Deterrent Strategy Planning for Asian Carp in the Ohio River Basin

2019 Technical Report

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Geographic Location: Ohio River Basin; Tennessee and Cumberland rivers

Participating Agencies: Tennessee Wildlife Resources Agency (TWRA), Tennessee Technological University (TTU), U.S. Geological Survey (USGS), Kentucky Department of Fish and Wildlife Resources (KDFWR), Mississippi Department of Wildlife, Fisheries, and Parks (MDWFP), Alabama Department of Conservation and Natural Resources, U.S. Army Corps of Engineers (USACE), Tennessee Valley Authority (TVA), Murray State University (MSU), West Virginia Division of Natural Resources (WVDNR), Indiana Department of Natural Resources (INDNR), Ohio Division of Wildlife (ODOW), and U.S. Fish and Wildlife Service (USFWS).

Introduction:

Invasive Asian carps are expanding their range in the Ohio River Basin. In 2007 the Aquatic Nuisance Species Task Force approved the Management and Control Plan for Bighead, Black, Grass, and Silver Carps in the United States (National Plan). In 2014 the Ohio River Basin Asian Carp Control Strategy Framework (Framework) outlined a series of approaches to deliver the National Plan within the Ohio Basin. Integrating state responses in the Ohio River basin with basin-wide and national plans has been a priority to agencies that are also responding to more localized prevention, control, and removal needs.

Currently, few tools are available to control expanding populations of Asian carp. Physical removal of carp through various methods may be effective, but is expensive, and ongoing efforts of this project intend to increase the efficiency and capacity of removal efforts. Non-physical deterrents may also be effective against the spread of Asian carp (electric barrier in the Chicago Area Waterway) but can be expensive to operate and maintain. The combination of harvest and deterrence may be an approach that reduces harvest targets while limiting the spread of Asian carp. However, non-physical deterrents remain in the testing phase of development.

Given the ongoing testing of a sound deterrent at Barkley Dam, there is a need to collect baseline movement data on Asian carp that can be used to evaluate a sound deterrent in future years. There is also a need for planning priority locations for implementation of deterrents as they are developed based on the known distribution of Asian carp in the Ohio River Basin. Continued monitoring of Asian carp movements to evaluate potential barriers is necessary.

Objectives:

1. Characterize the need for deterrents and evaluate priority locations for deterrent placement to control movement of Asian carp in the Tennessee and Cumberland rivers.
2. Collect baseline movement information among reservoirs to inform Asian carp deterrent efficacy and lock and dam passage.
3. Characterize the need for deterrents and priority locations for deterrent placement to control movement of Asian carp in the Ohio River.

Methods:

Objective 1

<u>Need for deterrents and priority evaluation</u>
A committee was formed in 2018 to characterize the need for deterrents and priority locations for deterrents to control movement of Asian Carp in the Tennessee and Cumberland Rivers. The committee was comprised of fisheries chiefs from KY, TN, MS, and AL; staff from the Planning Branch of the Nashville District US Army Corps of Engineers; and senior biological staff from the Tennessee Valley Authority.

The committee held multiple meetings beginning in 2018 and reached out to USGS and other scientists to understand the current state of deterrent science and technology to develop a strategic plan for best practices.

Objective 2

<u>Enhance Asian carp movement information</u>
To acquire movement information, fish were surgically implanted with acoustic telemetry tags and telemetry receivers were deployed to detect individual fish movements within the Ohio River subbasin (Figure 1). Within the Tennessee River, of the Ohio River subbasin, every lock and dam has telemetry receivers starting at the downstream end at Kentucky Dam upstream to Guntersville Dam. In the Cumberland River, Barkley Dam is outfitted with acoustic receivers. In 2019 the receiver array was expanded to include Cheatham Dam and Old Hickory Dam on the Cumberland River and their locks.

Silver carp were captured through boat electrofishing and then surgically implanted with VEMCO V16 acoustic transmitters, following the protocol developed by MSU and TTU. Tagged fish were also marked externally with a Floy Loop Tag inserted just posterior of the dorsal fin. Silver carp have been tagged in KY, TN, and MS. Tagging occurred when water temperatures were cool and survival and tag retention was high. Once tagging was complete fish were immediately returned to the body of water from which they were captured. To date, over 300 Silver Carp have been tagged in connected waters and with evaluation of the Bioacoustic Fish Fence (BAFF) tagging efforts have been increased (see KDFWR section below).

<u>Fish Tagging</u>
Tagged fish were monitored through stationary receivers as well as manual tracking trips made approximately once per week in Kentucky waters by KDFWR. A large network of VEMCO stationary receivers has been deployed throughout the reservoirs, lock chambers, and their tailwaters. A total of 44 VEMCO receivers are currently deployed by cooperating agencies (5 AL, 4 MS, 20 KY, and 15 TTU). New receivers were deployed at Cheatham Dam and Old Hickory Dam on the Cumberland River in spring 2019 by TTU. The targeted download timing to receive data from stationary receivers is quarterly and there is a multi-state effort for data sharing and reporting.

Two receivers had been previously deployed in Kentucky Lock and Barkley Lock to determine direction of travel for fish that pass through the lock chamber. Stationary receivers are deployed through two primary mounting systems in the reservoirs, anchored bottom mounts, and on navigational buoys. Receivers deployed in the lock chambers throughout the systems are deployed in steel cases lowered in ladder wells to prevent damage by barges and debris traveling through the locks. KDFWR retrieves and downloads stationary receivers in the reservoirs on a bimonthly schedule, and receivers in the lock chambers monthly. TN downloads receivers on a 3-month frequency, however extreme water levels in spring 2019 disrupted the schedule. Manual tracking was accomplished by using a VR100 and omnidirectional hydrophone deployed from a boat. The hydrophone was lowered into the water at 1km intervals and monitored for at least two minutes before moving to the next location. It was determined through range testing that the omnidirectional hydrophone could detect transmitters from a distance of 500m. Therefore, stopping at 1km intervals provided sufficient coverage of the lake. Telemetry data from manual tracking and stationary receivers collected by KDFWR was transferred to Dr. Spier at MSU for analysis.

KDFWR and TWRA participated in numerous conference calls and several in-person meetings regarding the Bio-Acoustic Fish Fence (BAFF) to be deployed in the downstream approach to Barkley Lock. KDFWR provided fish community data, baseline fish passage data from the current telemetry array, and local contacts for the group of researchers developing the study plan around the BAFF installation and testing. Multiple partner agencies have collaborated on the project.

Objective 3

In 2017-2018, KDFWR began acquiring information concerning Ohio River main-stem dams to assist with prioritizing their potential to accommodate an Asian carp barrier. A short literature search and research conducted since 2013 was used for the current priority recommendation.

Results and Discussion:

Objective 1

Need for deterrents and priority evaluation

Priority locations were first presented in the 2018 report and are under continued review and discussion. The emplacement of an experimental deterrent at Barkley Dam, the Bioacoustic Fish Fence (BAFF), has resulted in increased movement studies to determine barrier effectiveness. These are cooperative efforts among federal, state, and university partners.

Objective 2

Enhance Asian carp movement information

Silver carp (171) were collected by electrofishing, surgically implanted with VEMCO V16 transmitters, and tagged externally with a Floy loop tag. Four fish died immediately following their surgery, and one was labeled with a duplicate transmitter number and was not used in analyses. Most fish (150) were collected, tagged, and released in the Barkley tailwaters in anticipation of the activation of the Bio-Acoustic Fish Fence deterrent system.

Several native species were also tagged and released below Barkley Dam in 2019. Freshwater drum and smallmouth buffalo were collected while electrofishing, and gill nets were used to capture most of the paddlefish.

In 2019, record high rainfalls that resulted in flooding and the Federal Government shutdown interfered with the spring telemetry tagging season and receiver data downloads. After flooding, all collaborative partners failed to recover some receivers. Thus, some data to inform Objective 2 was lost. The TWRA dive team did a simulated "Search and Recovery" exercise at several receiver locations and were able to relocate two receivers maintained by TTU, but three others were not recoverable. Because of extreme spring flooding, tagging was limited in 2019. A four day tagging effort occurred at Pickwick Reservoir with Mississippi and Alabama state fisheries agencies. Transmitter downloads and tagging will continue through the period of performance.

Fish Detections

Current tracking efforts span Kentucky Lake and Lake Barkley entirely, and results confirm that fish move between the reservoirs and their tailwaters, and beyond. Because of their propensity to move to and from both reservoirs, this and future reports will analyze data as one system. During 2019, 223 individual silver carp were detected by either manual tracking or the stationary receivers located in Kentucky Lake, the Lower Tennessee River, Lake Barkley, and the Lower Cumberland River. Of those detected, 174 were silver carp tagged by MSU and KDFWR, and 49 were tagged by other agencies outside of Kentucky state waters (Table 1). Other species detected included bighead carp, freshwater drum, grass carp, paddlefish, smallmouth buffalo and a few unidentified fish (Table 2).

Silver carp detected that were tagged by other agencies may bias results because they are potentially more nomadic than fish tagged by KDFWR and MSU. Therefore, for these analyses, silver carp which were tagged outside of Kentucky state waters are considered a different population than the fish tagged in the lower Kentucky Lake, Lake Barkley, Tennessee, and Cumberland river systems. Thus, the following analysis will concentrate only on silver carp which were tagged by KDFWR and MSU in Kentucky state waters.

Mean daily speed analyses used an average of 4.9 fish per week (range 2 – 16 fish), and three or more fish were detected in 89% of the weeks. Mean daily speeds of 0.0 km/day does not indicate missing data, but that fish were not detected moving during that week. Maximum weekly average of mean daily speeds for silver carp was 15.7 km/day (N = 5 fish), and the maximum speed recorded for an individual silver carp, was 61.0 km/day. Movement rates correlated conditionally with surface temperature (Figure 2). Silver carp exhibited seasonal movement patterns during 2018 and 2019. Little movement was observed during colder months, a spike in activity occurred early in the spring, and a steady rate of activity was maintained until water temperatures decreased in fall. A 2-dimensional Kolmogorov-Smirnov test revealed a significant relationship between swimming speed (km/day) and water temperatures when temperatures increased above 16.4^{o} C ($D_{max} = 0.125$, $p = 0.000$; Figure 3). However, silver carp movement decreased sharply when water temperatures were above 30^{o} C. Movements of silver carp were not related to discharge levels (Figure 4).

Mean on the move (OTM) speed of KDFWR silver carp was 1.2 km/hr which extrapolates to 28.8 km/day (Table 3). Silver carp tagged by other agencies in the TNCR sub-basin had a higher mean OTM speed, which might be due to these fish being more nomadic than the population that were tagged in the lower Kentucky Lake and Lake Barkley systems.

Location of fish within each lake by date was also examined for Kentucky state waters. A daily average river kilometer (RK) was calculated for individual fish. Mean RK by fish and month was calculated to provide monthly average locations. Finally, the mean monthly RK across all fish was calculated to determine general locations of silver carp schools within the lakes each month. Median monthly RK in Kentucky Lake for 2017 – 2019 was 65.2 km which is near the Eggner's Ferry Bridge. Therefore, the mean location of silver carp each month was compared to this location near the bridge. To understand the relative position of silver carp, the median value of 65.2 was subtracted from each month's mean RK to get an adjusted RK. The adjusted RK for a month would be negative if the average location of the fish were downstream from the bridge, and positive if the average location was upstream from the bridge.

Silver carp in Kentucky Lake did not exhibit directionality in 2017, but there were fewer tagged fish and fewer receivers at that time. In 2018, fish were mostly detected near Kentucky Dam early in the year, but later moved up the reservoir (Figure 5). In early 2019, fish again were detected lower in the reservoir, made short movements up the reservoir, and ultimately returned near the dam later in the year.

In Lake Barkley, silver carp locations were inconsistent with time of year in 2017 and 2018, but the receiver array was not well-developed. In 2019, fish were predominantly detected up the reservoir. However, this might be an artifact of the calculations since the median monthly RK for Lake Barkley is 60.2 km which is near Carmack Bay, a location that is quite far downstream (Figure 6).

<u>Dam Passage</u>

Documented passages in 2018 - 2019 occurred at Barkley Dam (40) and Kentucky Dam (11), and 15 were verified without information to determine through which dam passage occurred (Table 4). The majority of crossings detected were silver carp, unsurprising since they represent most of the tagged fish in the system (Table 5). The "unknown dam" crossings (n=15) occur when fish which have completed passage, but were not detected by receivers located in lock chambers. Receivers' ability to detect fish varies with water conditions, and not all fish are detected passing. However, locks are small and probability of a fish passing through them undetected is low. Therefore, it is probable that fish cross through the dam gates when opened. In fact, 97% of the downstream crossings were not detected in a lock, while 97% of upstream crossings were detected inside a lock (Table 6). Indicating that fish are using different routes to cross the dams in the downstream direction compared to the upstream direction. The single upstream crossing which was not detected in the lock probably crossed through Barkley Lock (this fish was detected in the Barkley lock but was not detected upstream of the lock until several days later, thus we are unsure exactly when it crossed fully into Lake Barkley).

Silver carp downstream passages occurred through Barkley Dam on six dates (10 total passages) and the dam was spilling on each of those dates (mean spill volume = 740 m^3/s, s.d. = 346, N = 6, range = 523 – 1,419 m^3/s). Only two other fish were detected crossing Barkley Dam downstream; both were Paddlefish which crossed when the dam was not spilling. All upstream passages occurred when Barkley was not spilling (Figure 7).

At Kentucky Dam, silver carp passage downstream occurred on three dates, and the dam was spilling at a higher rate than when downstream passages were detected at Barkley (mean spill volume = 4,877 m^3/s, s.d. = 5,258, N = 3, range = 753 – 10,798 m^3/s). On March 10, 2019, a silver carp passed through Kentucky Dam downstream but was detected inside the lock, so although the lake was spilling that fish used the lock instead of the gates. On this date the spill discharge was extremely high, which may have implications for a maximum discharge threshold for fish passages and will continue to be monitored. Similar to Barkley Dam, most upstream passages at Kentucky Dam occurred when the dam was not spilling, but on two dates the lake was spilling water at a low volume when eight silver carp crossed upstream through the lock (Figure 8; mean spill volume = 474 m^3/s, s.d. = 915, N = 2, range = 0 – 2,376m^3/s).

Data indicates dam spillage affects downstream passage, but not upstream passage. Additionally, upstream crossings were not influenced when turbine discharges were included (total discharge; Figure 12 and Figure 13). However, silver carp did not cross upstream when total discharge levels were very high. High total discharge levels only occurred when water temperatures were low, and data indicates that the carp do not move as much during periods with low temperatures.

Previous analysis suggested that water temperature had the biggest influence on overall carp movement, so water temperatures during dam passages were examined. Upstream silver carp passages at the Lake Barkley Dam occurred at warmer mean temperatures than downstream passages (Figure 9). Water temperatures during 13 upstream passages were 15.1° – 32.3° C with a mean of 26.3° C (s.d. = 4.7). Water temperatures during downstream passages were 15.9° – 20.9° C with a mean of 18.2°C (s.d. = 2.0). Paddlefish passage occurred in both directions when water temperatures were very warm. Two downstream passages were detected when temperatures averaged 30.5° C (s.d. = 0.1), and four upstream passages when temperatures were 24.1° – 30.3°C (mean = 27.6°C; s.d. = 2.7).

Silver carp passages and water temperature data at Kentucky Dam indicated similar tendencies to passages at Barkley Dam (Figure 10). Water temperatures during silver carp downstream passages (n=3) were 8.8° – 18.4°C, and averaged 14.6°C (s.d. = 5.1). Upstream passages (n=6) occurred at 14.2° – 30.6°C and averaged 23.6 °C (s.d. = 7.1). Despite the low number of detections, this data at both dams provides evidence that silver carp upstream passages may occur at higher temperatures than downstream passages (Figure 11).

Since December 2017, fish have been collected, tagged, and released below Barkley Dam. Silver carp were predominantly tagged, but in 2019, freshwater drum, paddlefish, and smallmouth buffalo were also tagged (Table 7). No passages of freshwater drum have been detected, but percentages of all the remaining species tagged in the tailwaters, including silver carp, have been similar (5-6%; Table 8). One particularly adventurous paddlefish entered Lake Barkley from the tailwater, returned to the tailwater, and again entered the reservoir. Of the 16 fish tagged in the tailwaters which have crossed a dam, 13 crossed at Barkley Dam and three at Kentucky Dam. All these were upstream passages except for the previously mentioned paddlefish. Average time between tagging and initial passage through a dam for silver carp (n=13) was 180.2 days, but one crossed only two days after tagging (Table 9). At upper Tennessee River locks and dams, 90 unique transmitters were detected on the 12 recovered receivers 86 of which belong to Silver Carp. 32 of the 86 Silver Carp transmitters (37%) crossed the Pickwick Dam and 7 of the 32 Silver Carp transmitters crossed Pickwick Dam using either the primary or secondary lock system (22%). Use of the lock system was determined either by detection of a tagged fish by the receiver within the lock chamber or the movement of fish from the tailwater to the headwater of Pickwick Dam. Movement from the tailwater to the headwater would require use of the locking system whereas movement from headwater to tailwater could be attributed to fish flowing through open flood gates.

Movement of Silver Carp varied throughout 2018 and 2019 showed slight seasonal influence. Many of the Silver Carp that used the lock and dam systems for passage did so between March and July. All Silver Carp detected that crossed Pickwick Dam were tagged in Pickwick Lake at either Panther Creek or Indian Creek. No fish that were tagged in Kentucky Lake were detected crossing Pickwick Dam, suggesting that movement is targeted to downstream locations. Silver Carp that crossed from the tailwater to the headwater of Pickwick Dam using the lock systems were also fish originally tagged in Pickwick Lake. The movement from tailwater to headwater (upstream) occurred during July or later. No tagged Silver Carp were detected at Wilson or Wheeler Dams.

The receiver within the primary lock of Cheatham Dam detected 4 unique tags, 3 of which belong to Silver Carp. Tag 52062 was tagged in Hancock Biological Station on Kentucky Reservoir on Dec 13, 2016. Tag 24256 was tagged in Indian Creek on Pickwick Reservoir on Dec 5, 2018. This fish was detected within the Cheatham lock on three separate occasions and at both Pickwick Locks as well. Tag 28387 was tagged in Riverfront Marina on Kentucky Lake on Dec 4, 2017 and later detected at Cheatham Dam. Neither receiver from the headwater or tailwater of Cheatham Dam was recovered after floods, so definitive crossings of Silver Carp through the Cheatham Lock system cannot be determined at this time.

Objective 3

In order to help prioritize potential fish barrier sites on the Ohio River main-stem, KDFWR examined USGS reports which assessed environmental factors (i.e. water levels, flow rates, etc.) and other conditions required by fish for inter-pool movement in the river (Knights et al. 2003). In that report, Markland Lock and Dam (mile 531.5) was identified as a priority for a potential fish barrier. KDFWR biologists have collected telemetry data since 2013 to assess Asian carp movement in the Ohio River, and in particular, to detect movement among pools. Collectively, stationary receivers have been deployed in nine pools comprising a 500-mile receiver array. More than 570 of the invasive fish have been surgically implanted with ultrasonic transmitters within that river reach. Variations in Asian carp densities among the pools resulted in nearly 80% (445) of the fish being tagged in the Cannelton and McAlpine pools. Asian carp numbers are lower above the Markland Dam, and only 60 Asian carp have been tagged in its namesake pool. Despite this disparity in tag densities, only one tagged fish was able to complete an upriver passage through Markland Lock and Dam during almost six years (2013-2019) of telemetry efforts, which was in addition to the nine downriver passages that were detected through that dam over the same time period. These results underscore that Markland Lock and Dam is likely a high priority site for a barrier. Alternatively, during the past five years, receivers in and around the McAlpine Lock and Dam detected 18 bigheaded carp had successfully completed a total of 27 passages, including 18 downriver and 9 upriver. To date, telemetry results tend to agree with the conclusions from the 2003 USGS report that the Markland Dam provides the best option for a fish passage deterrence mechanism.

Summary and Recommendations:

Silver carp are able to move through lock and dam structures. Once through the locks, Silver Carp readily travel the TN River. However, no tagged fish have been detected at Wilson, Wheeler, Guntersville dams (Tennessee River) or Old Hickory Dam (Cumberland River). The KY-BK canal offers fish access to both reservoirs, fish have been detected moving through the canal into Barkley Reservoir and vice versa. Receivers placed in the Cumberland River during 2019 will help inform passage and barrier efficacy.

Data sharing of telemetry data among various agencies is encouraged with advancement. A shared document exists, however further sharing and integration into a larger framework should be discussed. For example, the sharing of .vrb databases and data quality protocol discussion would be a welcomed asset to this project and allow multiple agencies the opportunity to look at datasets across state lines. Incorporating Ohio River and Ohio River tributary data within a national framework (GLATOS and USGS) could facilitate data sharing and a more comprehensive national data sharing community.

Partners recommend:

- Planning for movement barriers should be a priority
- Tagging to increase the number of marked fish in the Tennessee and Cumberland river systems, tributaries to the Ohio River
- Maintenance of receiver arrays
- Sharing data across jurisdictions
- Determining whether high water levels and flows in spring 2019 compromised the current receiver array

Literature Cited:

Knights, B. C., J. H. Wlosinski, J. A. Kalas, and S. W. Bailey. 2003. Upstream fish passage opportunities at Ohio River Mainstem Dams. Completion report prepared for U.S. Army Engineer District, Nashville, CELRN-PM-P, P.O. Box 1070, Nashville, TN 37202-1070 by U.S. Geological Survey, Upper Midwest Environmental Sciences Center, 2630 Fanta Reed Road, La Crosse, Wisconsin, 54603.

Table 1. Detections of live silver carp by origin and year for Kentucky Lake, the Lower Tennessee River, Lake Barkley, and the Lower Cumberland River combined. Table values indicate the number of individuals detected.

	2016	2017	2018	2019
KDFWR*	36	38	82	174
MDWFP			9	24
TWRA			11	24
USFWS			1	1

*KDFWR = Kentucky Department of Fish and Wildlife Resources, MDWFP = Mississippi Department of Wildlife, Fisheries, and Parks, TWRA = Tennessee Wildlife Resource Agency, USFWS = U. S. Fish and Wildlife Service

Table 2. Detections of other live fish by species and year for Kentucky Lake, the Lower Tennessee River, Lake Barkley, and the Lower Cumberland River combined. Table values indicate the number of individuals detected.

	2016	2017	2018	2019
Bighead carp*	1	1	1	
Freshwater Drum				14
Grass carp			1	
Paddlefish	4	5	4	20
Smallmouth Buffalo				35
Unknown			4	9

*Bighead carp was tagged by Southern Illinois University, Carbondale (SIUC), freshwater drum were tagged by KDFWR, grass carp was tagged by the Missouri Department of Conservation (MDC), paddlefish prior to 2019 were all tagged by MDC and paddlefish in 2019 were a mix of fish tagged by MDC and KDFWR, smallmouth buffalo were tagged by KDFWR, and the unknown fish have not yet been identified.

Table 3. Mean "On the Move" swimming speed (OTM) for silver carp in Kentucky Lake, 2017 – 2019. OTM speed represents the swimming speed of a fish from one set of stationary receivers to the next set of receivers.

Agency	Mean Swimming Speed (km/hr)	s.d.	N	Range (km/hr)
KDFWR*	1.2	0.6	39	(0.2 – 2.5)
MDWFP	2.7	1.0	24	(0.9 – 4.7)
TWRA	2.4	1.2	22	(0.6 – 4.7)

*KDFWR = Kentucky Department of Fish and Wildlife Resources, MDWFP = Mississippi Department of Wildlife, Fisheries, and Parks, TWRA = Tennessee Wildlife Resource Agency

Table 4. Number of times fish crossed a dam 2018-2019. Fish crossing totals include any species tagged by any agency, including unknown species, and represent the total number of crossings (i.e. some fish crossed multiple times).

Dam Crossed	Downstream	Upstream
Barkley	12	28
Kentucky	3	8
unknown dam	14	1

Table 5. Number of times fish crossed a dam 2018-2019 by species. Values indicate fish tagged by any agency, and represent the total number of crossings (i.e. some fish crossed multiple times).

	Dam Crossed	Downstream	Upstream
Paddlefish	Barkley	2	4
	Kentucky	-	-
	unknown dam	-	-
Silver carp	Barkley	10	21
	Kentucky	3	7
	unknown dam	14	1
Smallmouth Buffalo	Barkley	-	2
	Kentucky	-	-
	unknown dam	-	-
Unknown species	Barkley	-	1
	Kentucky	-	1
	unknown dam	-	-

Table 6. Number of fish detections inside a lock and direction of travel (all species combined).

	Downstream		Upstream	
Dam Crossed	Not Detected in Lock	Detected in Lock	Not Detected in Lock	Detected in Lock
Barkley	12	-	-	28
Kentucky	2	1	-	8
unknown dam	14	-	1	-
TOTAL	28	1	1	36
% of total	97%	3%	3%	97%

Table 7. Number of fish capture, tagged, and released below Barkley Dam by species and date.

Date	Freshwater Drum	Paddlefish	silver carp	Smallmouth Buffalo
December 2017	0	0	20	0
January 2018	0	0	24	0
April 2018	0	0	17	0
April 2019	0	4	74	20
November 2019	20	12	76	21
TOTAL	20	16	211	41

Table 8. Number of fish collected, tagged, and released below Barkley Dam which crossed a dam.

	Freshwater drum	Paddlefish	Silver carp	Smallmouth buffalo
Did not cross a dam	20	15	198	39
Did cross a dam	0	1*	13	2
TOTAL FISH	20	16	211	41
Pct.	0%	6%	6%	5%

* This paddlefish crossed a dam 3 times

Table 9. Mean time (days) elapsed from tagging to first dam crossing by species for fish which were collected, tagged, and released below Barkley Dam.

	Paddlefish	Silver carp	Smallmouth buffalo
Mean time until first crossing (days)	28	180.2	40.0
s.d.	-	158.5	19.8
N	1	13	2
Range (days)	-	2 – 534	26 – 54

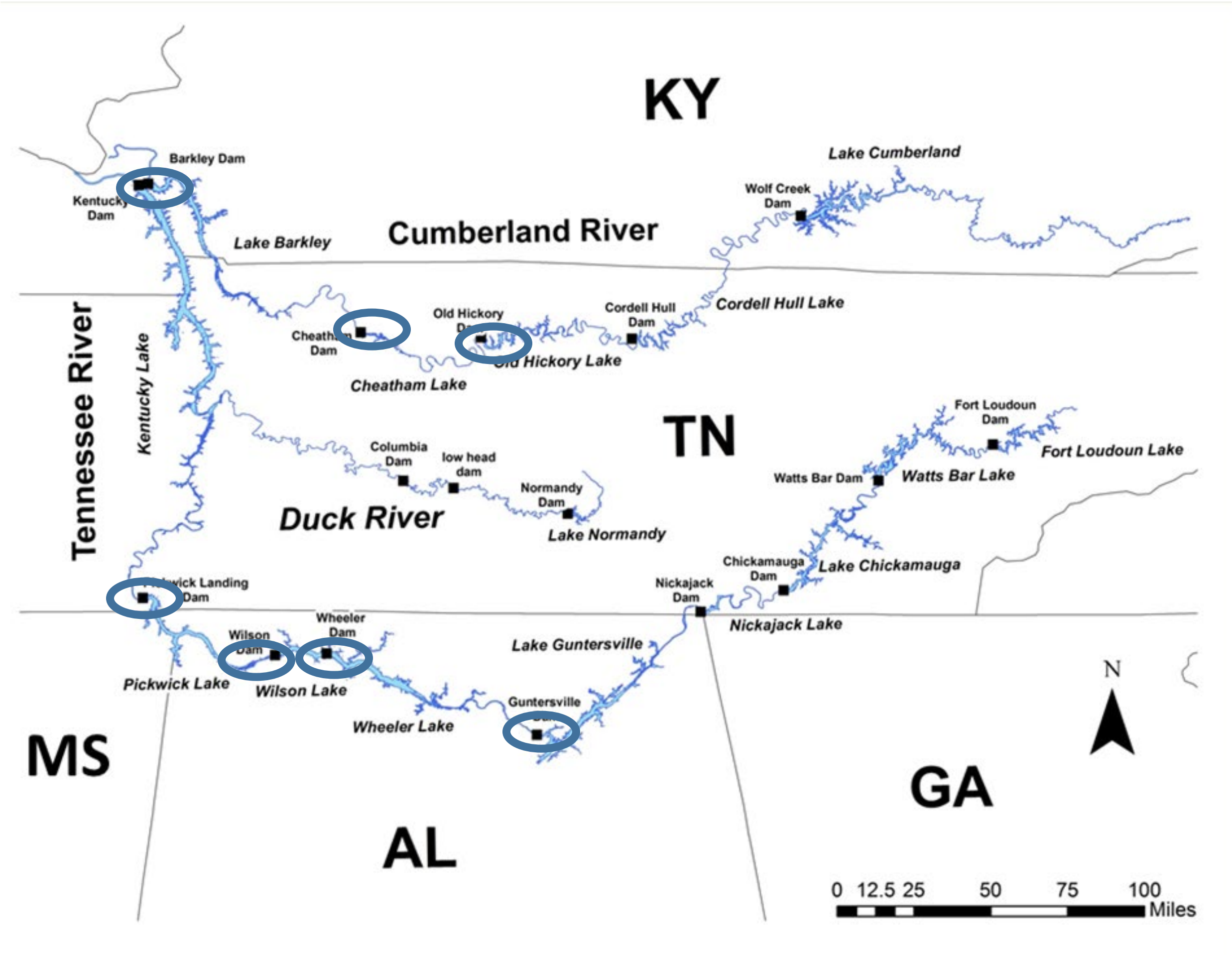

Figure 1. *The Tennessee River and Cumberland River locks and dams (circled) that are monitored using acoustic telemetry receivers to measure Asian carp upstream invasion.*

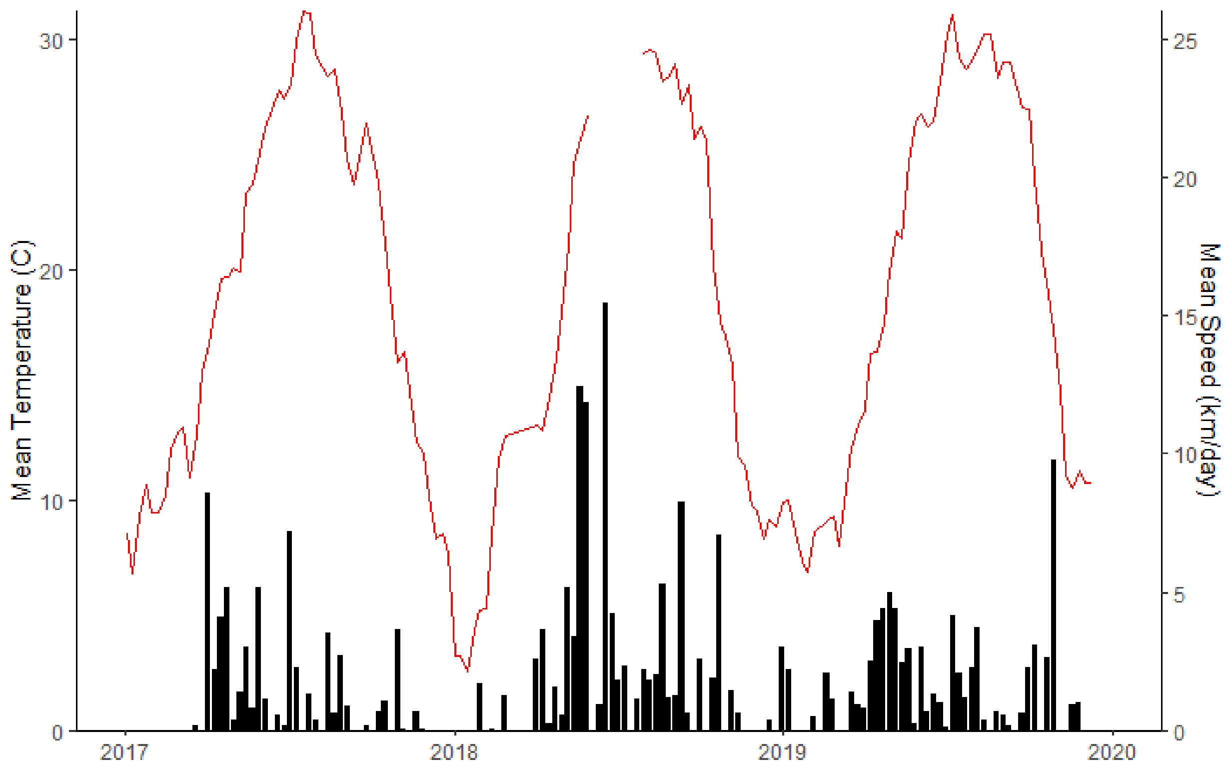

Figure 2. Mean weekly surface temperature (ºC, measured in Kentucky Lake) and mean weekly swimming speed (km/day) for silver carp in Kentucky Lake and Lake Barkley, 2017 – 2019.

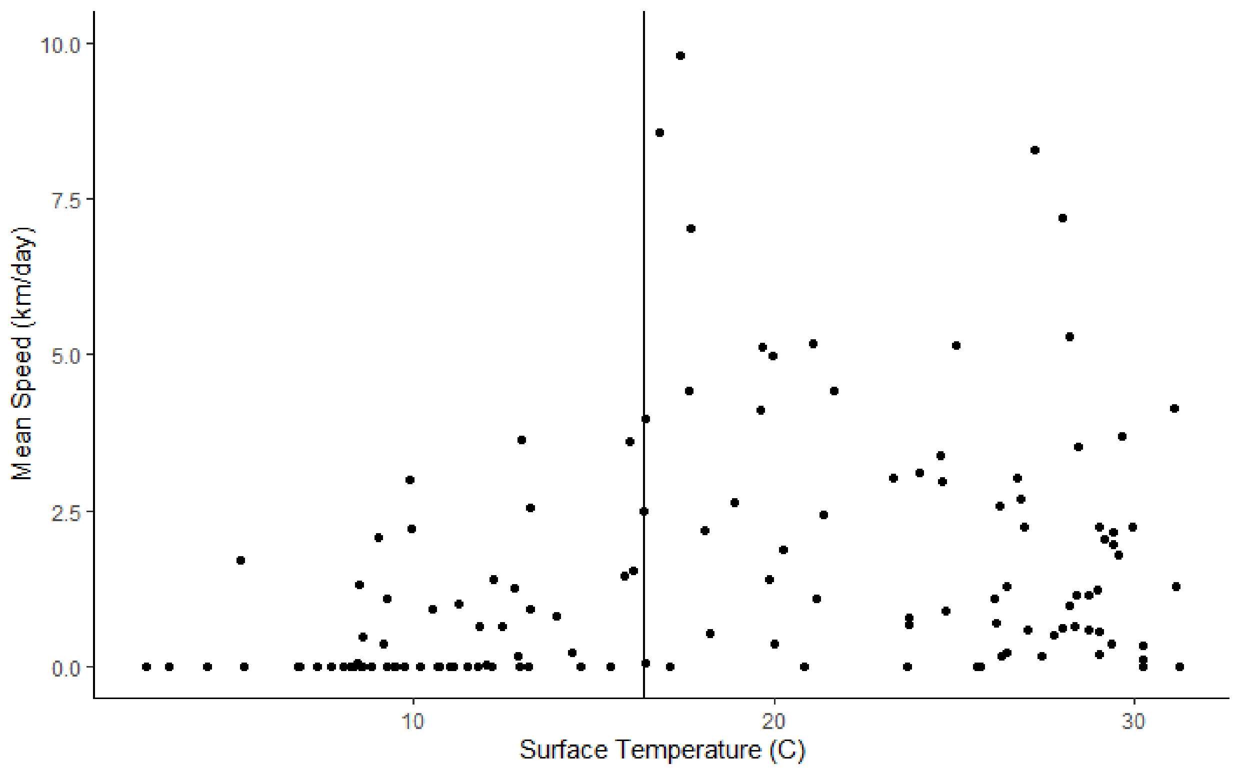

Figure 3. Comparison of silver carp mean weekly swimming speed (km/day) and mean weekly surface temperature (ºC). Two-dimensional Kolmogorov-Smirnov test suggests that the relationship between speed and temperature changes once temperatures rise above 16.4 ºC (as indicated by the vertical line, $D_{max} = 0.125$, $p = 0.000$).

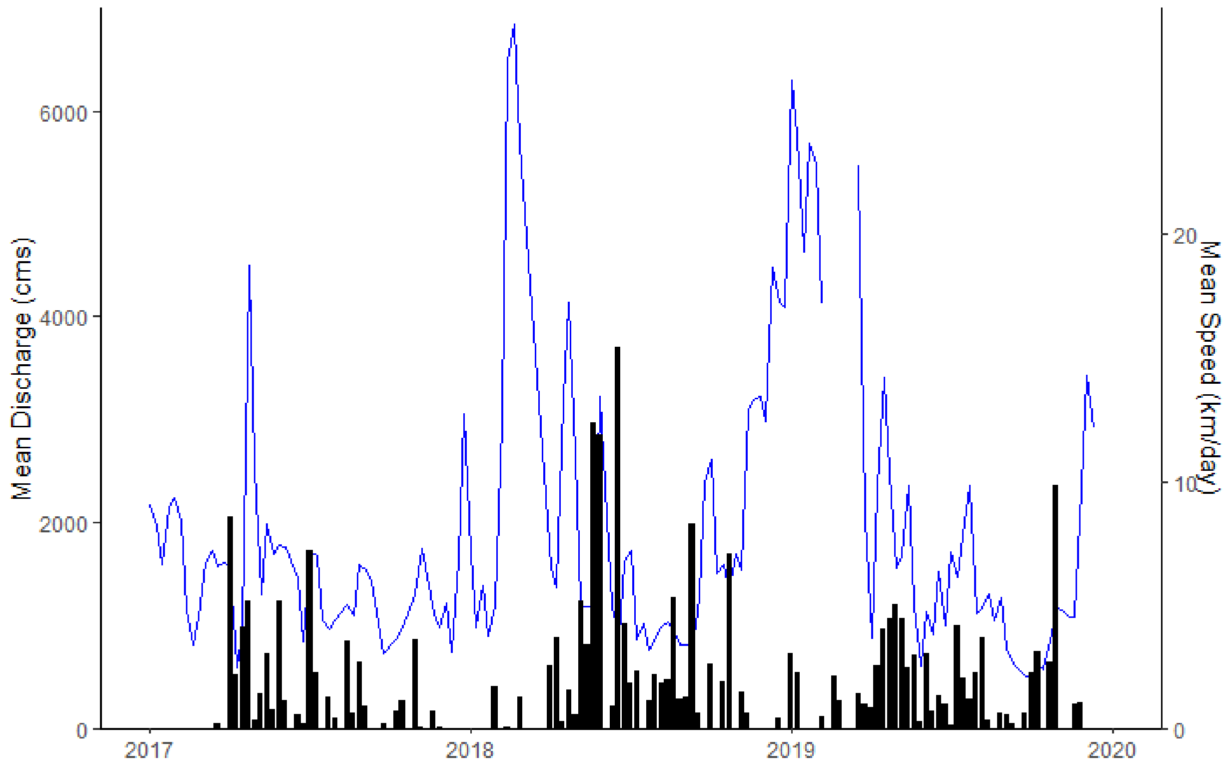

Figure 4. Mean weekly total discharge (m³/s, measured in Kentucky Lake) and mean weekly swimming speed (km/day) for silver carp in Kentucky Lake and Lake Barkley, 2017 – 2019.

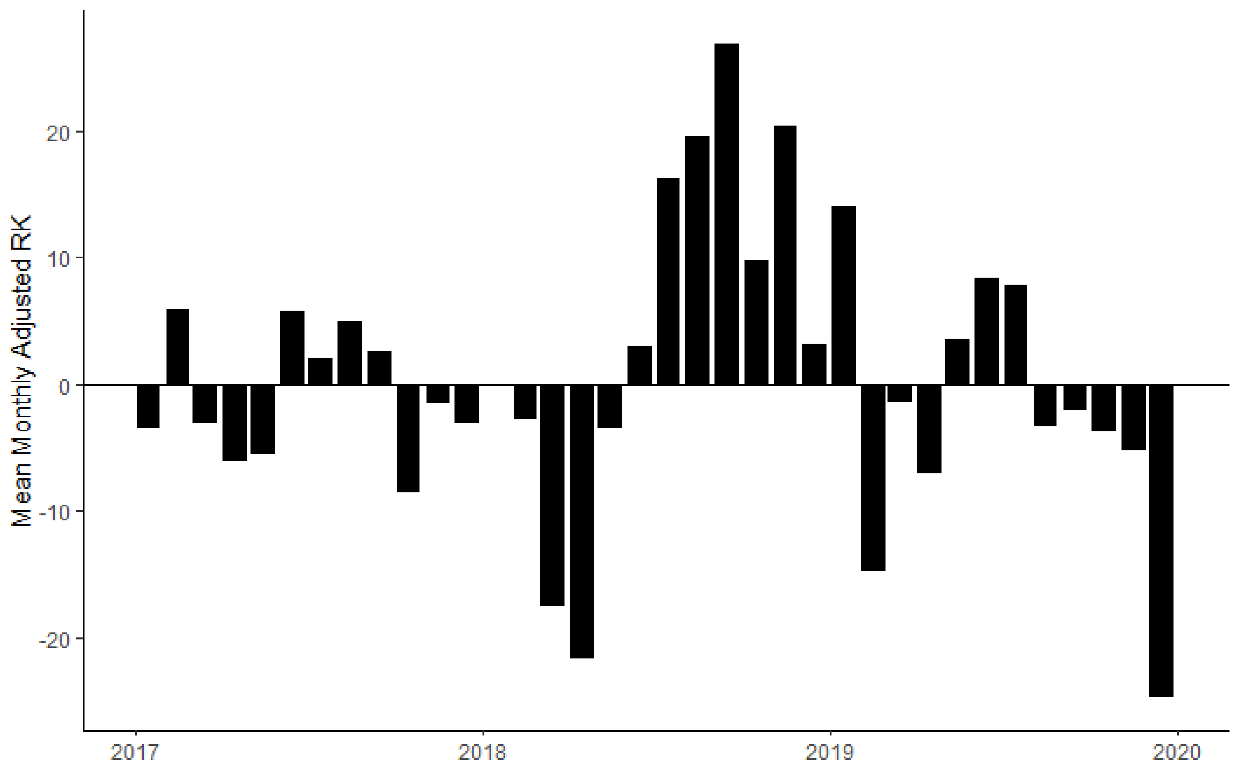

Figure 5. Mean monthly adjusted river kilometer (RK) for silver carp in Kentucky Lake. The RK is adjusted relative to RK 65.2 which is the median monthly RK over 2017 – 2019. Negative values represent locations downstream while positive values indicate locations upstream. The Kentucky Lake Dam is at RK 36 which would be an adjusted RK of –29.2.

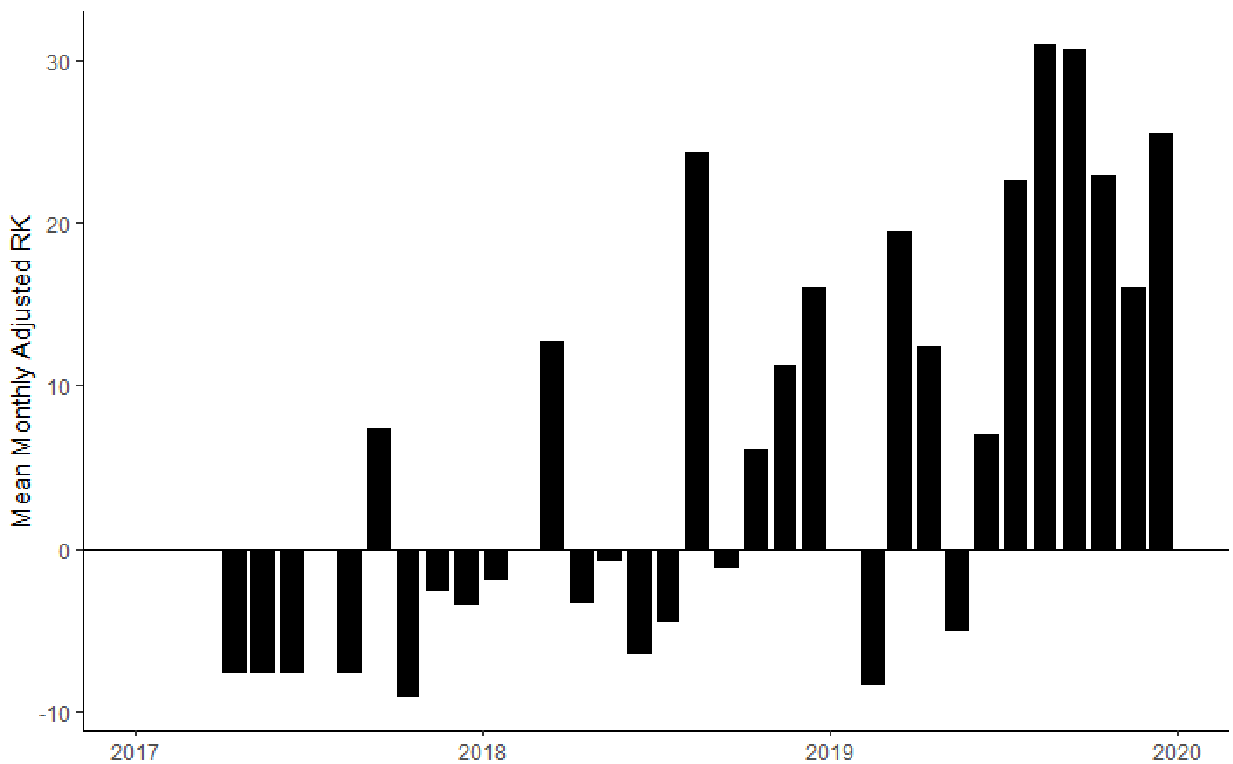

Figure 6. Mean monthly adjusted river kilometer (RK) for silver carp in Lake Barkley. The RK is adjusted relative to RK 60.2 which is the median monthly RK over 2017 – 2019. Negative values represent locations downstream while positive values indicate locations upstream. The Lake Barkley Dam is at RK 49 which would be an adjusted RK of -11.2.

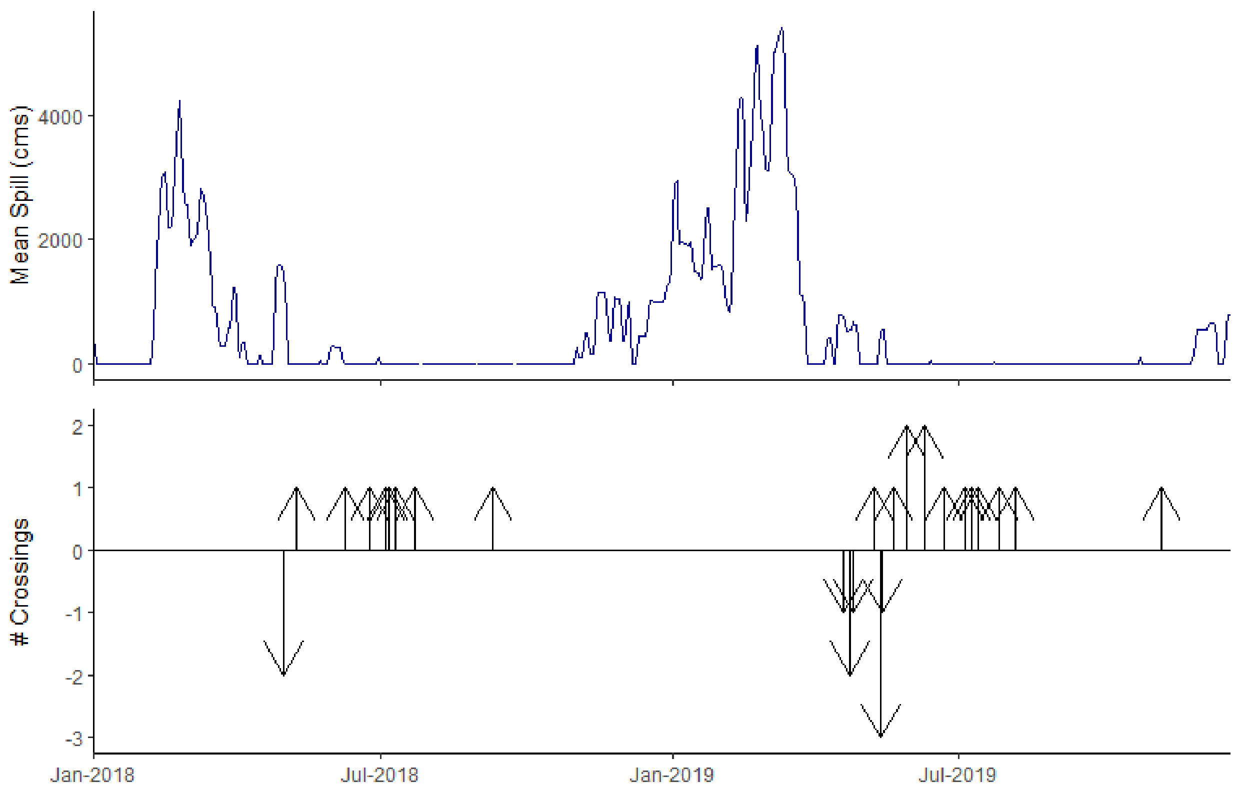

Figure 7. Rate of spilling (m^3/s) at Barkley Dam compared to the number and direction of silver carp crossings. Fish crossings are positive for upstream, and negative for downstream crossings.

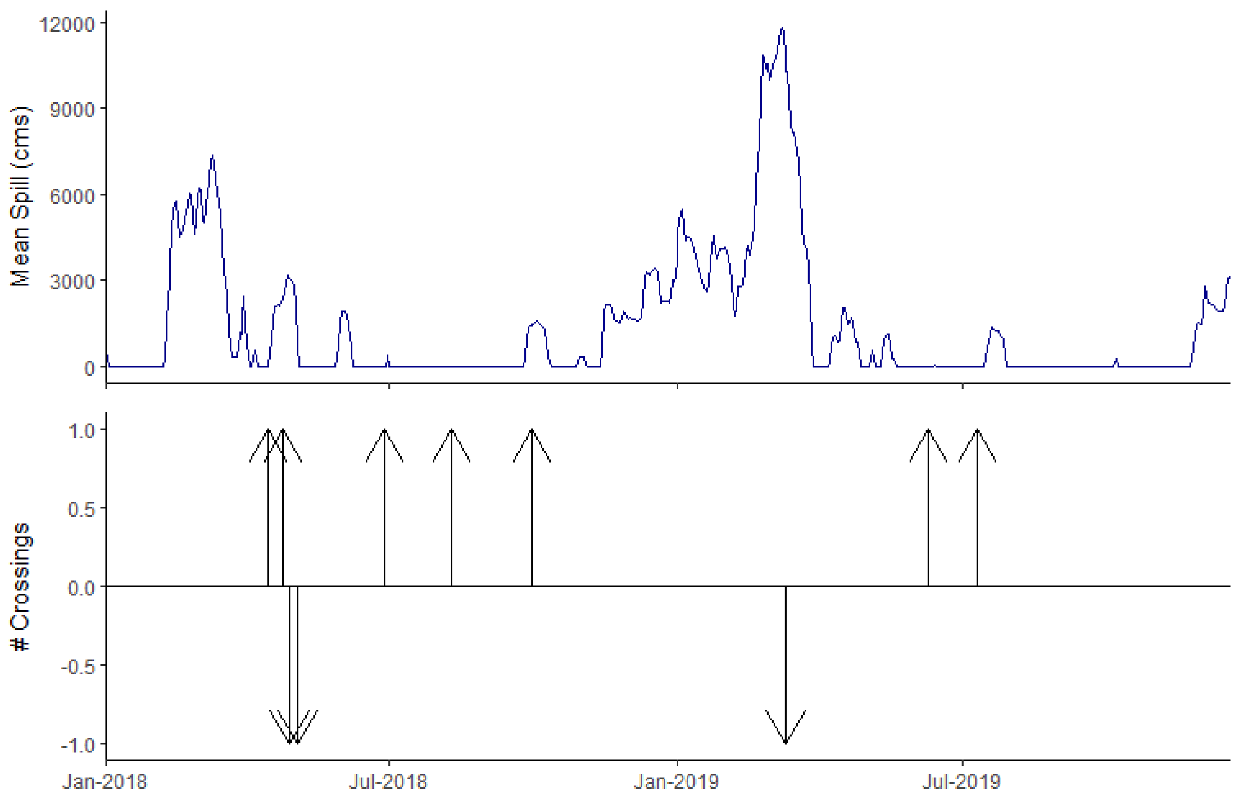

Figure 8. Rate of spilling (m^3/s) at Kentucky Dam compared to the number and direction of silver carp crossings. Fish crossings are positive for upstream, and negative for downstream crossings.

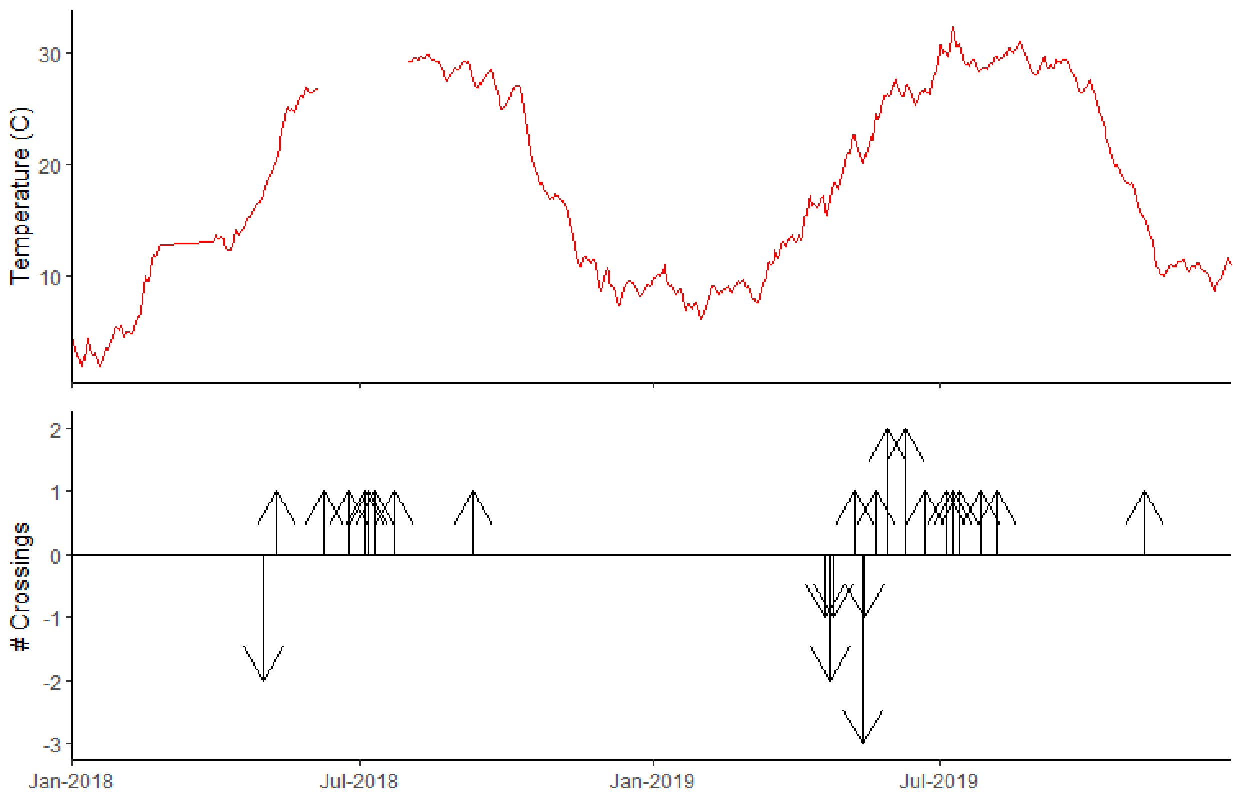

Figure 9. Surface temperature (ºC) at Barkley Dam compared to the number and direction of silver carp crossings. Fish crossings are positive for upstream, and negative for downstream crossings. Surface temperature data was recorded for Kentucky Lake.

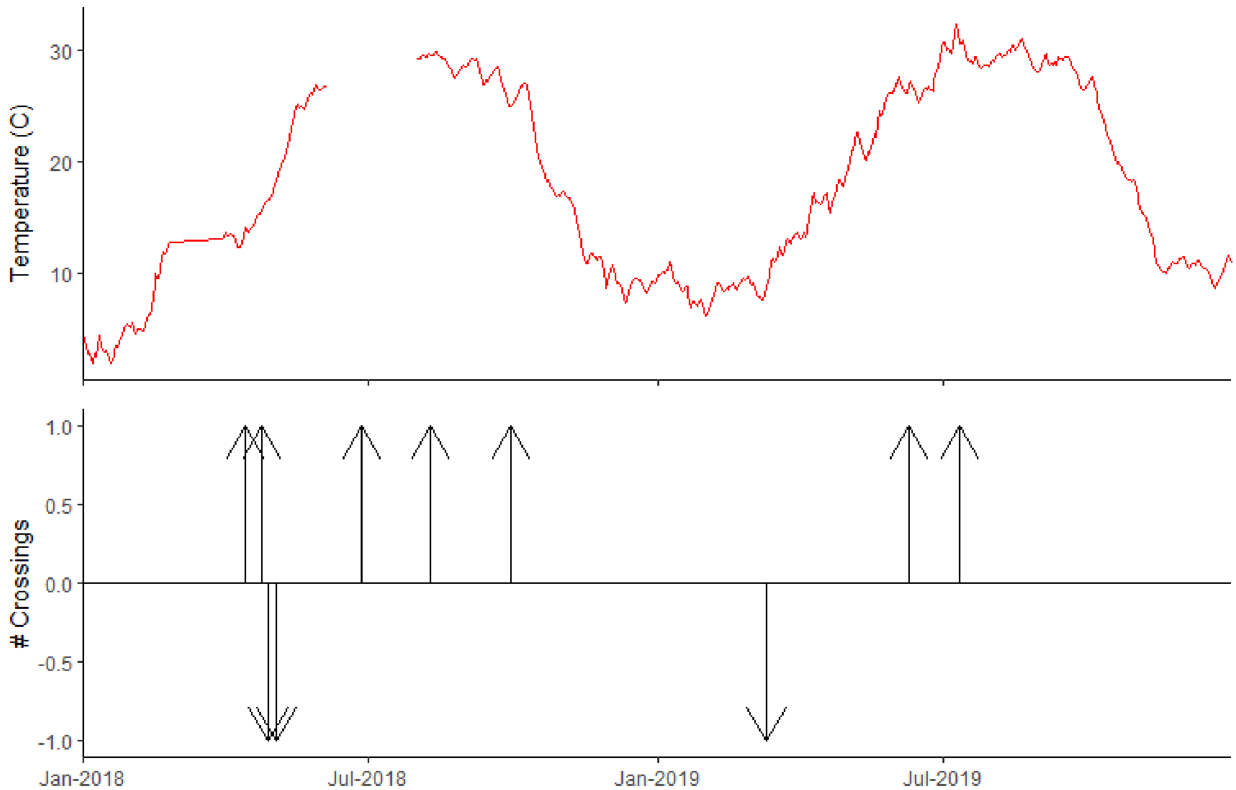

Figure 10. Surface temperature (ºC) at Kentucky Dam compared to the number and direction of silver carp crossings. Fish crossings are positive for upstream, and negative for downstream crossings.

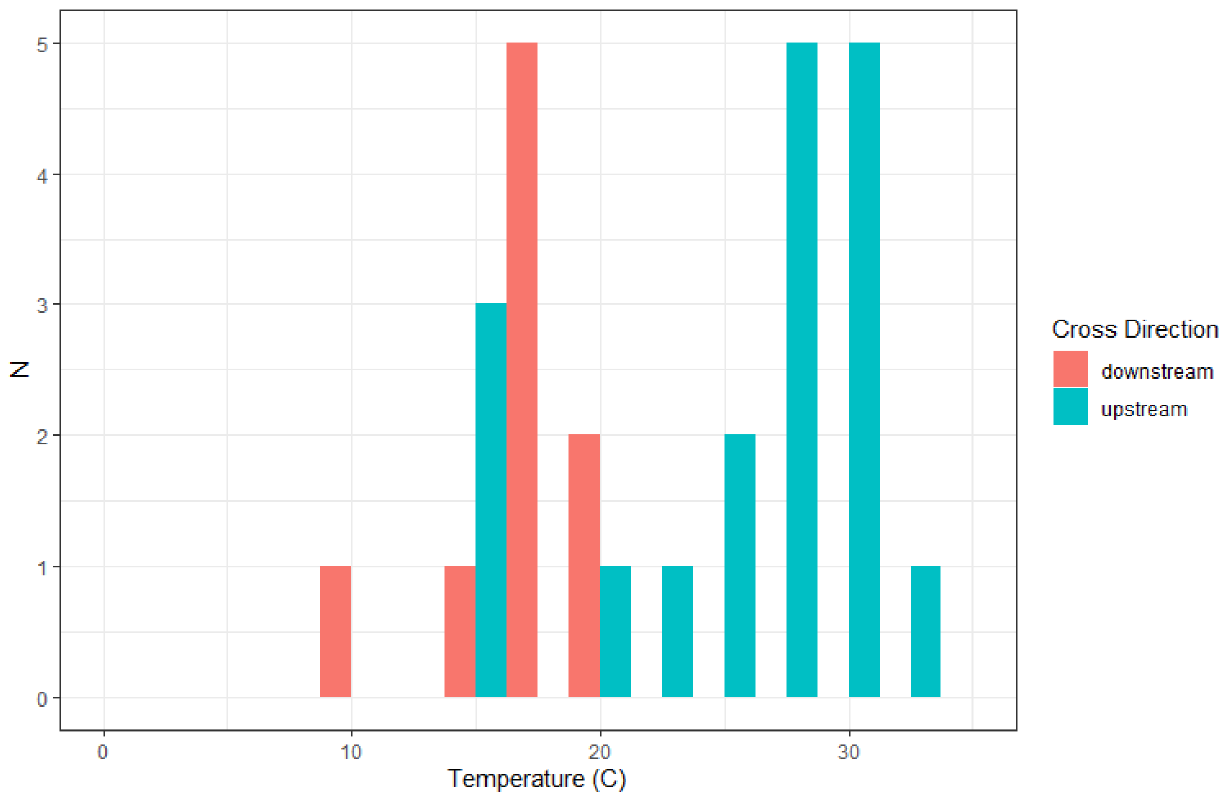

Figure 11. Frequency distribution for date of silver carp crossings at Kentucky and Barkley dams across a range of surface temperatures.

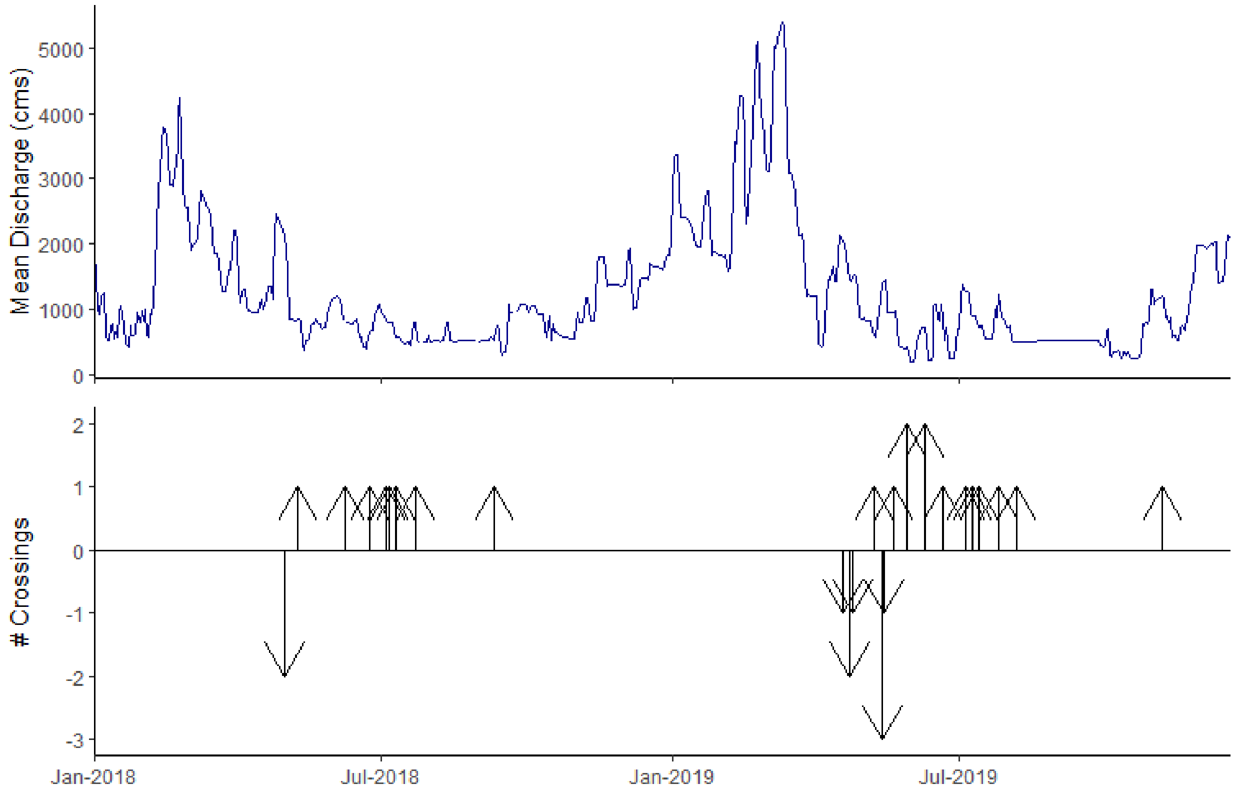

Figure 12. Mean total discharge rate (m^3/s) at Barkley Dam compared to the number and direction of silver carp crossings. Fish crossings are positive for upstream, and negative for downstream crossings.

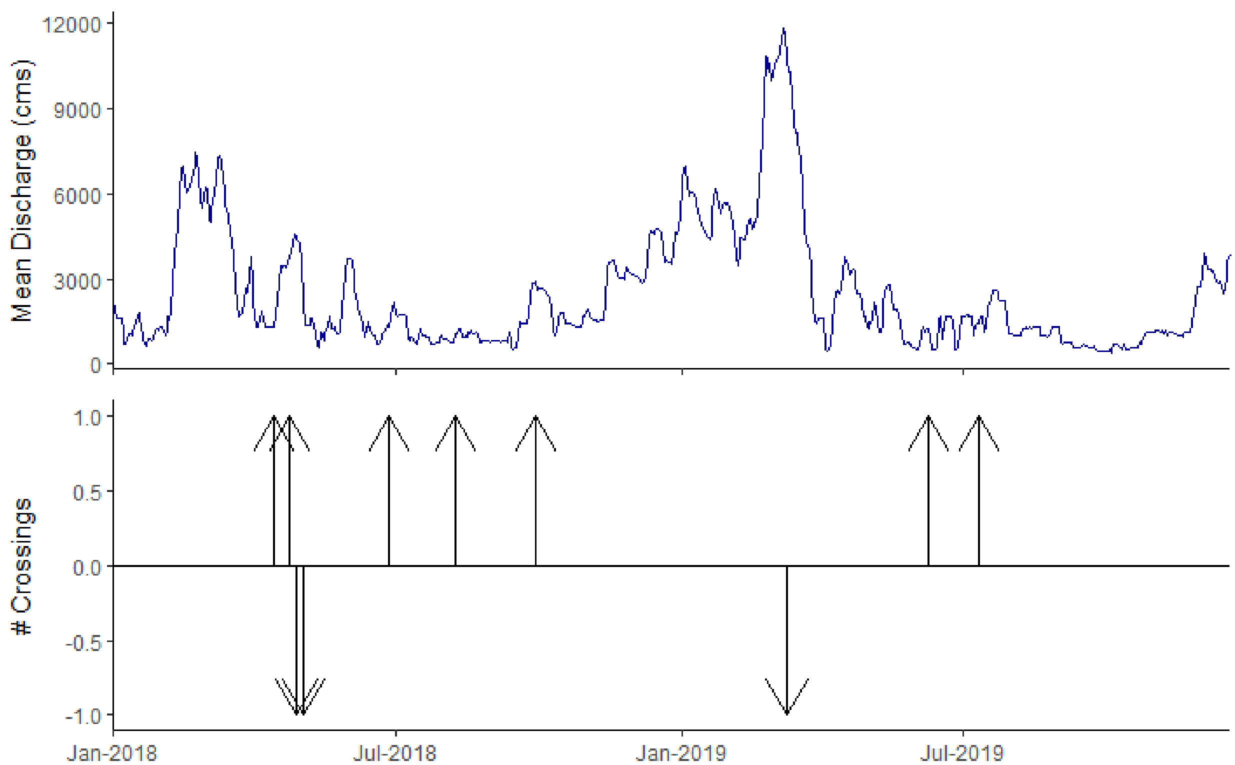

Figure 13. Mean total discharge rate (m^3/s) at Kentucky Dam compared to the number and direction of silver carp crossings. Fish crossings are positive for upstream, and negative for downstream crossings.