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Numeric Simulation Demonstrates That the Upstream Movement of Invasive Bigheaded Carp Can Be Blocked at Sets of Mississippi River Locks-and-Dams Using a Combination of Optimized Spillway Gate Operations, Lock Deterrents and Carp Removal

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Abstract: Invasive bigheaded carp are advancing up the Upper Mississippi River by passing through its locks-and-dams (LDs). Although these structures already impede fish passage, this role could be greatly enhanced by modifying how their spillway gates operate, adding deterrent systems to their locks, and removing carp. This study examined this possibility using numeric modeling and empirical data, which evaluated all three options on an annual basis in both single LDs and pairs under different river flow conditions. Over 100 scenarios were modeled. While all three approaches showed promise, ranging from 8 to 73% reductions in how many carp pass a single LD, when employed together at pairs of LDs, upstream movement rates of invasive carp could be reduced 98–99% from current levels. Although modifying spillway gate operation is the least expensive option, its efficacy drops at high flows, so lock deterrents and/or removal using fishing/trapping are required to move towards complete blockage. Improved deterrent efficacy could also offset the need for more efficient removal. This model could help prioritize research and management actions for containing carp.

Keywords: integrated pest management; model; hydraulic; acoustic deterrent; invasive fish; conservation

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1. Introduction and Mini-Review

The spread of invasive fish has contributed to the extirpation of many species of fish as well as a loss of biodiversity and ecosystem integrity across the globe [1–3]. When eradication is not possible, as is almost always the case [4,5], containment is the only option [2,3]. In rivers, containment can be complicated by the presence of migratory native fishes and flooding. Developing ways to selectively control the upstream movement of invasive fish has challenged North American fisheries managers since the turn of the 19th century, when the common carp, *Cyprinus carpio*, and sea lamprey, *Petromyzon marinus*, [6–8] became abundant. Only a few solutions have been identified, and none for large rivers where testing options are expensive and difficult. These complexities make numerical simulations of control options a valuable tool. Here, we use numerical models to evaluate three control options for invasive bighead carp, *Hypophthalmichthys nobilis*, and silver carp, *H. molitrix*, (collectively known as bigheaded carp) at the locks-and-dams (LD) they must pass to move upstream in a large river. Our findings describe several promising ways that a targeted and integrated approach can effectively control an important invasive fish. In this introduction, we review the bigheaded carp problem, Mississippi River LDs, and three ways to control bigheaded carp at these choke points; we then outline our study objectives and approach before proceeding to the methods.

1.1. The Bigheaded Carp Problem

Recently, bighead carp and silver carp from Asia have become a serious problem in the Mississippi River Basin of North America [9]. Bigheaded carp were introduced to Arkansas from Asia in the 1960s, escaped into the Mississippi River [10] and continue to invade the upper reaches of the Mississippi River Basin. These species are large (>20 kg), microphagous filter-feeding fish that compete with native planktivorous fish for food, driving reductions in their abundance, size and condition, while altering food webs [11–13]. Additionally, silver carp can jump up to 3 m out of the water, interfering with recreational boating [14]. Bigheaded carps reproduce in areas of flowing water and have semi-buoyant eggs that require long stretches of flowing water to hatch and recruit, making the pools between LDs a good place to control and remove adults because LDs restrict fish movement [15–17]. Carp are also sensitive to sound, making them susceptible to being blocked with acoustic (non-physical) deterrent systems [18–20]. Finally, bigheaded carps are not particularly strong swimmers [21], so their movement through LDs is open to manipulation, especially in systems with multiple LDs that create impassible water velocities.

Bigheaded carp presently comprise the majority of the fish biomass in many areas of the Mississippi River Basin, although they have yet to establish themselves in either the headwaters of the Mississippi River or the Laurentian Great Lakes. While carp passage into the Great Lakes is currently protected by an electrical barrier in the Illinois River [17], the headwaters of the Mississippi River remain unprotected because they are wide and prone to flooding and thus cannot support a simple electrical barrier, so new approaches at LDs are sought.

1.2. Mississippi River Locks-and-Dams

The Upper Mississippi River (UMR) is regulated by a series of 29 LDs operated by the US Army Corps of Engineers (USACE) and are named (and numbered) in a sequential fashion from north to south (Figure 1). Nearly all LDs have both a navigational lock and a gated spillway system. The USACE operates these structures in a manner that permits navigation while protecting the structures from erosion/scour by limiting water velocities. Spillway gates are seated at the bottom of the river and progressively raised to pass water and regulate water depth, but in so doing, create water velocities underneath them that fish may struggle to overcome. As LD spillway gates are lifted, the velocity of water passing underneath them is reduced, dropping to a minimal value when/as they come out of the water entirely (a condition known as “open-river”). In contrast, flow in navigational locks is very low to allow boats (and fish) to pass, but access is regulated by miter gate opening and the locks are a relatively small (~10%) part of most dams. Together, spillway gates and locks inhibit upstream fish passage. However, their effects on fish vary: some LDs exert large effects on fish passage and some very little—depending on their design, local river conditions, spillway gate operations (e.g., the number, location, and opening height of each gate), and the fish species (fish swimming ability varies greatly) and their size.

Several LDs whose spillways rarely open fully are known to greatly reduce upstream fish passage of native migratory species including lake sturgeon, *Acipenser fulvescens,* and paddlefish, *Polyodon spathula*, [22–24] as well as invasive species including both bigheaded carps [25] and common carp [26]. Notably, the swimming abilities of carps are very similar when size is considered [21,26]. While some migratory fishes have disappeared from the Upper Mississippi River (UMR) since LDs were installed, analyses of the current fish population structure suggest that LDs likely have little effect on the remaining populations of native fishes [27], although their effects on newly arriving invasive carp appear quite substantial. The abilities of fishes to surmount spillway gates varies with environmental conditions that include water velocity, water temperature, fish species, fish size, and physiological condition, LDs that experience open-river conditions less frequently are more likely, on average, to impede upstream fish movement [28]. Many LDs in upper regions of the UMR experience open-river conditions far less often than those in the lower portion of the river (Table 1, [29]). While some LDs have overflow systems that operate during high flow (Table 1), many do not, or they could be screened, and thus these LDs can be used in carp control.

Table 1. Summary of locks-and-dams (LDs) in the Upper Mississippi River (UMR). The percent time spent in open-river was calculated from historical records between 1970–2000 [29]. Δ River km is the distance (pool size) between that LD and the next one upstream [29]. The Upper and Lower Saint Anthony Falls Dam (upstream of LD 1 and lacking an operational lock) and Chain of Rocks Lock (downstream of LD 26) differ structurally from LDs 1–26 and are not included. The final column indicates whether the lock-and-dam has an additional uncontrolled overflow spillway that functions during high flow conditions. Consecutive LDs that experience open-river conditions less than 5% of the time are shaded. Two LDs that do not go into open-river (0%), because they do not have spillway gates are also shown (LD 1, LD 19).

Lock-and-Dam	% Open-River	River km	Δ River km	# of Gates	Other Spillway?
1	0.0%	1365	8	0	Yes
2	1.3%	1312	53	19	No
3	15.6%	1282	29	4	Yes
4	3.9%	1212	71	28	No
5	1.7%	1188	24	34	No
5A	13.9%	1172	15	10	Yes
6	9.7%	1149	23	15	Yes
7	4.7%	1131	19	16	Yes
8	3.9%	1093	37	15	Yes
9	18.4%	1043	50	13	Yes
10	19.7%	990	53	12	Yes
11	1.8%	938	51	16	No
12	13.9%	896	42	10	Yes
13	5.5%	841	55	13	Yes
14	0.5%	794	47	17	No
15	1.3%	777	17	11	No
16	16.8%	736	41	19	Yes
17	31.9%	703	33	11	Yes
18	12.1%	661	43	17	Yes
19	0.0%	586	75	119	No
20	33.9%	552	34	43	No
21	21.3%	523	29	13	Yes
22	16.5%	485	38	13	Yes
24	17.6%	440	45	15	Yes
25	20.5%	388	51	17	Yes
26	19.7%	323	65	9	Yes

Importantly, LDs influence each other and the fish that pass through them, synergizing the ability of each to impede overall fish movement upstream; although this has not been well studied. Further, it is likely that adjacent (consecutive and proximate) LDs could have greater influence on bigheaded carp populations more than other LDs separated by great distances because bigheaded carp require 50-100 km of turbulent open river to reproduce successfully [30]. Of course, short pools (50-100 km) also create excellent opportunities for fisheries managers to sample, catch, and remove carp that might pass the LD immediately below them.

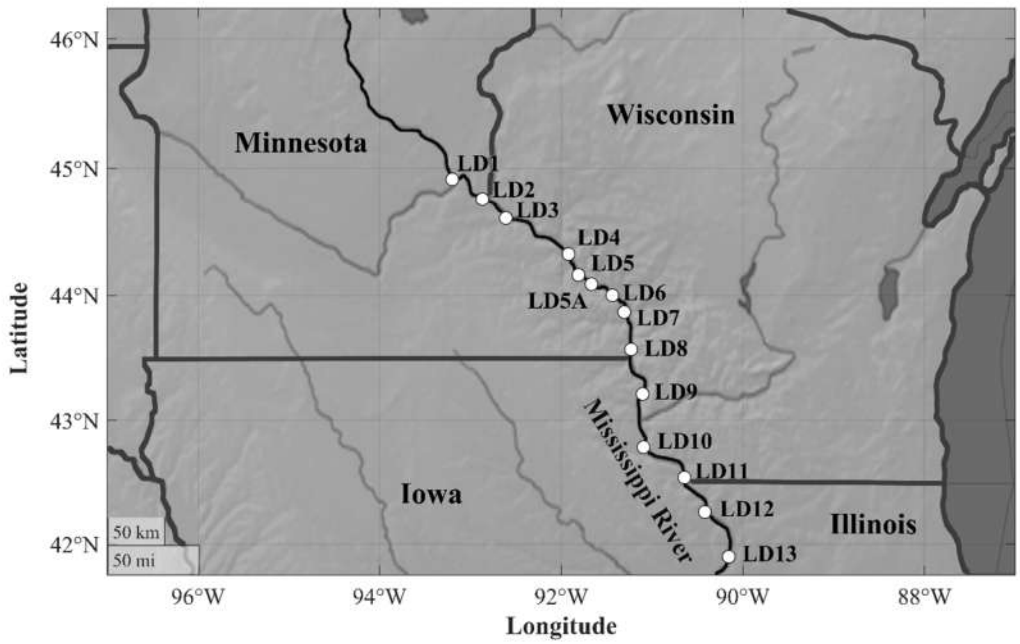

Figure 1. Location of locks-and-dams (LDs) in the upper portion of the Upper Mississippi River (UMR). See Table 1 for details on LDs.

1.3. Options to Control Carp Passage at Locks-and-Dams

Three good options exist to control carp at LDs: the spillway gates, the lock, and the pools above LDs into which fish must pass and where capture is possible. Of these, the spillway gates are of singular importance because they typically comprise 90–95% of the structure size and are at least partially open most of the time. Adjusting spillway gate openings is a good option to reduce carp passage. Its potential has been shown by both modeling [28] and descriptions of fish passage from fish tracking studies [26,31–33], the latter showing a strong correlation between spillway gate opening, water velocity, and passage. Numerical modeling at two relatively typical Mississippi River LDs, LD 2 and LD 8, has shown that fish passage through their gated spillways is dependent on hydraulic conditions that include velocities that exceed 5 m/s at lower gate openings through which very few fish can pass [26,28,34]. Further, we have developed a numeric fish passage model (FPM) that uses three-dimensional water velocities found around LD spillways gates to determine whether and/or how fish with known swimming abilities can (and do) swim through gates with different settings and river flow [28]. FPM simulations have also shown that the spillway gate operations presently used by the USACE can result in slightly unbalanced flow regimes at LDs, and thus create regions of low velocity that fish (carp) can swim through. Remarkably, this validated FPM describes ways ("optimized operating conditions") that spillway gate settings can be re-balanced to reduce carp passage, sometimes by as much as 50–75% [28,34]. As these modifications reduce scour, they have proven to be acceptable to the USACE [28]. Thus, modifying/optimizing spillway gate operations to balance water velocities at LDs when they are not in an open-river condition has great potential to restrict upstream carp passage at little to no cost.

A second option to control carp passage at LDs is to add deterrent systems to the lock chambers. LD lock chambers are designed to support barge navigation and thus have little measurable flow, making them well suited to these systems. Upstream fish passage through open lock chambers has been observed in the summer months for a number of fishes, including bigheaded carps [25,26,31]. Non-physical deterrent systems that use sound, or sound paired with other stimuli (i.e., air bubbles, strobe lights, carbon dioxide), are presently being developed for use in these systems [18,35–42]. Sound is favored because it is safe and, similarly to all ostariophysians, bigheaded carp have a wider hearing range and lower hearing threshold than many native fish. Laboratory tests using a variety of sound signals [37–41] and sound coupled with air-bubble curtains [36,38] have documented deterrent efficiencies between 75–97%. A test of a cyclic sound coupled with an air curtain and light (a bio-acoustic fish fence or "BAFF") blocked 95% of all carps in a creek, but further testing is required [42]. The effects of sound could be taxon-specific.

A third option to control bigheaded carp is fish removal in pools upstream of LDs. Removal is especially feasible in short pools where sampling to gauge effectiveness is reasonable and bigheaded carp may also be unable to reproduce. Carp removal could be achieved through subsidized targeted removal or possibly commercial ventures [43,44]. In the Illinois River, contracted harvest of bigheaded carp has been used successfully since 2010 to help reduce propagule pressure on the USACE electric barrier at Chicago [45]. Bigheaded carp are typically removed using short-set large-mesh gill and trammel nets. The gear used in the Illinois River selects for larger fish, and removal has been effective at decreasing the density of bigheaded carp populations restricted by a downstream LD [43,44,46].

1.4. Introduction to This Study

In the present study, a stochastic size-structured fish passage model (S-FPM) was developed to examine the potential for controlling bigheaded carp passage by blocking upstream passage using different combinations of modified gate operations, acoustic deterrence at navigational locks, and carp removal across pairs of consecutive UMR LDs. This model simulated passage of carp to examine ways it could be reduced. It examined many options at both single and consecutive LDs using known carp passage rates, monthly river discharge, several levels of lock deterrent systems, fish size, and different levels of removal. Our overarching goal was to determine whether and how an integrated approach to control bigheaded carp might be reasonable in the UMR and if so, what factors might best contribute to its efficacy. To address this, we asked several related questions: (1) What gains might be realized by managing bigheaded carp passage at two adjacent LDs versus just one?; (2) What benefits might be realized by modifying spillway gate operations at one or two LDs to reduce carp passage at different river flows?; (3) What are the benefits of adding a non-physical deterrent(s) to either individual or pairs of LDs and how do they compensate for increased fish passage at high flow?; (4) What additional benefits might carp removal schemes have on carp control?; and (5) How might these three options be employed together as part of an integrated pest management scheme? We focused on silver carp as it is the species of greatest concern and worked in sequential fashion, combining factors as we went to examine synergistic effects at varying river flows, the effects of which on spillway gate passage are complex but important. Lessons from silver carp should nevertheless apply to bighead and common carp as they have similar biologies. Possible effects of carp population size-structure and behavioral drive to attempt spillway gate passage were also examined. We use changes in fish passage rate as our metric, given the absence of data on silver carp population size in the upper reaches of the UMR.

2. Methods

The S-FPM was created to simulate and estimate annual upstream passage rates of bigheaded carp through either one or two LDs in the UMR. This model included 6 categories of variables including: (1) whether a single or a paired set of LDs is being managed; (2) local environmental variables (e.g., river flow); (3) carp population size-structure; (4) carp behavior/passage route; (5) carp passage rates at spillway gates and locks (and effects of deterrents on them); and (6) estimated effects of carp removal on overall passage rate (Table 2, see below). Over 100 scenarios were modeled using empirical data from LD 8, a relatively typical UMR LD (Table 1) which has 15 spillways gates and 1 operational lock. First, we describe the model, then the variables it uses, and then how it was deployed.

Table 2. List of stochastic size-structured fish passage model (S-PFM) variables and values. Where available, variable mean +/− standard deviation is provided. Variables are categorized by italicized section headings and further described in the methods. Data derived from common carp are noted with an (*), otherwise data come from silver carp. Q is river discharge. P_A_{US}, P_B_{US} are the proportions of fish that move upstream at LD A and LD B. P_A_L, P_B_L and P_A_S, P_B_S are the proportions of upstream swimming fish to atempt passage through the lock and spillway gates at each LD, respectively. PI_{lock}, PI_{spill} are the passage indices at the lock and spillway gates. At is the number of passage attmpts made per month at the spillway gates. D is the efficiency of a deterrent system inhibiting passage through the lock chamber. R is the proportion of fish removed from the intermediate pool.

Variable	Notation	Value	Source(s)
2.1.1. Environment			
River discharge	Q	50%, 20%, 5%, 1% exceedance flows	[47]
2.1.2. Fish population and size structure			
Population	-	50,000 per size class	N/A
Size classes	-	≤600, 700, 800, & 900 mm total length	[48]
2.1.3. Fish behavior—Upstream movement and route selection			
Proportion of upstream movement	P_A_{US}, P_B_{US}	87, 72, 52, 52, 45, 48, 13, 11 (+/−25%)	[49]
Lock route*	P_A_L, P_B_L	7.3+/−7.1%	[33]
Spillway routes*	P_A_S, P_B_S	27+/−16%	[33]
2.1.4. Fish behavior—Passage indices and deterrence			
Lock passage index*	PI_{lock}	5+/−5%	[31,33]
Spillway passage index	PI_{spill}	f(size, operation, discharge)	[28]
Attempts	At	1, 2, 5	[25]
Deterrence from lock	D	0, 25, 50, 75, 100%	[38,40,42]
2.1.5. Carp removal			
Removal	R	0, 5, 10, 40%	[17]

2.1. Model Framework

The S-FPM evaluates fish passage as a consequence of a series of junctions at either a single or two consecutive LDs (i.e., pairs of LDs with one located immediately upstream of the other so they synergize each's actions). While doing so it uses fish movement rates and route selection (i.e., the path fish pursue while swimming upstream) informed by both field data and fish spillway passage indices for LDs calculated using our fish passage model (FPM). Specific variables used in the S-FPM model include (Table 2): environmental conditions; fish population and size-structure; fish behavior—upstream movement and route selection; fish behavior—passage indices and deterrence; and carp removal. Fish passage at LD spillway gates is considered using our FPM which considers fish swimming performance with respect to species and size, as well as water velocities at specific LD spillway gates as informed by LD structure and river flow using computational fluid dynamics (CFD) [28]. When possible, silver carp data (e.g., swimming performance) were used but when not available, data were used from the closely related common carp (e.g., passage rates through spillways gates of LD).

The S-FPM model employs two LDs (LD A and LD B) and they have the same spillway gate operations, a realistic scenario because most UMR LDs have nearly identical structural components (Figure 2). LD 8 is used as the base conditions for each, which is reasonable because its design is typical of most LDs and it is also well studied [28]. Both LD A and LD B are associated with pools: Pool A is downstream of LD A, Pool B is located between LD A and LD B, and Pool C is located upstream of LD B. In the model, carp start in Pool A. and the S-FPM calculates passage rates of carp moving from Pool A to Pool C each month for a year (which thus includes seasonal effects). Each month a proportion of fish moves upstream (P_A_{US}, P_B_{US}) and then attempt to pass through one, or both LDs. While doing so, each upstream swimming carp is assigned to one of three routes: the spillway gate (P_A_S, P_B_S), the navigational lock (P_A_L, P_B_L), or both spillway and lock (P_A_{S+L}, P_B_{S+L}). The combined route of spillway and lock gives fish the opportunity to pass through either the lock or spillway (a scenario observed at LD8 [33]), while the other routes limit to just one route. The likelihood of passage through the lock chamber is modelled using mean passage rates of common carp observed at LD 8, while passage through the spillway gates has been determined using the fish passage index (FPI) previously calculated by Zielinski et al. [28]. Individual carp that pass either route (P_A_{pass}, P_B_{pass}) then move into the upstream pool and those in Pool B are subjected to the passage model again whereas those in Pool C remain upstream of LD B. Fish that do not either move upstream or attempt to do so and are blocked by either LD A or LD B's spillway gates (B_A_S, B_B_S) or lock chamber (B_A_L, B_B_L) return to their pool of origin and undergo the passage model the subsequent month (if/when the model simulation allows for future attempts- we tested 1-5 attempts). Those carp that pass LD A and are found in Pool B are also then subject to possible removal (R). River flow (i.e., discharge), proportion of upstream movement, route selection, and passage indices were updated monthly in the model. The total number of fish from each size class within each pool was recorded monthly and divided by the initial population size to determine the proportion of fish passing each LD (the percent). Finally, the number/proportion of carp eventually found in Pool C represents the proportion that passed both LDs while the combined proportion of fish in Pool B and Pool C reflect the proportion passing a single LD (LD A). The model was coded in Matlab (Mathworks, MA, USA) (Figure 2).

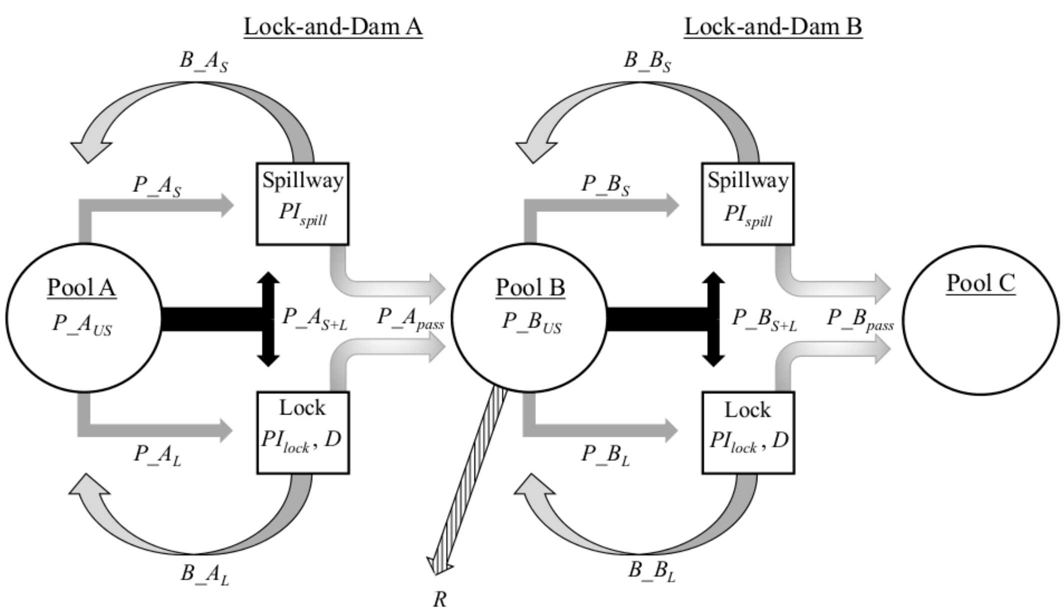

Figure 2. Schematic representation of the stochastic size-structured fish passage model (S-FPM). The model uses a silver carp population with five size classes that are released in Pool A (downstream).

2.1.1. Environment

Opportunities for fish passage at LDs vary with spillway gate openings and these were determined by river discharge. The S-FPM model examined 4 hydrologic scenarios in the UMR and which we describe as monthly exceedance values. Monthly exceedance discharge is equal to the median monthly discharge that is exceeded for some percentage of the time. Exceedance was calculated from 30 years of river discharge at LD 8; we identified 50%, 25%, 5%, and 1% exceedance discharge values [47]. In our case (LD 8), a 50%

and a 25% exceedance discharge condition does not require the spillway gates to be fully open anytime during the year, while the 1% exceedance discharge condition requires LD 8 to operate in open-river conditions 7 months of the year (Figure 3).

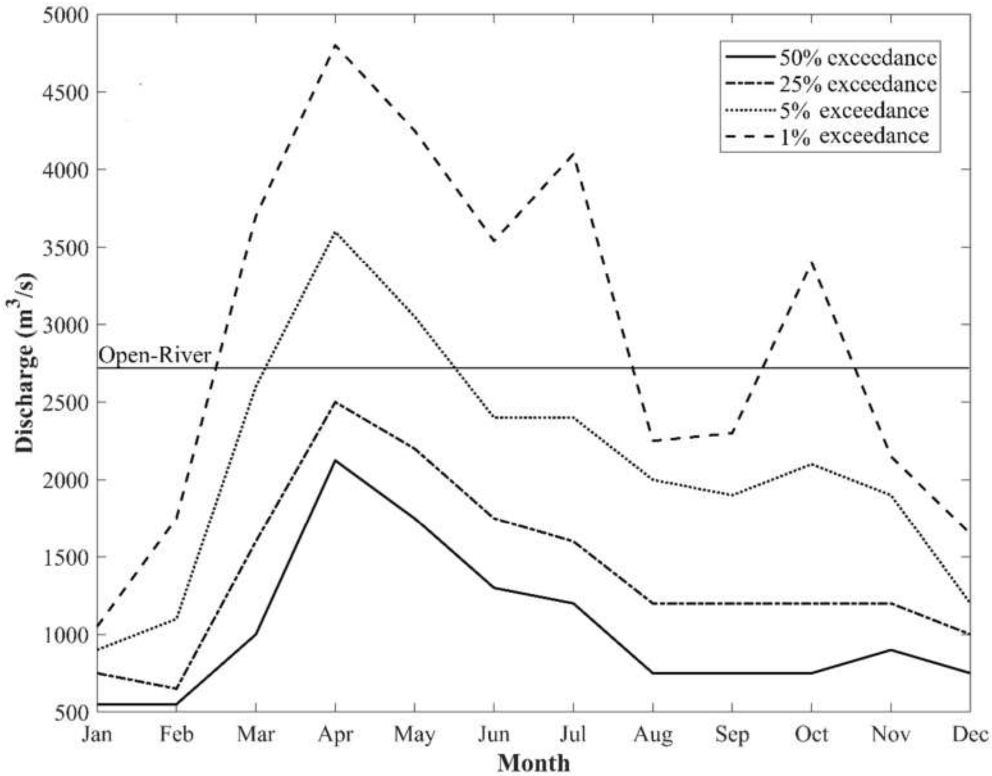

Figure 3. Monthly discharge at LD 8 based on 50%, 25%, 5%, and 1% exceedance durations between 1972–2000 [47]. Open-river conditions start when discharge is greater than 2718 m^3/s.

2.1.2. Fish Population and Size Structure

Each simulation used a population of 200,000 numeric silver carp from 4 size classes (50,000 carp per size class). This number was selected to minimize variance between model runs (the variance was calculated to be less than 0.5% for each size class at 50,000 fish). A size-structured approach was used because swimming performance, is influenced by fish size [21]. Each run of the model was initialized with a population of carp being placed into Pool A, which was assigned a body length from one of four 100 mm size classes based on data from either the UMR or Wabash River where carp have been established longer and are larger [48] (Table 3). Because most silver carp in the UMR have a total length of less than 600 mm, a size class whose swimming abilities are not known, the size distribution of carp used in the model was adjusted so that the smallest carp was 600 mm. This likely led to conservative (artificially high) estimates of passage rate as small fish cannot swim as fast as larger fish. For model simulations, the proportion of each size class of carp found within each pool was multiplied by the length-frequency percentage of a given population distribution (Table 3) to produce relevant size-specific results. The UMR population size-structure was used as the default in the S-FPM reported in the results although the impact of fish size-structure on the model was calculated for reference (see Supplemental data, Figure S1).

Table 3. Length-frequency distributions of silver carp (by 100 mm length increment) from the Upper Mississippi River (UMR) and Wabash River [48].

Total Body Length (mm)	% Frequency in the UMR *	% Frequency in the Wabash River
≤600	90	8
700	6	38
800	3	51
900	1	3

* 73% of the UMR silver carp population has a total length ≤500 mm.

2.1.3. Fish Behavior—Upstream Movement and Route Selection

Telemetry studies have shown that upstream movement rates of carp vary seasonally [49,50] and that carp take different paths through LDs [26,31,33] with carp moving upstream more vigorously in the spring than in summer and fall. Our S-FPM used seasonal upstream movement rates, and assumed fish did not move between November and February (Table 2). The proportion of each size class within each pool that was selected to move upstream (P_A_{US}, P_B_{US}) was randomly assigned from a normal distribution with a mean equal to the mean upstream movement measured by Coulter et al. [49] with a standard deviation of 25% of the mean. All individuals were then assigned a movement indicator (R_1) from a uniform random distribution (0-100) each month. In Pool A, individuals with $R_1 \leq P\_A_{US}$ moved upstream to challenge LD A. Any individuals that passed LD A were then assigned a new movement indicator once they entered Pool B and the selection process repeated itself.

Just as different numbers of bigheaded carp could move upstream (or not) in the river and our model, they could also choose different paths or routes, with some carp following the river's edge to encounter a lock, others moving to the center of the channel and encountering a spillway gate, and others demonstrating a mixed approach that included both options. Our model considered these three possibilities using available data. An ongoing study using acoustic telemetry is assessing the movement and passage of common carp at LD 8 [33] and we used its findings. Briefly, data collected in 2019 from over 100 transplanted, tagged common carp downstream of LD 8 found that 7.3% of all adult common carp approached only the lock chamber, 27% approached only the spillway gates, and the remainder explored both options. These values were employed and the proportions of upstream moving carp selected to move towards the lock chamber (P_A_L, P_B_L) or the spillway gates (P_A_S, P_B_S) were randomly assigned from a normal distribution with a mean and standard deviation derived from the common carp data collected by Whitty et al. [33]. All individuals moving upstream were assigned a route indicator (R_2) from a uniform random distribution (0-100) each month. In Pool A, individuals with $R_2 \leq P\_A_L$ attempted to pass through the lock chamber and individuals with $R_2 \geq 1 - P\_A_S$ attempted passage through the spillway gates. All remaining, unassigned fish attempted passage through both the lock chamber and spillway gates. Individuals passing LD A are assigned a new route indicator and the route selection process repeated for LD B.

2.1.4. Fish Behavior—Passage Indices and Deterrence

The likelihood of any fish (carp) passing through a lock chamber is dependent on a combination of opportunity and behavior. In contrast, the likelihood of them making through spillway gates is driven by opportunity, behavior, and swimming performance. Both were modeled for a single LD and consecutive LDs. First, we discuss passage rate at the spillway gates, then locks.

Spillway Gate Passage

Fish (carp) passage through spillway gates is dependent on several variables including fish species, size, behavior, and gate opening/water velocity (i.e., gate operations). To estimate the likelihood of carp passing through LD spillway gates, we used the fish passage indices (FPI) we developed earlier [28] for silver carp at LD 8. Briefly, the FPI was calculated using a FPM which pairs high-resolution water velocity data at specific gate settings with known fish swimming performance data to predict if, when, and where fish could pass through a hydraulic structure assuming the fish follows the path of least resistance (a conservative assumption) [28]. This FPM and its resultant FPIs have been validated in tracking studies of common carp at LD 2 [26] and LD 8 [33].

To create estimates of spillway passage, the S-FPM used FPI values [28] to assign a spillway passage index (PI_{spill}) at both LD A and LD B that was based on river discharge and fish length (we used data from the UMR and another location, see below). We calculated FPI for silver carp assuming both base (current/historical) gate operations and gate operations modified and optimized to restrict carp passage for five river discharges including open-river conditions [28]. We used linear interpolation to calculate the spillway passage index at intermediate discharges and the nearest value for discharges outside of the range [28] (Figure 4). Individuals assigned to the spillway route were then assigned a spillway passage indicator (R_3) from a uniform random distribution (0-100) each month. In Pool A, individuals with $R_3 \leq PI_{spill}$ successfully passed through LD A spillway gates while all remaining fish were blocked. Any individuals that passed LD A and were assigned to the spillway route were assigned a new spillway passage indicator and the spillway passage process repeated. The spillway passage index calculated for the S-FPM included an attempt variable (At) that allowed fish to challenge the spillway gates multiple times per month. Based on the average number of attempts observed by silver carp at Starved Rock Lock-and-Dam [25], the model assumed each fish following the spillway gate route was assigned 2 passage attempts per month. Over the 8-month period of our model, any given fish could attempt to pass through the spillway gates up to 16 times. Simulations using 1 and 5 attempts per month were also run to evaluate how attempt rate impacts passage estimates (Supplemental data, Figure S1).

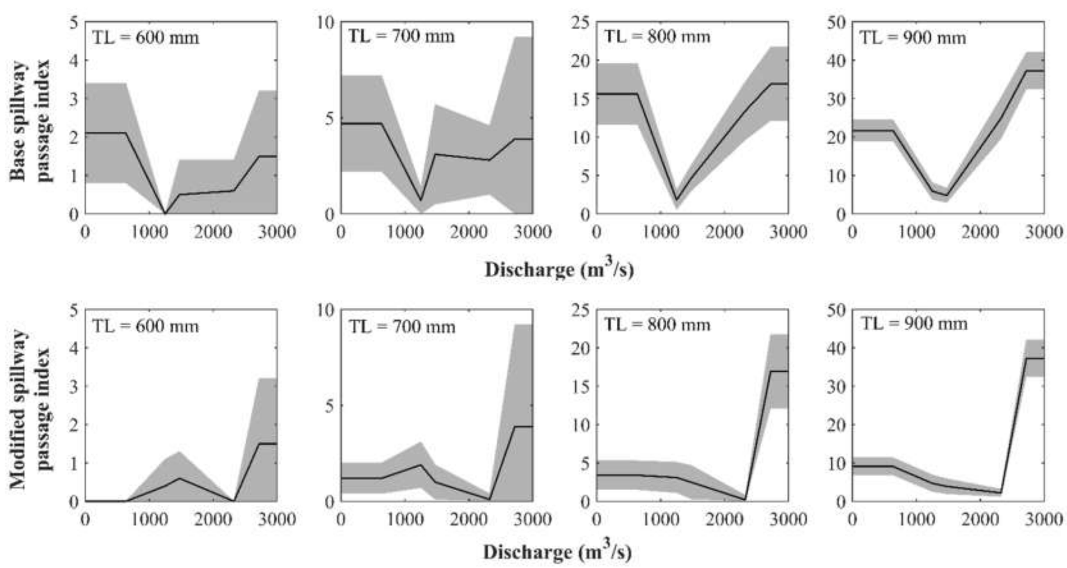

Figure 4. Spillway passage index for silver carp with a total length of 600-900 mm at LD 8 under base and modified gate operations [28]. The solid black line indicates the mean passage index and shaded area is the standard deviation. The passage index is calculated at 635, 1250, 1475, 2325, and 2720 m^3/s (open-river). Note, the different y-scales for each total length.

Lock Passage and Deterrents

Fish can only swim upstream through a lock chamber when a boat is locking through it and its miter gates are open. To do so, fish must enter the lock chamber, an area of high noise and turbulence, and their success in passing appears to be low. For instance, the rate of passages relative to the number of passage attempts was found to be 7% for silver carp at LD 26 [31] and 5% for common carp at LD 8 [33]. In our model, the lock passage index (PI_{lock}) at each LD was randomly assigned from a normal distribution with a mean and standard deviation from empirical data collected by Whitty et al. [33] and Tripp et al. [31]. As reported, passage rates [31,33] were measured relative to the number of passage attempts, so the lock passage index does not need to explicitly simulate multiple passage attempts through the lock chamber (i.e., passage rate is expected to be ~5% regardless of the number of attempts). Individuals assigned to the lock chamber route were assigned a lock chamber passage indicator (R_4) from a uniform random distribution (0-100) each month. In Pool A, individuals with $R_4 \leq PI_{lock}$ successfully passed through the lock chamber while all remaining carp were blocked. Individuals passing LD A were then assigned a new lock chamber passage indicator and the lock passage process repeated at LD B.

Of course, base passage rates through locks can, in theory, be reduced by adding deterrent systems to them. We included the possibility that a deterrent will be developed and successfully implemented for use in LD(s) in our model. Due to uncertainty in the specifics of the deterrent type and efficacy, we examined the impact of adding deterrents at one or both locks with several efficiencies: 0%, 25%, 50%, 75%, and 100%. Deterrent values were based on those already measured in the field and laboratory for acoustically based systems [36–42].

Lock and/or Spillway Passage

Finally, our model allowed for the possibility that some carp will attempt to move upstream using a combination of both locks and/or spillway gates (e.g., fish assigned to the spillway + lock chamber route). Each month these individuals were assigned both a lock chamber and spillway passage indicator. Similar to fish assigned to just the spillway route, fish were allowed multiple attempts to pass the spillway gate per month (if appropriate). If passage criteria were satisfied for either the lock chamber or spillway gates, that carp was deemed to have passed that LD.

2.1.5. Carp Removal

Physical removal of fish is commonly used to control populations of invasive species [43,51]. This approach is already being successfully employed in the Illinois River to control bigheaded carp using contracted commercial fishers [43,45,46]. Simulations using the Spatially Explicit Asian Carp (SeaCarP) model estimate 40% of the population needs to be harvested to reduce the risk of introduction into the Great Lakes, and it is possible this is presently being achieved in some areas [17] where the population seems to be constant. Several fishing techniques have been developed for this purpose and are still being improved including the "Modified Unified Method" from China [17]. We included the possibility of removal in our model as R (removal) and assign it values 0%, 5%, 10% and 40%. Each month, all individuals that move into Pool B were assigned a removal indicator (R_5) from a uniform random distribution (0-100). Individuals with $R_5 \leq R$ were then removed from the population. The likelihood of removal was the same for all sizes of fish in Pool B.

2.2. Model Simulation

Over 100 simulations were run to assess the individual and combined impacts of modified spillway gate operation, lock deterrence, and removal on silver carp passage rates through single and consecutive LDs (Table 4). For each simulation, we tracked the number of fish passing both LD A and LD B individually and the annual proportion of fish passing each structure was calculated by dividing the total passed by the initial population size. The proportion of carp passing LD A was the total passage rate expected at one LD and the proportion passing LD B is the total passage at two consecutive LDs. Modeling proceeded in 4 steps so we could systematically evaluate the role of different variables in a step-wise fashion with each variable (management action) being added to the previous case. We started by exploring the roles of the simplest management option, modified gate operation. First, passage rates during either base (current as determined from USACE historical records) or modified spillway gate operations to block silver carp were calculated and then compared at different flow (exceedance) scenarios. Second, the impact of adding non-physical (acoustic) deterrent(s) with several efficiencies to LD lock(s) were examined using modified spillway gate operations. Third, the impact of employing carp removal in the intermediate pool (Pool B) on overall annual passage was examined in combination with varying levels of lock deterrence, including none and assuming modified spillway gate operations. All cases used the carp size structure measured in the UMR distribution [48] while carp were allowed to attempt to pass twice a month, per expected values. After completing these runs at different flow (exceedance) conditions, we examined the average annual effects of several combinations of variables across all exceedance values expected in a year. We did this to evaluate the overall effects of individual variables. Finally, we assessed the impact of population size structure and spillway gate passage attempt rate assuming modified spillway gate operations, no lock deterrence, and no removal (Supplementary data, Table S3). A total of 104 simulations were run to accommodate all iterations over four hydrologic scenarios (Table 4), the results of which are presented in Supplemental data (Tables S1 and S2).

Table 4. List of unique model simulations. Brackets indicate range of values used in each simulation. Each simulation provides the annual proportion passing either a single or pair of two consecutive LDs.

No. of simulations	Exceedance Discharge (%)	Spillway Operation	Deterrence (%)	Targeted Removal (%)	Attempts	Size Distribution
4	(1, 5, 25, 50)	Current	0	0	2	UMR
80	(1, 5, 25, 50)	Optimized	(0, 25, 50, 75, 100)	(0, 5, 10, 40)	2	UMR
8	(1, 5, 25, 50)	Optimized	0	0	(1, 5)	UMR
12	(1, 5, 25, 50)	Optimized	0	0	(1, 2, 5)	Wabasha

3. Results

3.1. Effects of Managing Carp Using Consecutive LDs

Our model suggested that approximately 18.1% of silver carp of the size presently found in the UMR can be expected to pass a single typical LD under base (historical) spillway gate operating conditions during the course of a typical year with this rate increasing to 22.4% at high flows (Figure 5, Table S1). When two LDs were considered instead of a single LD, this rate dropped by 85% across all simulated flows to approximately 2.7% (Table S1). The effects of managing carp at two adjacent LDs locations were multiplicative.

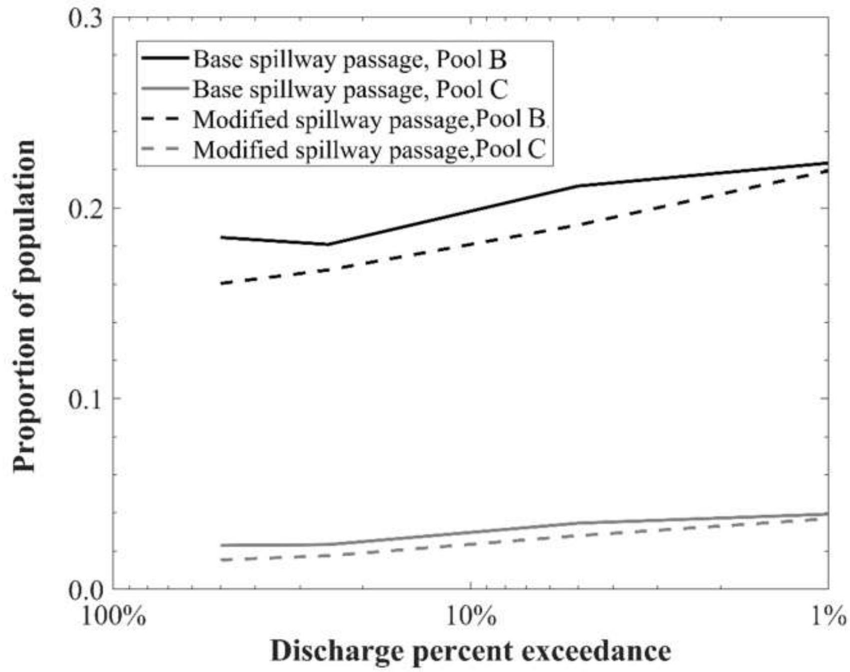

Figure 5. The proportion of silver carp passing a single LD (black lines) or two consecutive LDs (grey lines) under base spillway passage conditions (solid lines) or modified spillway gate conditions as calculated by our FPM (dashed lines).

3.2. Effects of Managing Carp by Modifying LD Spillway Gate Operations

Modifying spillway gate function at a single LD had notable effects, reducing the proportion passed by approximately 11% at an exceedance of 50% for one LD but dropping to only 2% at an exceedance of 1% when the river is mostly in open-river conditions (Figure 5, Table S2). When the effects of modifying spillway gate operations on passage through consecutive LDs was considered, the overall proportion passing two LDs decreased by about 88% to an overall value of only 1.5–3.7%. Notably, while consecutive LDs may be expected to go into open-river at similar times, they were unlikely to be identical and if the distance between them small, reproduction may be unlikely. Modifying spillway gate operations was thus especially beneficial at pairs of LDs that rarely go into open-river, but other options probably should be considered for the later scenario at higher flows (exceedances).

3.3. Effects of Adding a Non-Physical Deterrent to One or Both Locks

Adding a deterrent to the lock chamber of one or both LDs operating their spillway gates in a modified manner was very effective, especially when pairs of LDs were considered (Table 5, Figure 6 and Table S2). At a single LD, lock deterrence systems that were more than 50% effective reduced the number of silver carp that could pass to less than 10%. If a deterrent with 100% efficacy was used, the value dropped to 2% at the 50% exceedance flow, and to less than 10% at the 1% exceedance flow when gate operations were modified (Table S2). When two LDs were considered, each with a deterrent in the lock, the annual proportion of silver carp passing was less than 2% for a deterrent only 50% effective overall under all deterrence levels and modified gate operations. Notably, the relative impact of a lock deterrent on fish passage was relatively unaffected by flow conditions.

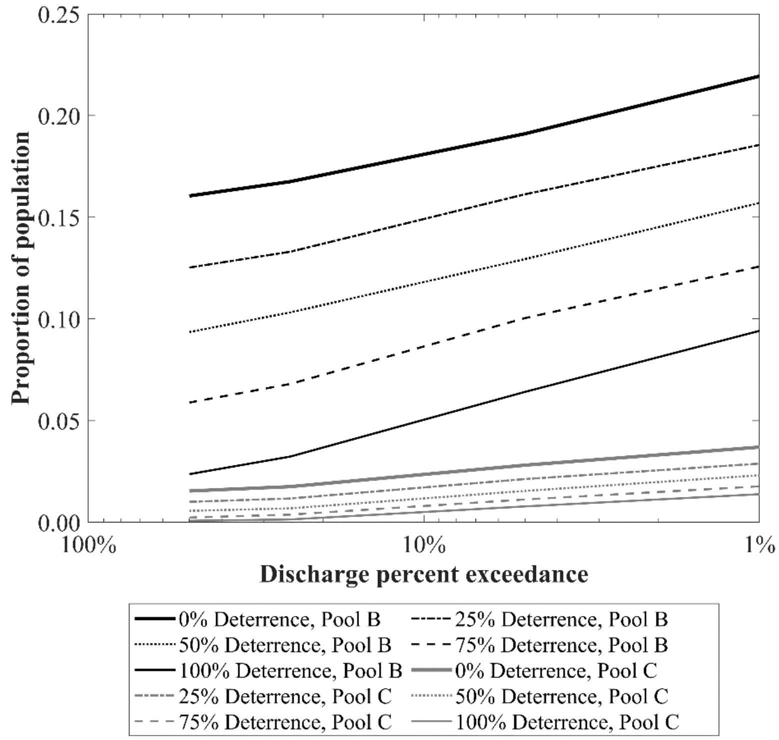

Figure 6. The proportion of upstream swimming silver carp passing through either a single LD (black lines) or two consecutive LDs (grey lines) equipped with nonphysical deterrents of different efficacies and using modified spillway gate operations.

Table 5. Summary of the estimated effects of pairing LDs, modifying their gate operation, adding a deterrent to the lock chamber and removing carp in the intermediate pool between them on the overall annual passage rates of the silver carp population with the size structure presently found in the UMR [48]. The annual proportion of carp passed is averaged across all four flow scenarios. Percent reduction is calculated relative to the proportion passed at a single LD (1 LD) under base gate operations conditions.

Case		Proportion Passed	% Reduction
Base gate operations			
	1 LD	0.200	NA
	2 LD	0.030	85
Modified gate operations			
	1 LD	0.185	8
	2 LD	0.025	88
Modified gate operations + deterrents			
	1 LD + 25% Det	0.151	24
	1 LD + 50% Det	0.121	40
	1 LD + 75% Det	0.088	56
	1 LD + 100% Det	0.054	73
	2 LD + 25% Det	0.018	91
	2 LD + 50% Det	0.013	94
	2 LD + 75% Det	0.009	96
	2 LD + 100% Det	0.006	97
Modified gate operations + removal at intermediate pool			
	2 LD + 5% removal	0.022	89

2 LD + 10% removal	0.021	90
2 LD + 40% removal	0.014	93
Modified gate operations + deterrents + removal at intermediate pool		
2 LD + 25% Det + 5% removal	0.017	92
2 LD + 50% Det + 5% removal	0.012	94
2 LD + 75% Det + 5% removal	0.008	96
2 LD + 100% Det + 5% removal	0.006	97
2 LD + 25% Det + 10% removal	0.015	92
2 LD + 50% Det + 10% removal	0.011	95
2 LD + 75% Det + 10% removal	0.008	96
2 LD + 100% Det + 10% removal	0.006	97
2 LD + 25% Det + 40% removal	0.010	95
2 LD + 50% Det + 40% removal	0.007	96
2 LD + 75% Det + 40% removal	0.006	97
2 LD + 100% Det + 40% removal	0.004	98

3.4. Effects of Carp Removal in the Intermediate Pool

Adding carp removal to a control scheme while utilizing modified gate operations and a deterrent had additional effects on reducing passage. Effects were multiplicative with a removal rate of 40% without lock deterrence reducing overall annual passage by 93% compared to a single LD with base spillway gate operations (Figure 7, Tables 5 and S2).

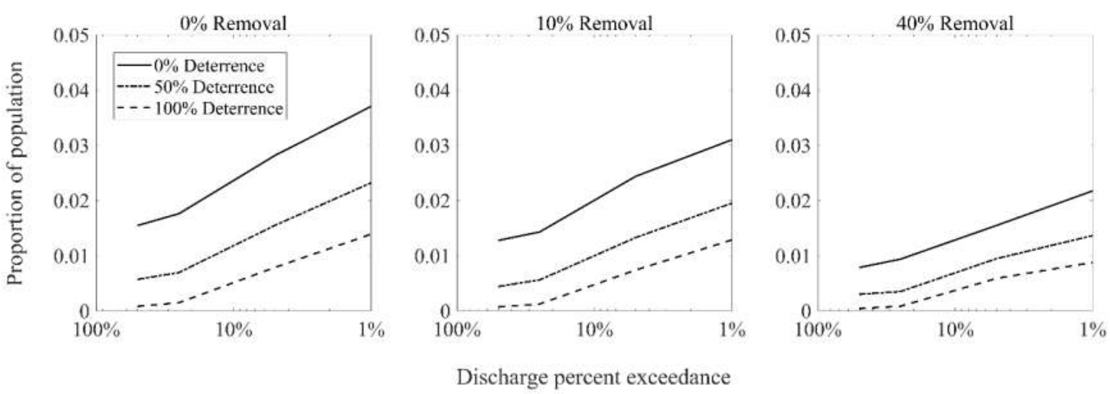

Figure 7. Proportion of silver carp passing two consecutive LDs equipped with non-physical deterrent systems with different efficacies and whose intermediate pool was subjected to carp removal.

3.5. Overview of the Averaged Combined Effects of Multiple Management Options

Lastly, we calculated average annual carp passage rates when all exceedance values were considered. These showed that when pairs of adjacent LDs were considered, only 3% of all carp attempting to pass can be expected to do so with 2 attempts, versus 20% at 1 LD (Table 5). Modifying gate operations drops this value to 2.5% (88% drop from one LD with base spillway operations). If a 50% effective deterrent is added to two LDs the average value decreased to 1.3 % and if the deterrent increases to 100% effective, the proportion passed drops to 0.6% (a 97% decrease vs. nothing occurring at one LD, the current situation). The addition of carp removal together with lock deterrents had the greatest impact on reducing silver carp passage rates. The best-case scenario reduced silver carp passage to only 0.4% and required 100% lock deterrence paired with 40% removal in the pool (Figure 7). Notably, several levels and types of carp removal and lock deterrence achieved the same level of passage reduction. For example, the annual passage rate at consecutive LDs could be reduced to less than 1% by pairing 10% removal rate with a lock deterrent with as little as 50% efficacy, even when exceedance values approached 1%. If the deterrent was close to 100% effective, values decreased by about half again (Table 5).

4. Discussion

Our simulations demonstrate that upstream passage of invasive silver carp in the UMR can be reduced to only 1-2% of current rates through an integrated approach that uses consecutive LDs and some combination of three tractable control techniques. These include reducing passage using spillway gate adjustment, adding non-physical deterrents to lock chambers, and removing carp from the intermediate pool. While modification of the spillway gate operation could occur with no modification to infrastructure, both lock deterrents and carp removal are likely to be costly, although they do not need to be highly efficient (i.e., 50% efficacy might suffice) to drive over 90% reductions in carp passage. Remarkably, carp control appears possible even during high river flows with an approach that employs pairs of strategically selected LDs. All of the control measures we describe can be implemented.

We believe that our simulations are reasonable because they are based on empirical data (ex. exceedance values, known gate settings, velocities, fish passage routes and swimming abilities) and a validated fish passage model that was designed to provide conservative overestimates of actual passage [28]. It is also promising that silver carp telemetry data suggest this species does not challenge LDs repeatedly [31,32]. The recent documented movement of significant numbers of adult bigheaded carp through both LD 19 [52] and LD 8 [53] attests to an urgent need to reduce bigheaded carp passage rates below the conditions currently existing at LD 8. A 50% reduction in passage rates seems possible using a single control option, while a 90% or greater reduction to an overall rate of just 2% appears attainable if both a deterrent and carp removal is used, even during times of high flow and need only be moderately effective (25%). Previous suppositions that carp can only be stopped at systems that lack operating gates [32] appear overly simplistic, which is important because only 2 of the 29 LDs in the UMR do not have bottom mounted spillway gates.

The most significant finding of our study is likely that bigheaded carp should not be managed at single LD, as has been the practice, but at pairs of LDs close to each other that rarely experience open-river conditions. Fortunately, three such locations exist in the UMR: LD 14–15, LD 7–8, and LD 4–5 (see management section below) (Table 1). Across all hydrologic scenarios, the cumulative impact of adding a second LD resulted in an average decrease in carp upstream passage of 85% compared to passage at a single LD. These LDs need to be located close to each other (50–100 km) to be effective, prevent spawning, and facilitate monitoring as well as possible removal.

Likely our next most important finding is that modifying LD spillway gate operations to reduce passage can be highly effective on an annual basis and would come at little cost because the predictive models have been developed and validated [26,28]. Simply modifying gate operations at a single LD decreases carp passage by about 8% overall. Multiplicative effects are expected if operations are optimized at two locations. Importantly, the modifications to gate operations we propose are safe for navigation and LD structural integrity as they do not induce additional scour [28]. While promising for both carp control and LD operations, the benefits of modified gate operations are restricted to the period when LD(s) are operating under controlled conditions (e.g., non open-river), so additional control options such as adding a lock deterrent and removing carp must be considered. Notably, the S-FPM model results we describe are conservative and estimate the upper limit of passage rates owing to our conservative assumption of fish behavioral drive and our assumption that carp can find the most efficient way upstream [28]. The hydrologic scenarios we considered were also conservative because the possibility of average monthly discharge surpassing the 1% exceedance flow for 12 consecutive months is low. For example, the 1% exceedance discharge conditions that would require LD 8 to operate in open-river conditions for 10 straight months, or 83% of the year, actually occur less than 5% of the time [29].

The third most important finding of this study is that a single approach to controlling carp is unlikely to suffice: an integrated approach is needed. Together the three options we described synergize with each other's activities, especially at times of high flow when passage through the spillway gates is high. By using all three options, none of them needed to be singularly effective. Ideally, three options would be implemented but two might suffice if used strategically.

The addition of non-physical deterrent systems to LDs had a notable effect on overall system efficacy that persisted during high river flows even if not highly effective. Typically, non-physical deterrents can be expected to reduce overall annual silver carp passage by about 5% even if the deterrents are only 25% efficient, and close to 20% overall if 100% efficient, the efficiency presently suggested for a BAFF [38,42]. If deterrents were used in two locks, the effects would be multiplicative at all flows. Notably, a BAFF guides fish away from the lock openings so it could be paired with a trap to remove carp as well as capture native species below the LD for possible movement upstream (although see [27]). A BAFF operating at 100% efficiency could thus drive a removal rate of about 20%, compensating for the cost and effort of running a removal program and supplement native fish conservation. Some level of species-specificity which might permit native fish passage may also be possible with acoustic deterrents, such as the BAFF, because carp are especially sensitive to sound [19,37,38,40–42]. Other types of deterrent systems that use CO_2 [36] could be considered, but the would not be species-specific. A BAFF is presently being tested at a LD on the Kentucky River and shows promise [54]. Deterrents appear likely to be a necessary component of an invasive carp control system and their continued development is encouraged.

Even modestly effective carp removal efforts would also be helpful in an integrated carp control program, especially if implemented in pools between paired, managed LDs. Removal would amplify the effects of modified gate operation and deterrents. Further, if a deterrent is not implemented, removal would be necessary, especially at times of high river flow when carp passage will be high. While the actual efficacy of carp removal is presently unknown, and numerous reports suggest it is low, it has adequately prevented the spread of adult silver carp further up the Illinois River [43,44]. Several techniques have been developed and improvements are being made to the "modified unified method" [17]. Notably, carp removal is likely to be especially effective in small pools where it would also limit possible spawning success, the ultimate objective of most fish control strategies [3]. The choice of LDs and the pool between them will be very important for removal strategies, and even modestly effective removal strategies, as low as 5%, would be beneficial. Admittedly, removing carp when there are low densities is difficult and may require use of radio-tagged Judas fish or perhaps eDNA [55,56]. Removal year-round is exceedingly labor-intensive, difficult [17], and expensive (Illinois spends more than a million dollars on this annually [53]). If less than 5% efficiency is realized in a UMR pool then a deterrent will be needed. More work on quantifiable removal options is needed. In any case, it is clear that an integrated approach using multiple control options at multiple LDs is highly desirable.

Our model also evaluated the importance of fish size on passage rates. Large silver carp, such as those found in the Wabash River appear nearly twice as likely to pass (Figure S1, Tables S3 and S4). The behavior of these fish is also important; an increased number of passage attempts significantly increased passage across all hydrologic conditions. For example, fish that attempted spillway passage 5 times per month had nearly a 2-fold increase in passage (Figure S1, Tables S3 and S4). This result is consistent with findings of others [57]. Fortunately, there is good reason to consider that the average attempt rate of bigheaded carp may not be higher than 5 attempts, although this requires study.

Our model has some notable strengths and weaknesses. Most important, as described above, our model assumptions are conservative and likely produce overestimates of passage. Indeed, they are based on empirical data and consistent with the slow upstream spread of bigheaded carp—over 10 years to pass LD 19 [52]. River flows are unlikely to be as consistently high as we modeled. Further, bighead carp are less likely to pass than silver carp based on their swimming performance [21]. Nevertheless, our model does have some uncertainties. First, we do not know the efficiencies of non-physical deterrents at LDs [38,42]. Second, the efficacy and size-selective nature of removal in rivers is unknown. Our model also does not account for fish population demographics.

5. Summary

This study clearly demonstrates that silver carp and likely other carps can be effectively (98%+) blocked at select pairs of LDs if they are operated in tandem and employ multiple approaches including modified gate operation, lock deterrents, and carp removal. These options could be used in multiple ways and need not be 100% efficient. Further information and improvement can come once an integrated control scheme is put into place.

6. Management Recommendations and Future Directions

It is reasonable to consider controlling invasive bigheaded carps at LDs in the UMR. Control strategies should employ pairs of LDs that are close to each other and rarely experience open-river conditions and at least two of the three options we have described. This could be extremely effective and economical. As the likelihood of carp passage increases with fish size, so does the chance of their reproducing, efforts should be timely. Three pairs of UMR LDs meet the criteria for successful control, but LD 4–LD 5 seem to have special promise because silver carp have not moved beyond them yet and bred, they are very rarely in open-river, Pool 5 is small, and they resemble LD 8 so their hydraulics are understood [28,34]. Ideally gate operations will be modeled and optimized. As with common carp control, developing ways to monitor carp abundance will be critical to success [4,5]. Detailed studies of carp movement around and through LDs will be extremely helpful as would further modeling efforts to improve model precision to guide carp control in UMR and elsewhere in the basin [58].

Supplementary Materials: The following are available online at www.mdpi.com/2410-3888/6/2/10/s1, Figure S1: Impacts of population size on passage, Table S1: Carp passage rates with and without gate modifications at different exceedances; Table S2: Carp passage rates with gate modifications at different control options at different exceedances; Table S3: Carp passage rates with and without gate modifications and different numbers of attempts.

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