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Open-File Report 2021–1068

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

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By Max Post van der Burg, David R. Smith, Aaron R. Cupp, Mark W. Rogers, and Duane C. Chapman

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

BAFF	bioacoustic fish fence
NEPA	National Environmental Policy Act
PEA	Programmatic Environmental Assessment
TVA	Tennessee Valley Authority

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Abstract

Controlling range expansion of invasive carp (specifically *Hypophthalmichthys* spp.) on the Tennessee River is important to conserve the ecological and economic benefits provided by the river. We collaborated with State and Federal agencies (the stakeholder group) to develop a decision framework and decision support model to evaluate strategies to control carp expansion in the Tennessee River. Using this decision framework, we assessed the efficacy of various barrier strategies (technologies and locations) on reducing bigheaded carp (*Hypophthalmichthys nobilis* [bighead carp] and *Hypophthalmichthys molitrix* [silver carp]) relative abundance under different patterns and magnitudes of population growth and movement. We also assessed whether or not these strategies induced tradeoffs between reducing bigheaded carp relative abundance and other considerations for public satisfaction, effects on lock operation, and native species. For the purpose of comparing options to control carp in a quantitative framework, we codeveloped a carp population dynamics model with the stakeholder group. We then used the model to compare invasive carp management options within the Tennessee River system. The actions we considered included barrier placement at lock and dam systems and targeted removal through harvest, which were believed to impede upstream carp spread and establishment. To account for the uncertainty in carp population growth and movement rates, the group developed four population models that varied in the underlying population dynamics and population growth rates. The models affected population growth through either the stock-recruitment relation or intrinsic density-dependent growth rate. We then tasked the stakeholder group to test various strategies using the model. We then developed a more formal optimization framework and solved for strategies that performed well under scenarios of barrier effectiveness, movement rate, recruitment frequency, fishing mortality, and variation in population growth rate. The results of our qualitative and quantitative analyses indicated that strategies designed to first protect reservoirs just above the leading edge of carp invasion by installing barriers and removing fish below that point would perform best; however, this depended on barrier effectiveness. When barrier effectiveness was high, simply cutting off the presumed source of carp and blocking the leading the edge was enough to stop carp invasion; however, lower effectiveness meant that more barriers would be needed to slow, but not completely stop, carp invasion. We discuss what these findings mean in terms of future monitoring and management efforts to reduce the potential for expanding carp invasion.

Introduction

The control of invasive carp is a complex issue for fishery and river management throughout the Midwest and southeastern United States. Over the past 30–40 years, four species of invasive carp (*Hypophthalmichthys nobilis* [bighead carp], *Mylopharyngodon piceus* [black carp], *Ctenopharyngodon idella* [grass carp], and *Hypophthalmichthys molitrix* [silver carp]) have spread throughout much of the Mississippi River Basin (hereafter "the basin"; Chick and Pegg, 2001). More recent population estimates have even indicated that some Midwestern States in the basin now support some of the highest silver carp abundances in the world (Sass and others, 2010). Fishery managers within the midwestern and southern parts of the basin are largely concerned with suppressing established populations to reduce the negative effects of invasive carp and preventing carp populations from reaching new areas through migration and range expansion (Asian Carp Regional Coordinating Committee, 2021). Once established, invasive carp can disrupt ecosystem processes necessary to maintain native fish habitat and sustain economically important recreational and commercial fisheries (Chapman and others, 2013; Cudmore and others, 2017). Unfortunately, eradication after invasive carp establish has largely been unsuccessful in the United States (Chick and Pegg, 2001); thus, there is a need to consider deterrents or barriers within management plans to proactively block migratory pathways and limit access to new areas (Noatch and Suski, 2012; Rahel, 2013).

Hydrologically connected water bodies that do not have established populations may be at risk from expanding invasive carp populations (Jackson and Pringle, 2010; Rudnick and others, 2012). Fortunately, these river and lake ecosystems also are in an opportune position for developing strategies to limit negative effects from invasive carp. In the Great Lakes, for example, introduction of invasive carp would create binational resource management challenges and could result in ecological and economic consequences (Asian Carp Regional Coordinating Committee, 2021; Robinson and others, 2021). Management agencies have recognized this threat and operate barriers (for example, U.S. Army Corps of Engineers Electric Fish Dispersal Barrier in Lockport, Illinois) to mitigate the risk of carp reaching Lake Michigan and are developing plans to block migration farther downstream on the Des Plaines River at Rockdale, Ill. (U.S. Army Corps of Engineers, 2018). Managers from other large river basins could also use this approach to control the spread of invasive carp; however, creating an effective and well-supported invasive carp management framework is challenging for several reasons.

Given the spatial footprint of invasive carp in North America, multiple jurisdictions and authorities are likely to be involved in their control (Herborg and others, 2007). For instance, Federal interests that involve interstate commerce and management of infrastructure may require integration with State and Tribal management actions and goals. Regulations and mandates from different authorities may also constrain actions at different scales, making collaborative management efforts difficult to implement; for example, one State usually would not have the authority to proactively control carp in another State to prevent spread, despite water pathways between the States. Furthermore, management effects are often delayed and interrelated, which can lead to unintended effects across multiple stakeholders. Given the economic and ecological values at stake, invasive carp management is likely to affect stakeholders in different ways. Failure to account for these differential effects could undermine public support for any strategies developed. Compounding these challenges is the fact that natural resources are inherently dynamic, thus increasing uncertainty and making it difficult to balance the expected benefits, risks, and costs of management.

Decision-analytic methods provide a collaborative framework for developing strategies under uncertainty and potentially competing objectives. Application of these tools to rigorously assess complex decisions typically involves first understanding the parts of a decision and then constructing a decision framework out of those parts to assess various alternatives (Gregory and Keeney, 2002; Runge and others, 2020). Although formal decision-analytic tools are not widely used in invasive carp management, these principles could be used to develop prospective strategies for managing invasive carp in areas where they are not yet established. For instance, Robinson and others (2021) developed a decision model for evaluating management actions to control spread of grass carp in Lake Erie, which supported the development of State-level invasive carp management plans.

In this report, we describe how we applied decision-analysis techniques to managing silver carp and bighead carp, hereafter referred to as “bigheaded carp,” in the Tennessee River system. Bigheaded carp are not yet believed to be self-sustaining in most of the Tennessee River, but individuals have been collected as far upstream as Guntersville Lake and are abundant in the lower reservoirs and thus pose a risk to the river ecosystem that supports ecological, economic, and recreational benefits. The Tennessee Valley Authority (TVA) began a Programmatic Environmental Assessment (PEA) for implementation of deterrents and barriers at lock and dam infrastructure on the Tennessee River under the National Environmental Policy Act (NEPA) to provide increased population controls. This PEA must account for the multiple Federal agencies tasked with managing resources and infrastructure in the river, State agency management objectives, and considerable uncertainty about carp population status and management effectiveness, as well as a period for public comment in accordance with NEPA. Here, we document the process used to help agency partners arrive at a recommended course of action to consider in the PEA. Goals of this project were threefold: first, identify shared management objectives; second, explore a set of plausible carp deterrent actions that would best balance those objectives; third, assess the role of uncertainty about carp biology and management effectiveness in the development of a deterrent strategy.

Study Site

The Tennessee River begins in Knoxville, Tennessee, and runs more than 1,000 kilometers to the Ohio River in the State of Kentucky. Over its course, the river flows through the States of Kentucky, Tennessee, Alabama, Mississippi, and back into Tennessee from downstream to upstream. The river is known for its ecologically diverse freshwater mussel species, though many of these species are in decline after changes in water quality, invasive species, and dam construction (Williams and others, 1993). Nine major lock and dam systems are located in the Tennessee River (fig. 1). These systems create nine separate reservoirs that are used for recreational boating and fishing. The lock and dam systems also facilitate commercial barge traffic between Knoxville and the Ohio River. Many of these dams were installed in the 1930s by the TVA with the intent of providing flood control and hydropower for communities in the Tennessee River Valley. The locks are managed and operated for navigation by the U.S. Army Corps of Engineers. Bigheaded carp detections are regularly made between Kentucky and Pickwick Dams, with only sporadic detections as far upstream as Nickajack Dam. As of the writing of this report, Pickwick Dam is considered to be the leading edge of bigheaded carp invasion in the Tennessee River.

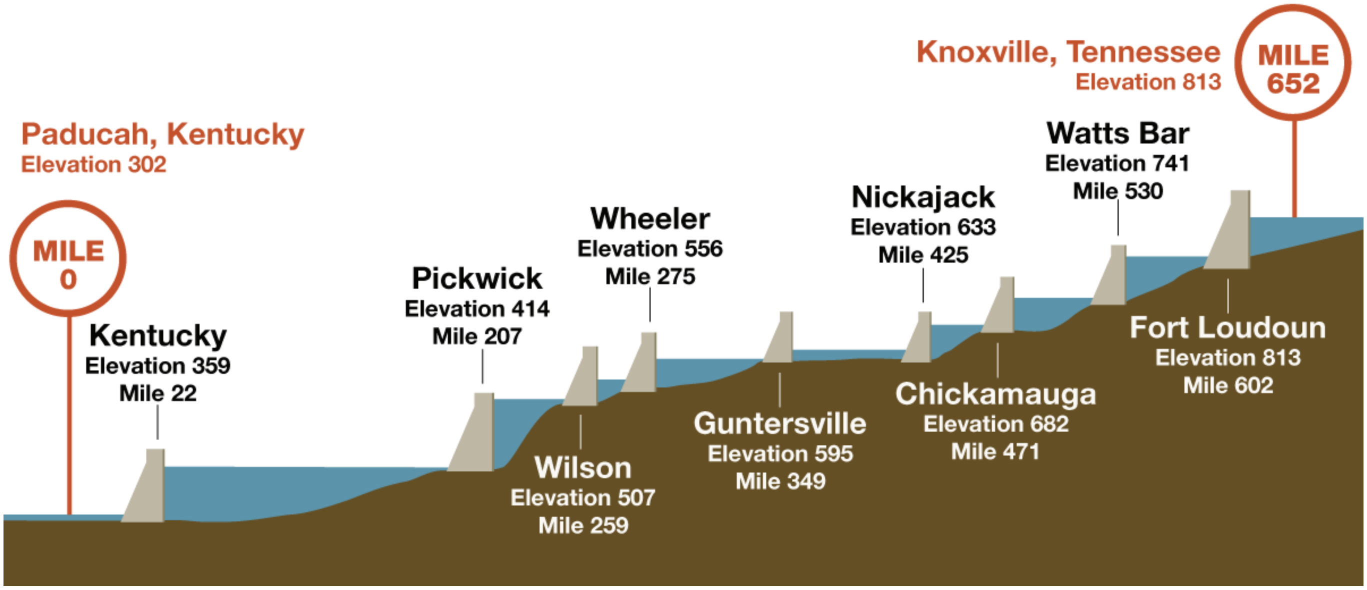

Figure 1. Location of lock and dam systems (at river mile markers) and change in elevation (in feet above the National Geodetic Vertical Datum of 1929) along the Tennessee River. These locks and dams are the locations that Federal and State fisheries managers considered in a 2020 decision-analysis workshop. [Image from Tennessee Valley Authority, 2021]

Decision-Analysis Process

We used the decision-analysis process outlined by Keeney (1992), Gregory and Keeney (2002), and Runge and others (2020). This process works by first developing a consensus statement of the decision to be made and the numerous considerations that should be included when making the decision; then, the stakeholders and decision makers specify the objectives they would like to achieve by making the decision. Next, they develop a set of alternative actions to meet those objectives; participants then assess the consequences of the alternatives in terms of the objectives. Finally, analysts conduct a formal analysis of tradeoffs and uncertainty with regards to the best set of actions. We should note that this process is compatible with regulatory frameworks like NEPA (Kurth and others, 2017). More specifically, decision analysis is compatible with the multiple stakeholder involvement stipulated in public decision making (Kurth and others, 2017); furthermore, multiagency involvement is not merely a procedural requirement but also results in high-quality and mutually agreeable decisions. Beierle (2002) determined that intensive stakeholder participation improved decision quality through the introduction of new information and ideas and increased access to relevant technical and scientific resources.

Consistent with this notion, we facilitated a multiple stakeholder decision-analysis workshop in the summer and fall of 2020. The TVA; U.S. Army Corps of Engineers; U.S. Fish and Wildlife Service; Tennessee Wildlife Resources Agency; Kentucky Department of Fish and Wildlife Resources; Mississippi Department of Fish, Wildlife and Parks; Alabama Department of Conservation and Natural Resources; and the Alabama Department of Environmental Management all participated in the workshop. The U.S. Geological Survey also participated by providing decision analysis, invasive carp biology, and deterrent technology expertise.

Decision Framing

The process of decision framing includes working with participants to develop a shared understanding of the decision to be made and the ultimate decision maker, clarity on the relevant authorities to make decisions, and any potential constraints that need to be considered in making the decision (Keeney, 1992). Recall that the motivation for forming this group was the announcement by the TVA of their intention to develop a PEA for the placement of bigheaded carp deterrent technology in the Tennessee River. More specifically, the TVA sought to assess the relative efficacy of deterrent technology (for example, behavioral and movement barriers) to be installed at TVA lock and dam systems throughout the river. To this end, the TVA wanted input from the other stakeholders in terms of which strategies to consider and prioritize within the PEA. The participants in the multistakeholder group described previously were tasked with recommending where and what type of deterrent technology should be used to control bigheaded carp within the Tennessee River system.

Objectives

Objectives are statements about what decision makers and stakeholders hope to achieve with deciding on a course of action (that is, their values; Gregory and Keeney, 2002). Typically, decision analysts try to translate objectives into a statement that contains an object of interest (or noun) and a direction of preference (for example, increase, decrease, maximize, minimize; Clemen and Reilly, 2001). The objectives that this group agreed upon can be found in table 1.

Ultimately, this group wanted to reduce bigheaded carp abundance above the leading edge and eventually minimize bigheaded carp abundance throughout the river; however, they also wanted to consider minimizing undesirable effects of deterrent technology to public recreation, river vessel traffic, and native freshwater mussels. Because many of these technologies can be costly, the workshop participants also wanted to consider minimizing the cost of any control strategy.

Alternative Actions

Creating a set of alternative actions to compare is the next step in decision analysis (Siebert and Keeney, 2015). A solution to a decision problem cannot be better than the best option considered; thus, decision analysts often stress the importance of thinking creatively and comprehensively about alternatives. For completeness, the group considered a wide range of potential action types, but the workshop participants decided that the focus of the analysis should be on barrier placement in combination with targeted removal. Our analysis mainly focused on the nine lock and dam systems on the Tennessee River (fig. 1). For completeness, we also considered two additional lock and dam systems that were not in the scope of the PEA: one furthest downstream where the Tennessee and Cumberland Rivers meet (that is, Barkley lock and dam) and where the Tennessee and Clinch Rivers meet (that is, Melton Hill lock and dam; table 2).

Barkley Dam was included because an experimental invasive carp deterrent, which has the potential to affect the effectiveness of management strategies on the Tennessee River, is being tested there. We included Melton Hill Dam to test whether or not management actions upstream from the focus area might have some benefit for lower reaches of the Tennessee River. Each of these locations differ in terms of their potential to support reproducing populations of invasive carp. We also considered five barrier actions: no barrier, an acoustic barrier, a carbon dioxide barrier, a "bioacoustic fish fence" (BAFF), and an electric barrier. Acoustic barriers operate by emitting sound into the water column at a frequency that deters approaching fish (Vetter and others, 2017). Carbon dioxide barriers work by creating a curtain of bubbles of concentrated carbon dioxide, which provides a chemosensory cue to approaching fish to avoid the area near the barrier (Cupp and others, 2021). The BAFF, originally developed by Fish Guidance Systems (https://www.fgs.world), operates similarly to the previous two barriers, except that it combines an acoustic stimulus with an air bubble curtain (rather than carbon dioxide) and high-intensity lights (Dennis and others, 2019). As the name implies, the electric barrier operates by creating an electrical field in the water column to deter approaching fish (Parker and others, 2016). Each of these barriers differ in installation and maintenance costs, effectiveness at deterring carp, and potential to affect other objectives, such as public safety. Because the State of Tennessee is already implementing targeted removal of bigheaded carp through contracted fishing, we also considered combining removal with barrier placement to increase carp mortality and reduce the number of potential migrants. Barrier effectiveness (that is, the proportion of passage attempts blocked) is an uncertainty and an active area of research. To evaluate the effect of uncertainty, the range in barrier effectiveness by barrier type was based on expert judgment; however, after further consideration, the workshop participants felt more comfortable assuming a wide range of barrier effectiveness without regard to the specific type of barrier (see "Decision Analyses" section). For the purposes of

Table 1. Objectives and objective descriptions depicting a set of values for a group of State and Federal management agencies interested in implementing bigheaded carp deterrent technology and removal efforts in the Tennessee River. These objectives were elicited during a series of workshops in the summer and fall of 2020.

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp)]

Objective	Description
Minimize carp abundance and distribution	Focus on relative abundance above the leading edge of the carp distribution.
Maximize public satisfaction	Effects of altering public safety and other public values.
Maximize recreational use	Effects of altering recreational access to the river.
Minimize negative effects on lock operations	Effect is due to interfering with lock operation and navigation.
Minimize negative effects on native species	All native species, but particularly imperiled freshwater mussels near Pickwick Dam.
Minimize cost	Include costs for barrier installation, barrier maintenance, and contracting for targeted removal.

Table 2. Potential locations for barrier placement considered by a group of Federal and State fisheries managers at a bigheaded carp deterrent workshop held in the fall of 2020. Described in the table are the dams on the Tennessee River, position on the river, number of locks, navigation activity (lockage rate per year based on 2017), and reservoir area above the dam.

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp); km², square kilometer]

Dam	River mile on the Tennessee River unless otherwise noted	Locks	Lockage rate per year	Reservoir area (km²)
Barkley	31 (Cumberland)	1	1,975	235
Kentucky	22	1	4,678	649
Pickwick	207	2	2,412	174
Wilson	259	2	2,437	37
Wheeler	275	2	2,437	271
Gunterville	349	2	1,733	279
Nickajack	425	1	1,198	42
Chickamauga	471	1	2,805	147
Watts Bar	530	1	1,443	158
Fort Loudon	602	1	1,349	59
Melton Hill	23 (Clinch)	1	4	22.0

this study, we assumed that the barrier at Barkley Dam would remain in place but that barriers could be placed at any of the nine dams on the Tennessee River or at Melton Hill on the Clinch River. We assumed that barriers could be installed and maintained indefinitely or removed sometime in the future.

Targeted removal of carp through harvest is completed through programs including the contracting of commercial harvesters paid to fish and remove bigheaded carp. The fishing mortality rate that is achieved through targeted removal is an uncertainty. In general, overharvesting of populations, which causes declining abundances, is achieved when fishing mortality exceeds natural mortality. Targeted removal can occur at any reservoir in the system but the cost to contract commercial harvesters is expected to rise inversely to carp density. We assumed that targeted removal could occur in one year but not the next in response to changing carp density.

Consequences—Predictive Modeling

To initiate the process of assessing the consequences of management options, the workshop participants developed a conceptual model of how possible actions could affect carp population processes and how changes in those processes could affect management objectives (fig. 2).

We then translated the conceptual model into a quantitative model that we could use to compare actions. The model included inputs for management actions of barrier placement at locks and dams and targeted removal through harvest designed to impede the upstream carp distribution. The base population model is

$$N_{t+1}=R_t+S_t\times N_t+I_t-E_t, \quad (1)$$

where

N is population abundance,
t is year,
R is recruits,
S is survival,
I is immigrants, and
E is emigrants.

Each reservoir within the river system was modeled as a separate population with movement (I and E) between adjacent reservoirs. Survival rate is a function of natural and fishing mortality

$$S=e^{-(M+F)}, \quad (2)$$

where

e is Euler's number,
M is natural mortality, and
F is fishing mortality.

Natural mortality was assumed to be a function of maximum age using the Hoenig model (Hewitt and Hoenig, 2005)

$$\ln(M)=1.44-0.982\times\ln(t_{max}), \quad (3)$$

where

ln is natural logarithm and
t_{max} is maximum age.

We assumed that the maximum age for carp in the stock-recruitment models was 13 years (Ridgway, 2016). This resulted in model parameter values of M=0.34 and S=0.71.

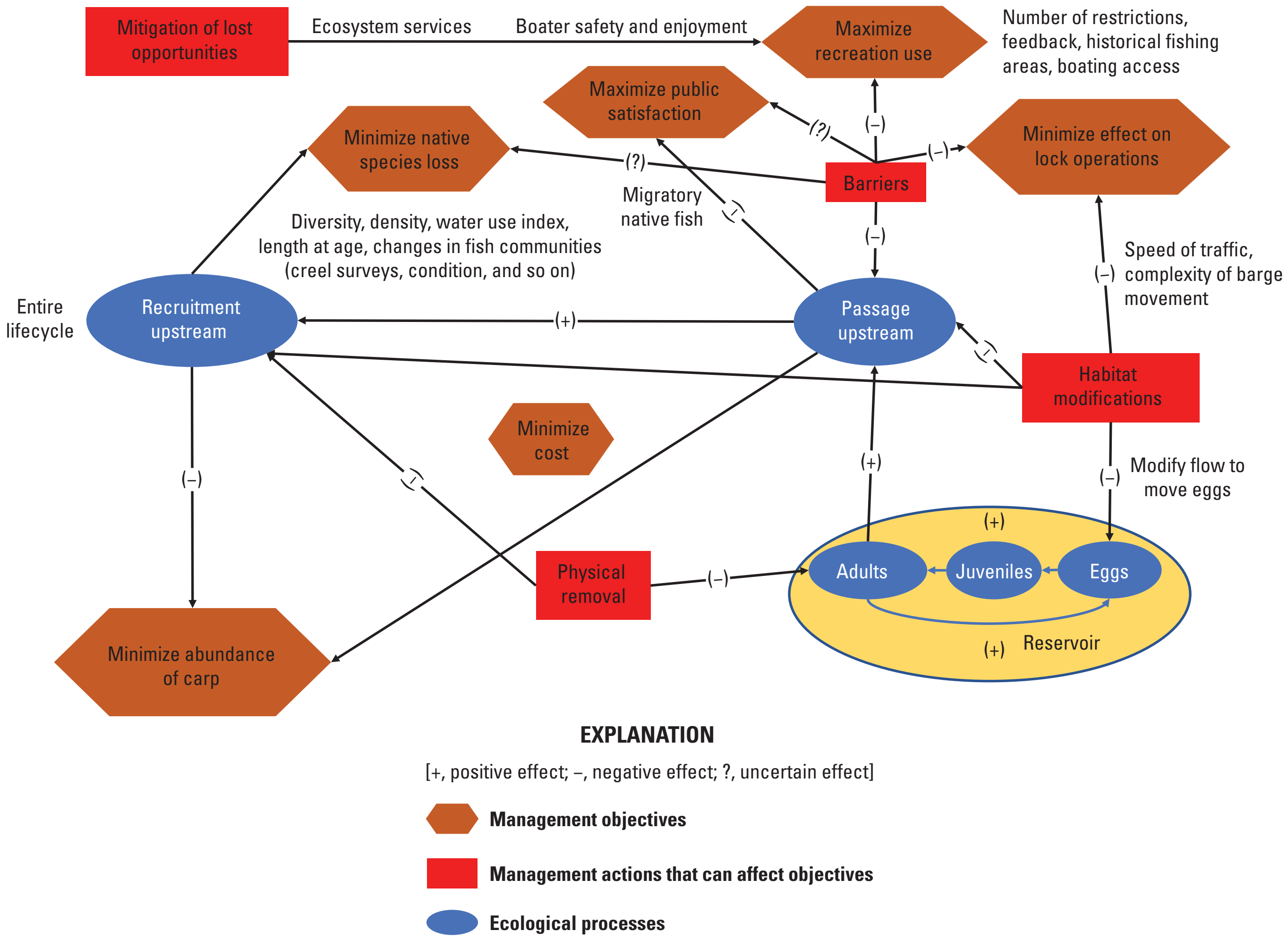

Figure 2. Conceptual model used in a decision-analysis workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River. [Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp)]

The number of migrants was a function of the net movement rate between reservoirs and reservoir-specific abundance. The number of immigrants is

$$I_t = i_t \times N_{jt}, \tag{4}$$

where

i is net movement rate into the reservoir and
N_j is abundance in the source (downstream reservoir) population.

The number of emigrants is

$$E_t = e_t \times N_{kt}, \tag{5}$$

where

e is net movement rate out of the reservoir into the upstream population and
N_k is abundance in the reservoir from which carp are emigrating.

The carp population growth and movement rates in this river system are unknown. To represent that uncertainty, we developed four population models that varied in the underlying population dynamics and population growth rates. The models affected population growth through either recruitment or intrinsic growth rate and carrying capacity. The four models include the following (table 3):

- Ricker stock-recruitment model (high growth),
- Beverton-Holt stock-recruitment model (moderate growth),
- Hockey stick stock-recruitment model (high growth but depensation threshold), and
- Density-dependent exponential growth model (low growth).

The model parameters were calibrated to result in about the same abundance at year 20 in the absence of barrier placement or targeted removal (table 3).

Table 3. Models and parameters used in a decision-analysis workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River. Models were parameterized to result in similar relative abundance in the Tennessee River system at year 20.

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp); *E*, expectation; *R*, recruits; *SS*, spawner abundance; *a*, recruitment per spawner near *SS* = 0; *e*, Euler's number; *b*, density-dependent compensation; *I*, indicator of whether spawner abundance is above or below a threshold; <, less than; *p*, peak; *d*, depensation; *N*, total abundance; *t*, time; *r*, intrinsic growth rate; *K*, carrying capacity]

Models	Functions	Parameter descriptions	Parameters
Ricker stock-recruitment model	$E[R\|SS]=aSSe^{-bSS}$	Peak recruitment = $a/(be)$ Abundance at peak recruitment = $1/b$	$a = e^{(1.67142)}$ $b = 0.00065$
Beverton-Holt stock-recruitment model	$E[R\|SS] = \frac{aSS}{1 + bSS}$	a = recruitment per spawner near $SS = 0$ Peak recruitment = a/b	$a = 3.7728134498$ $b = 0.00208799$
Hockey stick stock-recruitment model	$E[R\|SS] = I*b$ if $SS < SS_p$ and $E[R\|SS] = SS_p$ otherwise, where $b = R_p/(SS_p - SS_d)$, $I = 0$ if $SS < SS_d$ and $I = 1$ otherwise	SS_d = depensation threshold, R_p = peak recruitment SS_p = abundance at peak recruitment	$SS_d = 50$ $SS_p = 2000$ $R_p = 1775$
Density-dependent exponential growth model	$N_{t+1} = N_t e^{r\left(1 - \frac{N_t}{K}\right)}$	r = intrinsic growth rate K = carrying capacity	$r = 0.6$ K is a function of reservoir size

For the remainder of the model parameters, we relied on expert opinion and information from other models and analyses to serve as proxies. Recruitment is integral to population modeling but is likely to vary among populations based on local environmental conditions. A population would have the potential for ideal levels of recruitment when all necessary conditions (such as adequate drift distance to accommodate the early life history requirements of bigheaded carp, temperatures, habitats, and turbidities) are adequately met. The FluEgg model (Garcia and others, 2015) simulates the physical processes in a river and how those processes affect where carp eggs could settle. Applying this model to a stretch of river could help provide an index of where there may be adequate conditions for recruitment. We used opinions from two experts and preliminary output from the FluEgg model applied to the Tennessee River to develop recruitment potential scores. These scores ranged from 0 to 1, where 1 indicates all recruitment conditions are fully met and 0 indicates that the reservoir provides no potential for recruitment (table 4). We calculated these recruitment potential scores by averaging the ranks of the two experts and those from the FluEgg model. We then standardized the ranks by normalizing them, then multiplying each value by 10, and then adding 1. We then divided one by the standardized rank to calculate the recruitment potential.

Operationally, in the population model, recruitment potential in the *j*th reservoir (P_j) was multiplied by the number of yearly recruits (R_{jt}); that is, $R^*_{jt} = R_{jt} * P_j$, where $R*_{jt}$ was the realized recruitment in reservoir *j* at time *t*. Anecdotal observations indicated that carp cohorts appeared annually in sections of the lower Tennessee River where recruitment conditions were favorable for recruitment; however, we do not have adequate data to assess whether or not we should expect annual recruitment every year. We incorporated recruitment into the population model as the proportion of years that recruitment was expected to occur. Scenarios included every year, every other year, or every fifth year. In the density-dependent growth model, we modeled reservoir-specific carrying capacity (*K*), as a function of reservoir surface area relative to Kentucky Lake and the assumed carrying capacity in Kentucky Lake. We assumed this carrying capacity to be 1.5 times the current abundance based on energetics modeling (Wood, 2019). We computed carrying capacity in the *j*th reservoir (K_j) as the carrying capacity in Kentucky Lake (K_{KY}) times the ratio of the area of the *j*th reservoir (A_j) to the area of Kentucky Lake (A_{KY}); that is, $K_j = K_{KY}(A_j/A_{KY})$.

Movement of bigheaded carp between water bodies, and the effects of movement reduction, have been studied using tagging and telemetry among pools on the Illinois River (Coulter and others, 2018) and at lock and dam systems in the Mississippi River (Fritts and others, 2021), as well as model simulations in the Great Lakes Basin (DuFour and others, 2021). However, published works did not translate directly to what we needed for modeling carp dynamics within the Tennessee River system; Coulter and others (2018) estimated monthly movement, DuFour and others (2021) estimated seasonal movement, and Fritts and others (2021) estimated residency. We relied on expert opinion to estimate carp movement. We elicited these estimated values using the elicitation protocol outlined in O'Hagan (2019). Experts considered movement to be a function of the number of locks and lock activity (lockages) and conditions within the reservoir downstream from the dam, such as habitat suitability and population density. Although some factors could be dynamic (for example, density), a constant, reservoir-specific net movement rate was elicited from the individual experts and then aggregated mathematically into a pooled statistical probability distribution (table 5).

Table 4. Reservoir-specific recruitment potentials used in a simulation of bigheaded carp expansion in the Tennessee River. The simulation was part of a decision-analysis workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River.

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp)]

Reservoir	Individual expert-based rank[1]		FluEgg rank (1 = very good, 2 = good, 3 = fair, 4 = poor)	FluEgg rank converted to 1 to 10 rank	Average rank	Standardized rank	Recruitment potential (0 to 1 scale)[2]
	Expert 1	Expert 2					
Kentucky	3	1	1	1	1.67	1.38	0.72
Pickwick	4	5	3	7	5.33	5.62	0.18
Wilson	9	8	4	10	9.00	9.85	0.10
Wheeler	2	1	1	1	1.33	1.00	1.00
Guntersville	1	2	1	1	1.33	1.00	1.00
Nickajack	4	3	3	7	4.67	4.85	0.21
Chickamauga	6	4	1	1	3.67	3.69	0.27
Watts Bar	7	6	2	4	5.67	6.00	0.17
Fort Loudoun	8	7	2	4	6.33	6.77	0.15
Melton Hill	10	10	4	10	10.00	11.00	0.09

[1]For individual expert-based rank, 1 is highest, 10 is lowest, and ties are acceptable.

[2]For recruitment potential, 1 indicates all recruitment conditions are fully met, and 0 indicates that the reservoir provides no potential for recruitment.

Table 5. Net movement rates elicited from individual experts and aggregated into a pooled statistical probability distribution (represented by percentiles). These rates were used to parameterize a bigheaded carp simulation model for the Tennessee River. This simulation was part of a decision-analysis workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River.

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp); %, percent]

Movement from reservoir	Movement to reservoir	Percentiles from the pooled distribution		
		5%	50%	95%
Barkley	Kentucky	−0.133	0.022	0.154
Kentucky	Pickwick	0.000	0.002	0.061
Pickwick	Wilson	−0.021	0.006	0.158
Wilson	Wheeler	−0.033	0.011	0.240
Wheeler	Guntersville	−0.036	0.007	0.128
Guntersville	Nickajack	−0.021	0.006	0.105
Nickajack	Chickamauga	−0.029	0.005	0.126
Chickamauga	Watts Bar	−0.029	0.005	0.126
Watts Bar	Fort Loudon	−0.019	0.005	0.064
Fort Loudon	Melton Hill	−0.010	0.003	0.028

The current carp distribution in the Tennessee River extends upriver from the Ohio River to at least Pickwick Lake. Density and reservoir size, which determine relative abundance, vary among reservoirs. Based on recent surveys, relative abundance is shown in table 6 for Barkley, Kentucky, and Pickwick Lakes (M. Rogers, U.S. Geological Survey, Tennessee Tech Cooperative Fishery Research Unit, unpub. data, 2020).

Decision Analyses

We completed two analyses for this study to evaluate the sensitivity of carp management options to our assumptions. Our first analysis focused on how to make tradeoffs among the management objectives described previously. We began by

Table 6. Initial relative abundance of carp within the Tennessee River as measured by catch per unit effort (from M. Rogers, U.S. Geological Survey, Tennessee Tech Cooperative Fishery Research Unit, unpub. data, 2020). These abundances were used to parameterize a bigheaded carp simulation model for the Tennessee River. This simulation was part of a decision-analysis workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River.

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp); km^2, square kilometer; CPUE, catch per unit effort]

Reservoir	Area (km^2)	CPUE	Relative abundance
Barkley	235	16.09	3,777
Kentucky	649	8.71	5,651
Pickwick	174	6.67	1,163

asking participants to rank how well placing a barrier at each lock and dam would perform on each of the objectives. Next, we asked participants to rank how well the five barrier types (including "no barrier") would perform at each lock and dam for each objective. Using these ranks along with the predicted relative abundance as the attributes, we then completed tradeoff analyses to determine the best combination of barriers constrained by cost. Attributes were standardized to range from 0 to 1. To perform this analysis, we needed to develop a utility function whose value would reflect the aggregate performance of an action across multiple objectives. The parameters of the utility function were as follows:

w_i = weight for the *i*th objective,

θ_{ij} = standardized attribute for the *i*th objective for barrier placement at the *j*th dam,

φ_{ijk} = standardized attribute for the *i*th objective for placement at the *j*th dam of the *k*th barrier type,

I_{ijk} = indicator (0, 1) for barrier placement at the *j*th dam of the *k*th barrier type,

U_j = expected utility for the barrier placement at the *j*th dam

$$= \sum_i w_i \theta_{ij} \prod_k I_{jk} \varphi_{jk} \text{ and}$$

U = expected utility for barrier placement strategy = $\sum_j U_j$.

Given the limited time to complete the decision analysis, we did not perform a formal weighting exercise, such as swing weighting; however, the State agencies expressed the sentiment that the most important consideration for them in choosing a barrier and a location would be the effectiveness of that action in reducing carp abundance. Through further discussions, we determined that a weight (w_i) of 0.7 on minimizing carp abundance would express this sentiment, with the remaining 0.3 allocated equally among the other objectives. We used linear integer programming in Microsoft Excel's Solver to search for the best performing barrier placements indicated by the optimal combination of indicator variables I constrained by the number of barriers (1, 2, 3, or 4) as a proxy for cost. Relative abundance above Wilson Dam (Wilson Lake) at the 20th year was predicted using the population model set under scenarios where fishing mortality was zero and where fishing mortality was the same as natural mortality. The optimal decisions based on the mean or highest (that is, worst case) abundance among the models were compared to evaluate sensitivity of the decision to uncertainty. The separate tradeoff analyses were performed using rankings provided by four group members to evaluate sensitivity of the decision to stakeholder preference.

The next level of analysis allowed decision makers and systems experts to interact with a simple spreadsheet model to experiment with management actions (barriers and targeted removal). We used the deterministic model explained in the previous section to develop a spreadsheet model that simulated the spread of bigheaded carp from the Ohio River up through the locks and dams in the Tennessee River. The simulation began by assuming that carp were only found in the reservoirs downstream from Wilson Dam. Carp were then allowed to move upstream according to the model dynamics explained in the previous sections. The model tracked the progression of carp upstream over a period of 20 years under each of the four population models described previously. Participants were also allowed to adjust the assumptions about mortality caused by targeted removal efforts, as well as the rate at which carp were able to move upstream. Participants were allowed 1 week to work with the model after which they were asked to describe their options and which of the options they preferred.

To formalize this last step, we wrote a script in the R programming environment (R Core Team, 2020) to implement the spreadsheet simulation tool and then used a simple greedy heuristic algorithm to search through possible barrier and removal options over a 20-year period. The greedy heuristic algorithm we used iteratively searches through all the possible actions and picks the single best performing action, which it removes from further consideration. It then searches through the remaining available actions, chooses the next best performing action, removes it from further consideration, and so on. We ran this algorithm under a few assumptions. First, we assumed only one barrier type but that its effectiveness varied (50, 75, 95, and 100 percent of carp deterred). We did this because workshop participants expressed discomfort in our first decision analysis with making guesses as to the effectiveness of barrier types. They felt much more comfortable with the idea of determining the level of effectiveness needed to slow carp movement upstream. We further assumed only one barrier installation could occur each year and that, once installed, the barrier would be in place for the remainder of the period. For instance, suppose our model indicated that the most effective option was to place a barrier at Pickwick Dam in the first year. No other barrier installations could occur in the first year, and that barrier would remain in place for the remaining 19 years. But an installation could occur at another dam in the second year, and so on. For the removal decisions, we assumed that a maximum of three reservoirs could be targeted for removals each year and that a barrier would be left in place at Barkley Dam (to reflect the BAFF that is installed there). We assumed that removal mortality was equal to natural mortality and that all population parameters were set to their median values. The objective function in this case was to minimize total carp abundance above Kentucky Dam at the end of 20 years. This abundance was computed as the weighted mean of all four population models, assuming equal weights on all the models.

Results

The tradeoff analyses revealed consistency in optimal barrier placement across stakeholder preferences (rankings), assumed fishing pressure, and mean or worst-case response (table 7).

Pickwick, Wilson, and Kentucky Dams were identified consistently as optimal locations to place one to three barriers. Only when the cost constraint was relaxed to allow for a fourth barrier did variation among scenarios or stakeholders appear. Guntersville was identified as the optimal fourth barrier seven out of eight times based on the mean predicted abundance. Nickajack was identified as the optimal fourth barrier five out of eight times based on the worst-case (highest) predicted abundance; Chickamauga was identified two out of eight times. Melton Hill was identified as optimal in isolated cases, appearing in one out of eight scenarios. The barrier type most commonly identified was the BAFF system; exceptions were infrequent selection of carbon dioxide at Kentucky Dam and acoustic for the fourth barrier.

The results of the heuristic optimization indicated that, when effectiveness was low, the optimal solution included a total of seven barriers that would need to be installed each year (fig. 3*A*, *B*). As effectiveness increased, fewer barriers were needed to slow carp spread upstream (fig. 3*C*, *D*). The results also indicated that the timing of barrier placement changed somewhat when barrier effectiveness varied. When effectiveness was low, the optimal solution was to first place a barrier at Kentucky Dam, followed by one at Wilson Dam and then one at Guntersville Dam (fig. 3*A*, *B*). In essence, the model seems to imply that arresting movement at Kentucky Dam and then protecting uninvaded reservoirs farther upstream would be best early on. When effectiveness was higher, the model indicated initially placing a barrier at Pickwick Dam, followed by Kentucky and Wilson Dams (fig. 3*C*, *D*). If the barrier was 100-percent effective, only two barriers at Pickwick and Kentucky Dams would be needed. The model rarely recommended removal-only actions and tended to couple removals and barriers together (fig. 3); furthermore, the location of removals depended on barrier effectiveness and generally tended to focus on removing fish between Pickwick and Nickajack Lakes. Combining the removal and barrier actions resulted in more fish in the Tennessee River when barrier effectiveness was low compared to when barrier effectiveness was high (fig. 4); however, even a 50-percent effective barrier resulted in fewer fish in the river compared with the “do nothing” option.

Table 7. Results from a multicriteria decision analysis focused on optimal carp barrier placement in the Tennessee River. This analysis was done at a workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River. The barrier locations and types that optimized a multiple objective utility function are listed. The function was constrained by cost indicated by number of barriers. The tradeoff analysis assumed that the Barkley Dam barrier remained in place and that installation of additional barriers occurred 2 years from the fall of 2020. The multiple objectives are listed in table 1. Relative abundance of carp upstream from Wilson Dam (that is, above Pickwick Lake) was used as the performance metric for minimizing carp abundance and distribution. For the other objectives, rankings were provided by four members of the stakeholder group to use as performance metrics (members are numbered 1 to 4). The rankings indicated how well each objective was met by placement of a barrier at each location of a barrier type.

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp); F, fishing mortality; M, natural mortality; BAFF, bioacoustic fish fence; CO_2, carbon dioxide]

Group member	Priority	F=0				F=M			
		1 barrier	2 barriers	3 barriers	4 barriers	1 barrier	2 barriers	3 barriers	4 barriers
		Relative abundance above Wilson Dam—Mean response							
1	Location	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Melton Hill	Pickwick	Pickwick, Wilson	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Guntersville
	Barrier type	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, acoustic	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF
2	Location	Pickwick	Pickwick, Wilson	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Guntersville	Pickwick	Kentucky, Pickwick	Pickwick, Wilson, Guntersville	Kentucky, Pickwick, Wilson, Guntersville
	Barrier type	BAFF	BAFF, BAFF	CO_2, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF
3	Location	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Guntersville	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Guntersville
	Barrier type	BAFF	BAFF, BAFF	CO_2, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF

Table 7. Results from a multicriteria decision analysis focused on optimal carp barrier placement in the Tennessee River. This analysis was done at a workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River. The barrier locations and types that optimized a multiple objective utility function are listed. The function was constrained by cost indicated by number of barriers. The tradeoff analysis assumed that the Barkley Dam barrier remained in place and that installation of additional barriers occurred 2 years from the fall of 2020. The multiple objectives are listed in table 1. Relative abundance of carp upstream from Wilson Dam (that is, above Pickwick Lake) was used as the performance metric for minimizing carp abundance and distribution. For the other objectives, rankings were provided by four members of the stakeholder group to use as performance metrics (members are numbered 1 to 4). The rankings indicated how well each objective was met by placement of a barrier at each location of a barrier type.—Continued

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp); F, fishing mortality; M, natural mortality; BAFF, bioacoustic fish fence; CO_2, carbon dioxide]

Group member	Priority	F=0				F=M			
		1 barrier	2 barriers	3 barriers	4 barriers	1 barrier	2 barriers	3 barriers	4 barriers
Relative abundance above Wilson Dam—Mean response—Continued									
4	Location	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Guntersville	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Guntersville
	Barrier type	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF
Relative abundance above Wilson Dam—Worst-case response									
1	Location	Pickwick	Pickwick, Wilson	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Melton Hill	Pickwick	Pickwick, Wilson	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Nickajack
	Barrier type	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, acoustic	BAFF	BAFF, BAFF	CO_2, BAFF, BAFF	CO_2, BAFF, BAFF, BAFF
2	Location	Pickwick	Pickwick, Wilson	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Chickamauga	Pickwick	Pickwick, Wilson	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Nickajack
	Barrier type	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, acoustic	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	Acoustic, BAFF, BAFF, BAFF

Table 7. Results from a multicriteria decision analysis focused on optimal carp barrier placement in the Tennessee River. This analysis was done at a workshop in the fall of 2020 to assess various bigheaded carp control strategies in the Tennessee River. The barrier locations and types that optimized a multiple objective utility function are listed. The function was constrained by cost indicated by number of barriers. The tradeoff analysis assumed that the Barkley Dam barrier remained in place and that installation of additional barriers occurred 2 years from the fall of 2020. The multiple objectives are listed in table 1. Relative abundance of carp upstream from Wilson Dam (that is, above Pickwick Lake) was used as the performance metric for minimizing carp abundance and distribution. For the other objectives, rankings were provided by four members of the stakeholder group to use as performance metrics (members are numbered 1 to 4). The rankings indicated how well each objective was met by placement of a barrier at each location of a barrier type.—Continued

[Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp); F, fishing mortality; M, natural mortality; BAFF, bioacoustic fish fence; CO_2, carbon dioxide]

Group member	Priority	F=0				F=M			
		1 barrier	2 barriers	3 barriers	4 barriers	1 barrier	2 barriers	3 barriers	4 barriers
Relative abundance above Wilson Dam—Worst-case response—Continued									
3	Location	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Nickajack	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Nickajack
	Barrier type	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, acoustic	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, acoustic
4	Location	Pickwick	Pickwick, Wilson	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Chickamauga	Pickwick	Kentucky, Pickwick	Kentucky, Pickwick, Wilson	Kentucky, Pickwick, Wilson, Nickajack
	Barrier type	BAFF	BAFF, BAFF	BAFF, BAFF, BAFF	BAFF, BAFF, BAFF, acoustic	BAFF	BAFF, BAFF	CO_2, BAFF, BAFF	BAFF, BAFF, BAFF, BAFF

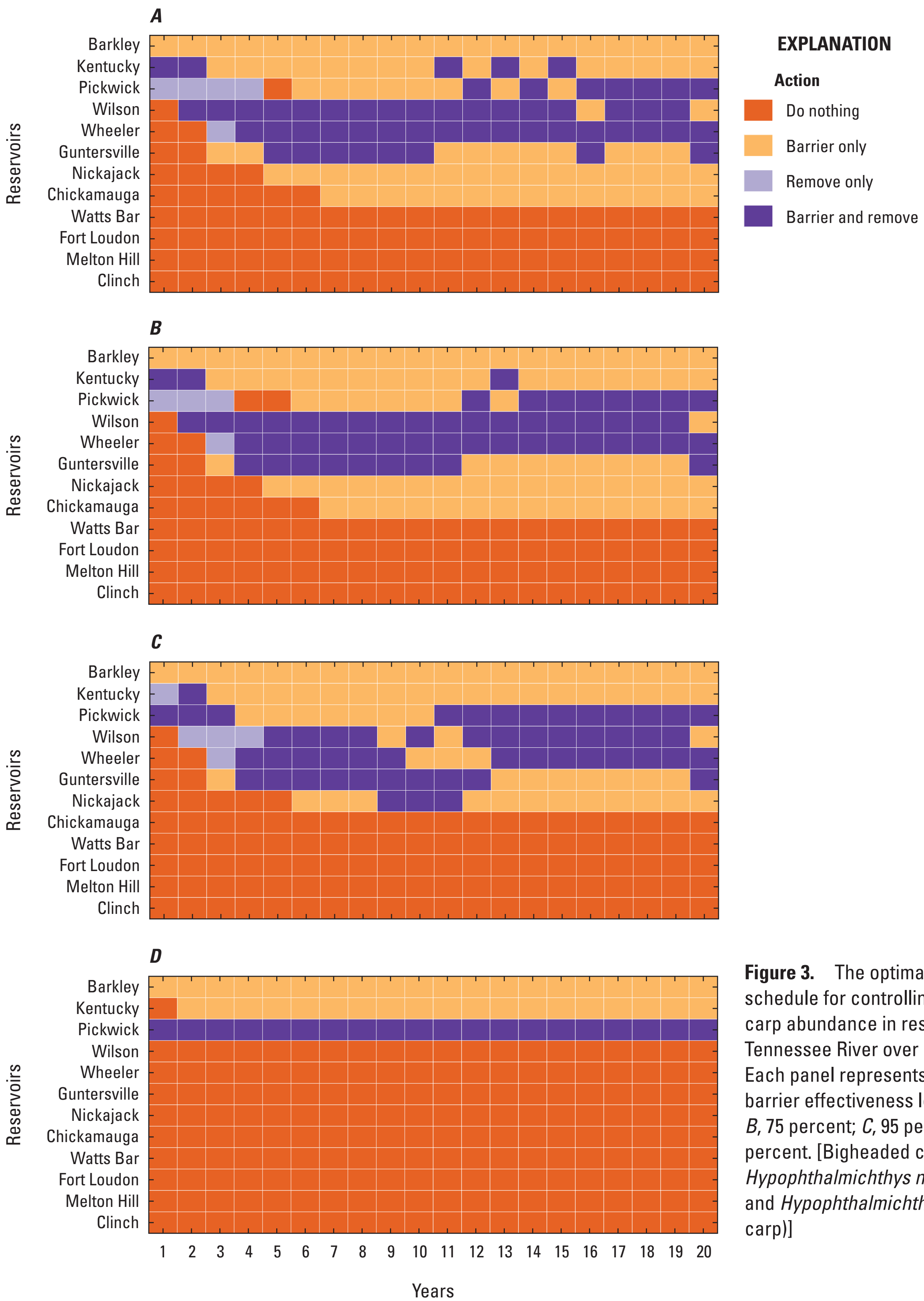

Figure 3. The optimal barrier and removal schedule for controlling bigheaded carp abundance in reservoirs in the Tennessee River over a 20-year period. Each panel represents an assumed barrier effectiveness level. *A*, 50 percent; *B*, 75 percent; *C*, 95 percent; *D*, 100 percent. [Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp)]

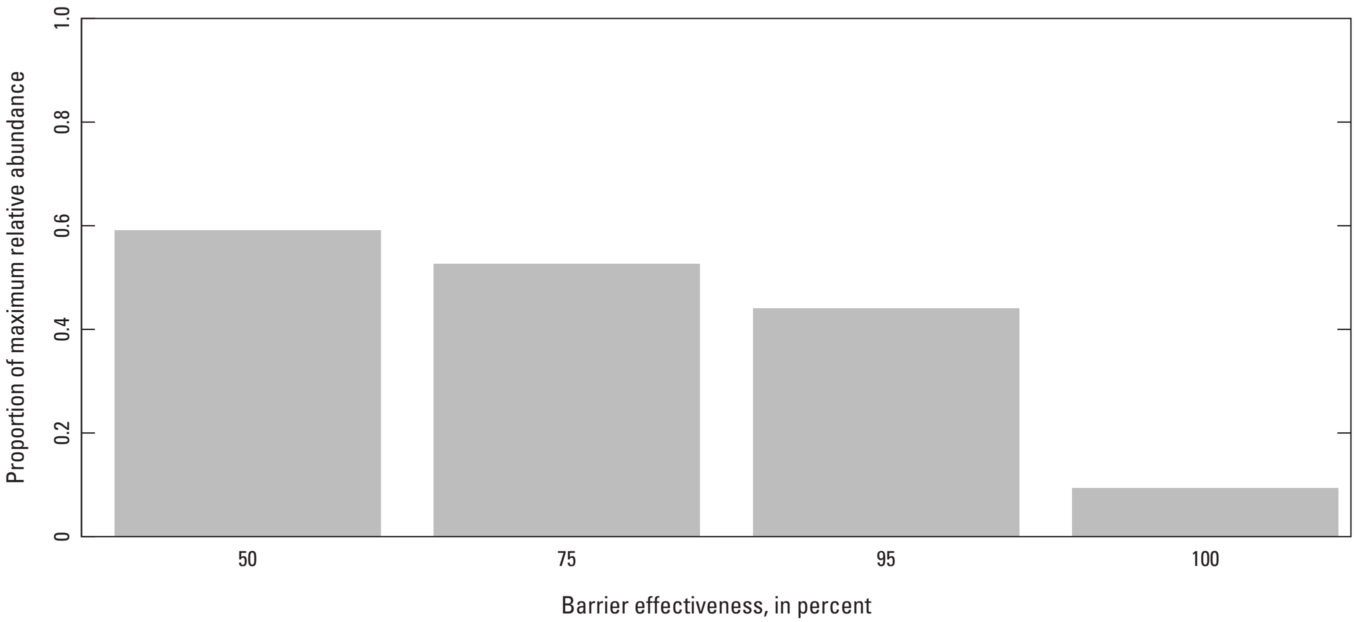

Figure 4. The proportion of relative abundance expected with implementation of bigheaded carp removal and barrier strategies at the end of a 20-year simulation in the Tennessee River. The proportion of relative abundance represents the expected performance (that is, expected relative abundance) under each strategy divided by the expected relative abundance when the "do nothing" option is implemented. [Bigheaded carp refers to *Hypophthalmichthys nobilis* (bighead carp) and *Hypophthalmichthys molitrix* (silver carp)]

Insights and Discussion

Our analyses are consistent with the intuitive notion that barriers installed downstream on the Tennessee River could arrest or slow carp movement upstream despite uncertainty about population dynamics. Both approaches to analyzing options identified installation of barriers at Kentucky and Pickwick Dams would be optimal choices. Lessening the migration of new carp into the Tennessee River system and reducing biomass into the reservoirs at the leading edge of the invasion is expected to minimize the carp population throughout the system; however, our analysis indicates that the implementation of this strategy will depend critically on the assumed rate of upstream movement and barrier effectiveness.

More nuanced strategies appeared in the tradeoff analysis, which indicated that the optimal order of barrier placement would be at Kentucky, Pickwick, and Wilson Dams, respectively, but if a fourth barrier is within budget, then adding a barrier at Guntersville, Nickajack, or Chickamauga Dams would be good choices. Further, the tradeoff analysis indicated that the BAFF system most frequently performed best on the multiple objectives, but the carbon dioxide barrier at Kentucky Dam and the acoustic barrier at upriver locations were optimal for some scenarios.

In addition to the tradeoff analysis, we used a heuristic optimization analysis to model sequential barrier placement and targeted removal incorporating uncertain effectiveness. When barrier effectiveness was low (that is, 50 or 75 percent), the model initially placed a barrier at Kentucky Dam, followed by upstream dams, but avoided Pickwick until year six. Only when the barrier effectiveness reached 100 percent did the model select Kentucky and Pickwick Dams for initial barrier placement. Targeted removal enhanced the effect of barrier placement. But even when barriers were 100-percent effective, extirpation of carp was not achievable because carp were already in the system, and targeted removals only added to natural mortality; thus, the success of any strategy will depend on barrier and removal effectiveness.

In summary, the tradeoff analysis and heuristic optimization model supported the initial placement of at least one barrier at Kentucky and Pickwick Dams; however, the timing and sequence of the additional barriers were context specific. Generally, placing other barriers between Pickwick and Chickamauga Dams over the subsequent 7 years was predicted to reduce the carp population upstream from Pickwick Dam. Presumably, being able to put barriers at all dams, given uncertainty about the rate of invasion, would likely result in the largest amount of protection for upstream reservoirs; however, more realistically, when funding would permit only one or two barriers each year, the strategy of alternating downstream protection and upstream protection may be beneficial. Furthermore, increased barrier effectiveness would reduce the number of barriers needed to control carp abundance, especially when combined with intensive targeted removal efforts.

The analyses were based on collaboratively developed stakeholder input so that those stakeholders could make reasoned recommendations to the PEA led by the TVA.

Although we framed the decision analyses specifically for the Environmental Assessment, the collaborative approach has strategic advantages broadly applicable to other systems. The durability of any decision is enhanced through stakeholder-driven processes and is key to follow through and successful implementation (Beierle, 2002). Although a collaborative approach can take more time than a single decision-maker approach, it can be managed within an allotted timeline. Many river systems in the Midwest and the southeast are at risk for invasive carp, where managers face difficult decisions because of conflicting objectives and knowledge gaps. Because time is of the essence when controlling invasive species, scientists and managers are not likely to have all the desired data about recruitment or deterrent effectiveness before deciding on control measures. The approach we present here for evaluating decision options in the face of substantial knowledge gaps could be helpful for those other systems.

Because management of invasive carp will involve a sequence of linked decisions, there will be opportunities to test assumptions, learn, and adapt to new knowledge (Williams and others, 2007; Runge, 2020). Monitoring will be needed to provide feedback between the current knowledge used to model the carp invasion and the results from implementing management actions (that is, barrier placement or targeted removal) based on predicted carp population conditions. Monitoring will need to measure the key parameters (for example, carp movement rates, barrier effectiveness) and variables (for example, carp abundance in reservoirs) in the predictive model. Although predictive modeling and monitoring programs provide a good starting point for adaptive management, institutional commitment may be the most substantial hurdle over the next few decades; however, an adaptive approach would benefit the effort to control invasive carp in the Tennessee River and other large river systems.

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