 0.607 | 0.398 | 0.402 | |
| | — | 0.795 | 0.174 | −2.279 | |
| | — | 0.765 | 0.232 | −0.946 | |
| | — | 0.818 | 0.139 | −2.979 | |
| | — | 0.808 | 0.225 | −1.459 | |
| North Dakota[1] | — | 0.746 | 0.173 | −0.690 | Lackmann and others, 2021 |
| North Dakota[2] | — | 0.850 | 0.144 | −0.690 | |
| *Ictalurus furcatus* (Valenciennes in Cuvier and Valenciennes, 1840; blue catfish) | | | | | |
| Oklahoma | — | 0.898 | 0.063 | −0.665 | Boxrucker and Kuklinski, 2006 |
| | — | 0.853 | 0.136 | −0.151 | |
| | — | 0.860 | 0.133 | −0.919 | |
| | — | 0.964 | 0.077 | −1.843 | |
| | — | 1.050 | 0.095 | 0.114 | |
| Kansas River, Kansas | — | 0.941 | 0.120 | −0.560 | Dean, 2020 |
| Mississippi River | — | 1.243 | 0.080 | −0.771 | Winders and McMullen, 2019 |
| Missouri River | — | 1.294 | 0.070 | −0.061 | |
| Kansas and Missouri Rivers | 0.010 | — | — | — | Dean and others, 2022 |
| | 0.020 | — | — | — | |
| | 0.030 | — | — | — | |
| Oklahoma | 0.010 | 0.882 | 0.040 | −2.510 | Griffin and others, 2022 |
| Lake Wilson, Alabama | — | 1.303 | 0.081 | −0.243 | Holley and others, 2009 |
| Ohio River | — | 1.413 | 0.063 | −1.248 | Siegel, 2021 |
| Mississippi River | — | 0.830 | −0.145 | −1.019 | Stewart and others, 2009 |
| Mississippi River | — | 1.243 | 0.086 | −0.771 | Winders and McMullen, 2019 |
| Missouri River | — | 1.294 | 0.077 | −0.061 | |
| *Acipenser fulvescens* (Rafinesque, 1817; lake sturgeon) | | | | | |
| Attawapiskat River, Ontario | 0.055 | 1.421 | 0.040 | — | Bruch and others, 2016 |
| Lake Huron | — | 1.632 | 0.090 | — | |
| Lake Nipissing, Ontario | — | 1.654 | 0.080 | — | |
| Ottawa River, Ontario and Quebec | — | 1.319 | 0.060 | — | |
| Rainy River, Minnesota and Ontario | — | 1.665 | 0.060 | — | |
| Winnipeg River, Ontario and Manitoba | 0.020 | 1.664 | 0.060 | — | |
| Black Lake, Michigan | 0.076 | 1.769 | 0.056 | −0.8815 | Baker, 1980 |
| Ottawa | — | 1.138 | 0.075 | −2.990 | Haxton and Findlay, 2008 |
| | — | 1.473 | 0.066 | −0.850 | |
| | — | 1.289 | 0.061 | −3.000 | |
| | — | 1.191 | 0.087 | −1.540 | |
| Winnebago System, Wisconsin[1] | 0.081 | 1.664 | 0.052 | −4.527 | Bruch, 2008 |
| Winnebago System, Wisconsin[2] | 0.071 | 1.889 | 0.045 | −2.485 | |

**Table 1.3.** Von Bertalanffy Growth Model parameters with the original study citation and the corresponding study location. —Continued

[Parameters include *Cm,* conditional natural mortality; $L_\infty$, theoretical maximum length at time=∞ ; *K,* growth coefficient, and $T_0$, theoretical time when length is 0 ($T_0$).—, no data]

| Locality | *Cm* | $L_\infty$ | *K* | $T_0$ | Citation |
|---|---|---|---|---|---|
| *Polyodon spathula* (Walbaum, 1792; American paddlefish [paddlefish]) | | | | | |
| Upper Mississippi River | 0.170 | 1.383 | 0.070 | −0.165 | Hupfeld and others, 2016 |
| Lower Mississippi River | — | 1.134 | 0.100 | −4.334 | S.J. Tripp, J.E. Garvey, and A. Asher, Southern Illinois University, unpub. data, 2012 |
| | — | 1.132 | 0.130 | −2.649 | |
| | — | 1.185 | 0.094 | −4.383 | |
| Mississippi River Basin | — | 1.073 | 0.298 | −1.330 | Sharov and others, 2014 |
| | — | 1.072 | 0.290 | −0.710 | |
| Lower Mississippi River | 0.180 | 1.083 | 0.137 | −0.941 | Risley and others, 2017 |
| Arkansas River | 0.070 | 0.992 | 0.218 | −0.298 | Leone and others, 2012 |
| Mississippi and Ohio Rivers | 0.093 | 0.973 | 0.190 | −0.340 | Wilberg, 2019 |
| *Scaphirhynchus platorynchus* (Rafinesque, 1818; shovelnose sturgeon) | | | | | |
| Wabash River, Indiana | 0.028 | 0.825 | 0.122 | −1.998 | Kennedy and others, 2006 |
| Lower Mississippi River | 0.020 | 0.730 | 0.213 | −0.972 | Morrow and others, 1998 |
| Upper Mississippi River Pools 4–18 | 0.100 | 0.767 | 0.219 | −0.202 | Koch and others, 2009 |
| Upper Mississippi River Pool 14 | 0.100 | 0.756 | 0.261 | 0.003 | |
| Upper Mississippi River Pool 16 | 0.100 | 0.681 | 0.252 | −0.088 | |
| Upper Mississippi River Pool 18 | 0.100 | 0.760 | 0.218 | −0.250 | |
| Wabash River, Indiana | 0.020 | 0.771 | 0.141 | −1.413 | Nepal KC and others, 2015 |
| Middle Mississippi River | — | 0.792 | 0.160 | −1.540 | Tripp and others, 2009 |
| | — | 0.781 | 0.130 | −1.230 | |
| | — | 0.771 | 0.140 | −1.130 | |
| | — | 0.812 | 0.110 | −1.990 | |
| Missouri River | 0.070 | 0.660 | 0.273 | −0.269 | Quist and others, 2002 |
| | — | 0.660 | 0.168 | −0.269 | |
| | — | 0.660 | 0.191 | −0.269 | |
| *Ictiobus bubalus* (Rafinesque, 1818; smallmouth buffalo) | | | | | |
| Middle Mississippi River | — | 0.730 | 0.086 | −5.050 | Love and others, 2019 |
| Upper Mississippi River: Pool 4 | — | 0.125 | 0.619 | 0.160 | Maxson and others, 2024 |
| Upper Mississippi River: Pool 13 | — | 0.261 | 0.747 | 0.050 | |
| Upper Mississippi River: Pool 26 | — | 0.145 | 0.550 | 0.170 | |
| Illinois River | — | 0.136 | 0.528 | 0.030 | |
| Illinois River: Peoria Pool | — | 0.145 | 0.488 | 0.140 | |
| Illinois River: La Grange Pool | — | 0.150 | 0.558 | 0.140 | |
| Middle Mississippi River | — | 0.116 | 0.730 | 0.090 | |

[1]Samples taken at this location were from males.

[2]Samples taken at this location were from females.

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