Blue catfish population characteristics and dispersal along a Great Plains river gradient

Q. J. Dean

J. P. Werner

Mark A. Pegg
mpegg2@unl.edu

M. J. Hamel

Received: 1 June 2021 | Revised: 11 April 2022 | Accepted: 21 April 2022
DOI: 10.1002/rra.3985

RESEARCH ARTICLE

WILEY

Blue catfish population characteristics and dispersal along a Great Plains river gradient

Quintin J. Dean[1,2] | Jacob P. Werner[1,3] | Mark A. Pegg[1] | Martin J. Hamel[1,4]

[1]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska, USA
[2]Inland Fisheries Tyler District Fisheries Managment Team, Texas Parks and Wildlife Department, Tyler, Texas, USA
[3]Fisheries Division, Southeast District, Nebraska Game and Parks Commission, Lincoln, Nebraska, USA
[4]Warnell School of Forestry and Natural Resources, University of Georgia, Athens, Georgia, USA

Correspondence
Quintin J. Dean, Texas Parks and Wildlife Department, 75707, Tyler, 11942 FM 848, Building A-400, Texas, USA.
Email: quintin.dean@tpwd.texas.gov

Funding information
Kansas Department of Wildlife, Parks and Tourism

Abstract

Understanding movement and dispersal dynamics of mobile, large-river fishes is essential to adopting an ecologically relevant spatial scale for research and management. Movement and dispersal patterns of Blue Catfish*Ictalurus furcatus*, a large-river specialist, have been mostly investigated in large river systems within their native range, with little emphasis on tributaries and the influence of connectivity. Here, we examine longitudinal movement patterns, natal environments, and population demographics of Blue Catfish in a tributary system of a large Great Plains river. Blue Catfish tagged in the Kansas River were recaptured in five different rivers of varying size and order, and individual movement was highly variable (0–475 rkm). Adult fish (>400 mm) collected within segments (i.e., Segment 1 and 2) of the Kansas River with connectivity to the Missouri River displayed relatively equal natal contributions from the Kansas River (34–48%) and Missouri River (38–65%) while disconnected river segments contained a high percentage (64–87%) of individuals that originated from reservoirs located on tributaries to the Kansas River. The Kansas River segments (Segment 1 and 2) connected with the Missouri River had lower instantaneous mortality ($Z = 0.19$, SE $= 0.05$) and higher proportions of large fish (PSD-M = 9 & 11, PSD-T = 3 & 5, respectively) compared to disconnected reaches ($Z = 0.27$, SE $= 0.08$; PSD-M = 3, PSD-T = 0). Mean length of Blue Catfish collected in disconnected reaches were greater than those from connected reaches for individuals at age-3 and age-6, and relatively equal at age-10. Our data provide additional resolution to movement and dispersal patterns of Blue Catfish within large-river tributary systems, highlight the role of localized reservoir stock contributions, and illustrate species plasticity across varying levels of river network connectivity.

KEYWORDS
catfish, connectivity, fish entrainment, ictalurus furcatus, low-head dam, natal environment, otolith microchemistry, tributaries

1 | INTRODUCTION

Objective-based management of fish populations relies on information regarding population characteristics at an ecologically relevant spatial scale (Peterson & Dunham, 2010; Porreca et al., 2016). Quantifying population characteristics for species in open systems is challenging as individual variations in movement patterns or natal environment may negate the selection of a singular, ecologically relevant spatial scale (Paukert & Galat, 2010). For example, mobile species occupying dendritic, river networks may frequent different river systems (i.e., tributaries) or regulatory jurisdictions warrant management decisions that reflect the broad spatial scale of the population (Pracheil, Pegg, Powell, & Mestl, 2012; Pugh & Schramm Jr., 1999; Siddons, Pegg, & Klein, 2017). Selecting a spatial scale to investigate and manage mobile riverine species can be influenced by the myriad of anthropogenic alterations on large-river systems. Dams operated for hydropower, flood control or navigation often alter the form and function of lotic systems and their communities (Eitzmann & Paukert, 2010; Pegg, Pierce, & Roy, 2003; Stanford & Ward, 2001). Dams also alter or block pathways to spawning, feeding, and overwintering habitats among large-river species (Jennings & Zigler, 2009). Diminished connectivity and changes in community structure among river reaches separated by dams may elicit changes in population vital rates, creating ecologically disconnected populations with unique characteristics (Hamel, Spurgeon, Pegg, & M. A., 2021; Hamel, Spurgeon, Steffensen, & Pegg, 2021; Paukert & Makinster, 2009). This effect may be exacerbated in species such as Blue Catfish *Ictalurus furcatus* that rely on connectivity between tributary and main-stem river habitats for various life-history strategies.

Blue Catfish are a mobile, large-river specialist that historically occupied large, warm-water riverine habitats in the Mississippi River drainage, including the Missouri River and its larger tributaries (Graham, 1999). Blue Catfish characteristically migrate upstream or into tributary habitats for spawning and retreat to large-river habitats for overwintering (Graham, 1999). For example, 10–18% of Blue Catfish occupying the Missouri River used tributary systems during the putative spawning time (Garrett & Rabeni, 2011). Similarly, 19% of tagged Blue Catfish in the Upper Mississippi River used one or more major tributaries during a three-year study (Tripp et al., 2011). The recruitment contribution of tributary systems to large-river (≥ ninth stream order) populations of Blue Catfish is thought to be minimal (Laughlin, Whitledge, Oliver, & Rude, 2016), however the relative importance of large-river contributions to smaller tributary populations remains uninvestigated. Information regarding movement and dispersal characteristics of tributary populations (stream order 5–8) and their relationship with main-stem river systems is essential to further create a holistic ecological understanding of Blue Catfish populations in lotic systems.

Fisheries managers are increasingly interested in improving the understanding of Blue Catfish ecology as the popularity and distribution of the species continues to increase (Arterburn, Kirby, & Berry, 2002; Porath, Kwak, Neely, & Shoup, 2021). The response of Blue Catfish to diminished habitat connectivity or habitat alteration has been unaddressed and may have ramifications for managing catfish fisheries in disjointed or modified river systems. For example, both Flathead and Channel Catfish exhibited distinct population dynamics and demographics among fragmented and altered stretches of the lower Missouri River (Hamel, Spurgeon, & Pegg, 2021). Identifying potential impacts of diminished habitat connectivity on vital rates of Blue Catfish populations is essential to determine appropriate management decisions such as size and harvest restrictions and stocking rates. Here, we examine population characteristics (i.e., growth, mortality, and size structure), natal origins, and longitudinal movement patterns of Blue Catfish across a gradient of connectivity and habitat alteration between the Kansas River and Missouri River created by three dam structures. These data collectively provide insight into how anthropogenic influences may differentially structure Blue Catfish population demographics and dynamics, and movement and dispersal patterns of Blue Catfish occupying the lower Kansas River. This study will provide insight into how catfish populations might function in altered large-river systems, providing a basis for assessing catfish in altered riverine systems.

2 | METHODS

2.1 | Study area

The Kansas River originates at the confluence of the Smokey Hill and Republican rivers in north central Kansas and flows 274 river kilometers (rkm) eastward to the Missouri River (Sanders Jr, Higgins, & Cross, 1993) (Figure 1). Four federal reservoirs are located in close proximity to the Kansas River and have established, self-sustaining populations of Blue Catfish; Perry, Clinton, Milford, and Tuttle Creek reservoirs. Previous studies have shown that entrainment of Blue Catfish from established reservoir populations has supplemented existing (Graham & DeiSanti, 1999) or established new populations in downstream river systems (Bonvechio, Bowen, Mitchell, & Bythwood, 2012; Homer & Jennings, 2011). Contributions of entrained individuals from reservoir populations provides an additional dynamic to movement, dispersal, and population demographic patterns within our study area. Therefore, we quantified the proportional contribution of fish originating from reservoir environments from Blue Catfish captured in the Kansas River.

We used three dams or weirs as natural breaks to divide the lower Kansas River into three distinct river segments. Segment 1 was between the Missouri River confluence and Johnson County Weir (rkm 24), Segment 2 was between the Johnson County Weir and Bowersock Dam (rkm 84), and Segment 3 was between Bowersock Dam and Topeka Weir (rkm 141).

The size and stature of the dams create a gradient of habitat connectivity between the Kansas River and the greater Missouri River system. The Johnson County and the Topeka weirs are municipal water diversion structures that may present a barrier to upstream movement of fish during low flow, while allowing upstream passage during high flow (J. Werner, University of Nebraska-Lincoln, Master's

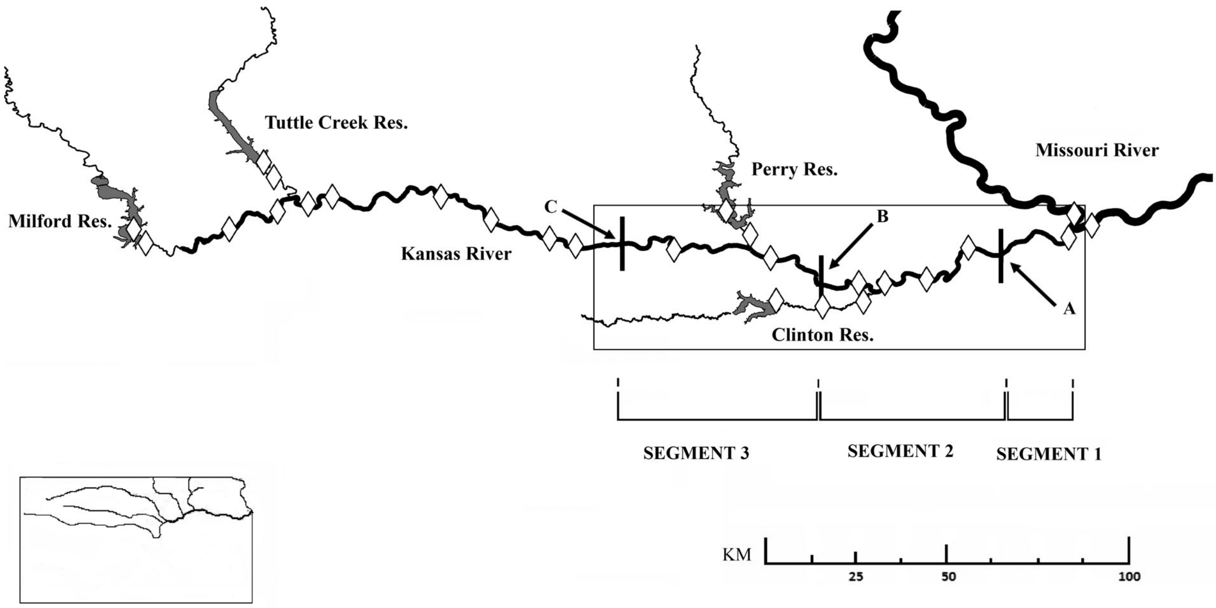

FIGURE 1 The lower Kansas River (boxed) divided into three segments at the location of anthropogenic barriers: the Johnson County Weir (a), Bowersock Dam (b), and the Topeka Weir (c). Location of water sample collection sites are indicated by white diamonds

Thesis). Bowersock Dam is a low-head dam considered to be a complete barrier to upstream fish passage (Eitzmann, Makinster, & Paukert, 2007; J. Werner, University of Nebraska-Lincoln, Master's Thesis), but may allow limited downstream movement.

2.2 | Sampling

Fish were collected between May and August 2018 and 2019 using pulsed DC low-frequency electrofishing (LFE) (4 amps, 15 pulses/s, 15 hz) and bank poles (BP). Sampling was conducted along riverbank and side channel habitats. Electrofishing transects were chosen at random within each river segment and transect length was limited to 30 min or available habitat. Bank poles were equipped with a 6/0 circle hook, silver carp *Hypophthalmichthys molitrix* cut bait and 85 g lead sinker and deployed over-night (see Dean, Hamel, Werner, & Pegg, 2021). Catch-and-release catfish angling tournaments during the studies duration were used to increase the sample size of larger fish for the mark-recapture portion of the study. All fish at tournament events were released at the confluence of the Missouri and Kansas rivers; the location of the initial capture was not recorded.

2.3 | Population characteristics: Data collection

Total length (mm) and weight (kg) were recorded for each Blue Catfish. Lapilli otoliths were collected during July and August 2018 for age, growth, and microchemistry analysis. Otolith collection was limited as concurrent research objectives relied on tagged and released individuals. Otoliths were collected from approximately 25 juvenile (200–400 mm) and 25 adult (> 400 mm) fish from each river segment. Tissue was removed and otoliths were cleaned with Nanopure water. Otolith nuclei were marked, placed in silicone molds, and embedded in epoxy (Epoxicure Epoxy Resin and Hardener, Buehler Inc., Lake Bluff, Illinois). Cross sections (0.5 mm) were taken from the transverse plane of each otolith using an ISOMET low-speed saw. Annuli were revealed by sanding cross sections (1,500, and 3,000 grit) and polished using 3 μm lapping film. Otoliths were attached to microscope slides using double-sided tape and photographed using a high-resolution digital camera. Additional light sources were used to optimize annuli clarity. Ages were assigned to each fish by three independent readers and discrepancies were resolved by a concert reading.

2.4 | Population characteristics: Data analysis

Proportional size distribution (PSD) indices were used to compare the size structure among years, sampling gears and river segments (Anderson & Neumann, 1996; Guy, Neumann, Willis, & Anderson, 2007). The following minimum lengths were used to classify each fish into a PSD category: stock (300 mm), quality (510 mm), preferred (760 mm), memorable (890 mm), and trophy (1,140 mm) (Gablehouse Jr., 1984; Guy et al., 2007). Chi square tests were used to compare PSD indices between years for a given river segment and across river segments (Ogle, 2016). We also adjusted probability thresholds using a Bonferroni correction when multiple comparisons were made.

Length-at-age was determined using the Dahl-Lea method of back-calculation:

$$L_i = \frac{S_i L_c}{S_c}$$

where L_i is the estimated length at age i, S_i is the otolith radius at the ith annulus, L_c is total length at capture, and S_c is the radius of the entire structure (Isely & Grabowski, 2007). Three ages representing general anatomical benchmarks were used to compare growth among river reaches; pre-gonadal development (age-3; Graham, 1999), approximate age of sexual maturity within the same ecoregion (age-6; Graham & DeiSanti, 1999) and post-gonadal development (age-10). Mean length at age-3, age-6 and age-10 were compared across river segments using analysis of variances (ANOVA, $\alpha = 0.05$) with Tukey's studentized range (HSD) test for multiple comparisons.

Individual age estimates were assigned to all unaged fish with an age-length key using the Isermann and Knight (2005) method to resolve fractionality using the FSA package in Program R (R Core Team, 2018). Weighted catch curves were used to estimate instantaneous mortality (Z) and annual mortality (A) for age classes fully recruited to gear, where Z is the slope of the weighted linear regression and $A = 1 - e^{-Z}$ (Ogle, 2016; Ricker, 1975). Combined data from 2018 and 2019 were used to provide sufficient data for each age category and mitigate effects of variable recruitment (Miranda & Bettoli, 2007). Age classes with less than five individuals were excluded to mitigate influence of older individuals (Miranda & Bettoli, 2007). Instantaneous mortality estimates were compared across river segments using LFE catch data with analysis of covariance (ANCOVA, $\alpha = 0.05$).

2.5 | Movement and dispersal: Data collection

Fish captured between 200 and 400 mm (i.e., juveniles) received a standard T-bar tag (Floy FD-94) and fish greater than 400 mm (i.e., adults) received a larger T-bar tag (Extra Wide T Floy FD-94; Floy Tag and Manufacturing, Inc., Seattle, Washington). Tags were inserted below the dorsal fin through the pterygiophores (Daugherty & Buckmeier, 2009). Each tag contained a unique identification number, a phone number to report recapture information and notification of reward upon reporting. Anglers that reported capturing tagged fish were interviewed to determine the recapture location. The distance (rkm) between capture events following the river thalweg was then calculated using Google Earth (earth.google.com/web/). Data provided by recaptured fish included movement orientation (downstream vs. upstream), distance traveled (rkm), days at large, fate (harvest or release) and date of recapture.

Otoliths previously used for age and growth analysis were also used for natal origin, and environmental history analysis following the same procedures. Otoliths were also collected from adult fish (> 400 mm) captured in Milford ($n = 5$), Perry ($n = 6$), Clinton ($n = 5$) and Tuttle Creek ($n = 5$) reservoirs to represent individuals of known environmental history for microchemistry analysis. Otoliths were analyzed for (i.e., strontium (^{88}Sr) and calcium (^{43}Ca)) using a Thermo X-Series2 (Thermo-Fisher Scientific, Waltham, MA, USA) inductively coupled plasma mass spectrometer (ICPMS) paired with a CETAC Technologies (Teledyne-CETAC Technologies, Omaha, NE, USA) LSX-266 laser ablation system. The laser (beam diameter = 100 μm, scan rate = 5 μm/s, laser pulse rate = 10 hz, laser energy level = 75%, wavelength = 266 nm) ablated a transect extending from one side of the otolith nucleus to the edge of the opposite side of the otolith. A standard developed by the U.S. Geological Survey (MACS-3; CaCO3 matrix) was used every 15–20 samples to adjust for instrument drift. Each sample was preceded and followed by a 30 s gas blank measurement. Data were reported as the Sr:Ca ratio (mmol/mol).

The otolith edge (outer 30 μm) was used to determine recent environmental history of each fish (Zeigler & Whitledge, 2010). Data points from the ablation transect located within the nucleus of the otolith were isolated to examine natal origins. Remaining transect data were used to describe life-long movement patterns of individuals (Duncan, 2019).

Water samples were collected to assess the spatiotemporal variation in trace elemental composition of the Kansas River basin and Missouri River (Ciepiela & Walters, 2019). Initial water samples were collected in the fall 2017 with additional samples collected in the winter, spring, and summer of 2019. Three water samples were collected from sixteen sites along the Kansas River ($n = 48$), the Missouri River ($n = 7$) upstream and downstream of the Kansas River confluence as well as Perry ($n = 4$), Clinton ($n = 6$), Milford ($n = 4$), and Tuttle Creek ($n = 4$) reservoirs and their effluences each year. Water samples were collected using a syringe filtration technique described by Shiller (2003). A sterilized 250 mL vial was thoroughly rinsed and filled with water from a given site. A pre-cleaned polyethylene 50 mL syringe was then rinsed with the sample and approximately 15 mL was filtered through the syringe to limit contamination (Shiller, 2003). Approximately 5 mL was initially filtered through a Whatman Puradisc PP 0.45 μm syringe filter to rinse a 15 mL sample vial. The remaining sample was used to fill the 15 mL vial used for analysis. Elemental concentrations of strontium (Sr), barium (Ba), magnesium (Mg) and calcium (Ca) were analyzed at the University of Southern Mississippi's Trace Analysis Lab using a high resolution Inductively Coupled Plasma Mass Spectrometry (ICPMS; Thermo-Finnigan Element 2).

2.6 | Microchemistry: Analysis

Water and otolith samples were grouped by water body for statistical analyses. Distribution of the water Sr:Ca ratio data were assessed for normality using a visual inspection of a quantile-quantile plot. Water samples from each site were combined among all years and seasons to calculate the mean and inter-quartile ranges. Spatial variation in water signatures among segments of the Kansas River and other river systems were examined using analysis of variance (ANOVA) coupled with Tukey's studentized range (HSD) test for multiple comparisons.

We established threshold values for each potential natal environment to identify the natal environment of individuals captured in the Kansas River. The linear relationship between mean otolith and water Sr:Ca at each site was used to estimate a predicted range of otolith Sr:Ca values representative of Kansas River and Missouri River water signatures. Fish of known sources (i.e., reservoirs) and juvenile fish (<400 mm) from segment two were used to mitigate the influence of recent immigrants on model fit. The standard error of the linear regression was calculated using the *predict.lm* function from the stats package (R Core Team, 2018) and served as threshold values for each environment. Natal origin data were summarized for each segment using the proportional distribution of natal environments.

Ablation transect data were used to retrospectively examine movement patterns of individual fish throughout their lifespan. Ablation transect data from the nucleus to the otolith edge were assessed for movement between water bodies where 10 consecutive data points (30 μm) of the ablation transect represented a single water body (Figure 2). Individuals were assigned to one of four movement patterns; resident, transient, immigrant, or returning emigrant. Individuals that originated and remained within the Kansas River for their entire life were classified as residents. Fish that moved between river systems at least three times were classified as transients, regardless of natal origins. Fish that did not originate from the Kansas River and had a single movement event into the Kansas River were classified as immigrants. Lastly, individuals that originated in the Kansas River, emigrated to another water body and returned to the Kansas River without additional movement events were classified as returning emigrants. We acknowledge that short bouts to different river systems may not be reflected in the otolith microchemistry, but assume that movement patterns such as these are not influential for determining movement dynamics.

3 | RESULTS

3.1 | Population characteristics

A total of 1,310 Blue Catfish ranging from 37 to 1,310 mm were captured using both gears (2018: $n = 822$; 2019: $n = 488$) (Figure 3a). Total LFE effort was 6,424 min with a mean sampling transect of 26.3 min ($n = 244$, SE = 0.6). Total BP effort was 897 hook nights (2018: $n = 432$; 2019: $n = 465$). Low-frequency electrofishing captured a wider range of sizes (37–1,235 mm; $n = 1{,}193$) and had a smaller mean length (mean = 290 mm; SE = 7.15) compared to bank poles (503–1,310 mm; $n = 117$; mean = 776 mm; SE = 15.4). About 33% ($n = 398$) of all fish captured with low-frequency electrofishing were stock length and 100% of fish captured with bank poles were stock length ($n = 117$).

Proportional size distribution did not vary across years for low-frequency electrofishing ($\chi^2 = 1.84$, df = 4, $p = 0.76$), bank poles ($\chi^2 = 1.50$, df = 4, $p = 0.82$), or combined gears (CG) ($\chi^2 = 0.44$, df = 4, $p = 0.97$), therefore further analyses combined data from both years. PSD analysis of bank pole sampling was excluded due to low sample size. PSD varied among river segments for low-frequency electrofishing ($\chi^2 = 16.543$, df = 6, $p = 0.01$) and combined gears ($\chi^2 = 25.474$, df = 8, $p < 0.01$). Segment three varied from both segment one (CG: $\chi^2 = 15.63$, df = 4, $p < 0.01$; LFE: $\chi^2 = 10.1$, df = 3, $p = 0.02$;) and segment two (CG: $\chi^2 = 23.58$, df = 4, $p < 0.01$; LFE:

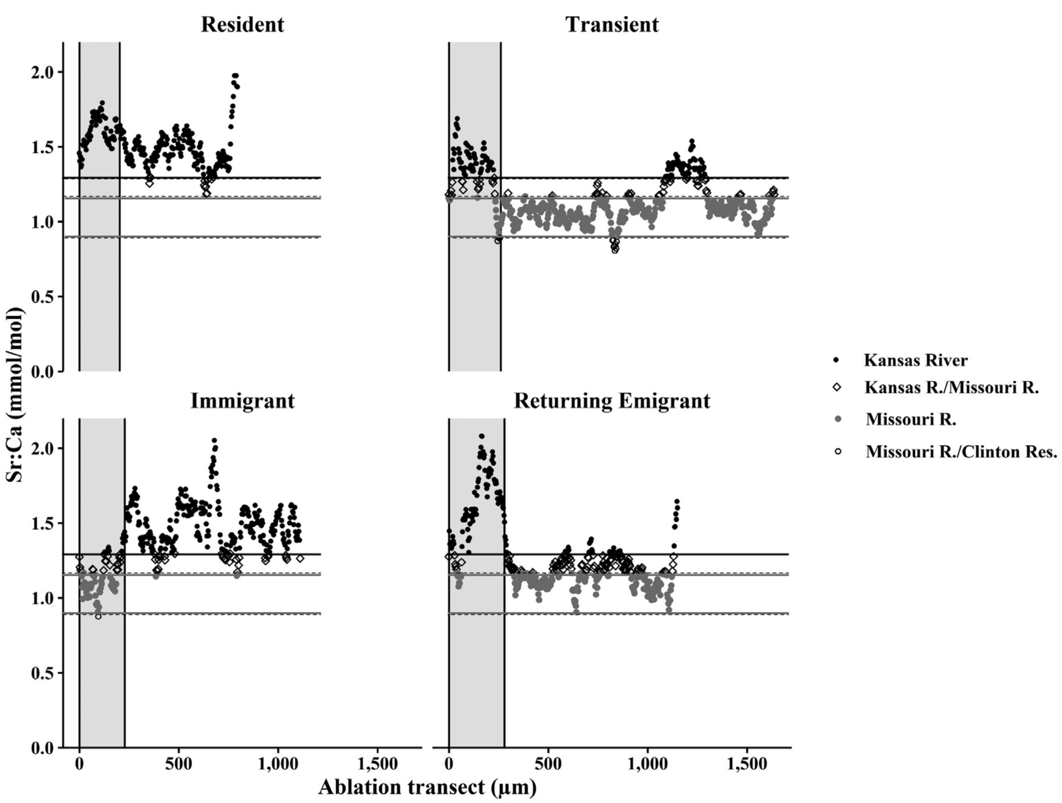

FIGURE 2 Example of environmental history plots created to categorize individual fish into four life-long movement patterns; resident, transient, immigrant, and returning emigrant. Shaded regions represent values indicating natal environments

$\chi^2 = 11.45$, df $= 3$, $p < 0.01$) (Table 1). Similar proportions of large fish were collected in segment one (CG: PSD-M = 9, PSD-T = 3) and segment two (CG: PSD-M = 11, PSD-T = 5) while segment three displayed a truncated size structure with an absence of trophy length fish and few memorable length fish (PSD-M: CG = 3).

A total of 116 fish were aged and ranged from 1 to 19 years. We collected 47 otoliths in segment one (maximum age = 13), 39 structures in segment two (maximum age = 19) and 30 structures from segment three (maximum age = 12). Results of Tukey's HSD indicated the mean age of fish collected with LFE in segment two ($n = 143$, mean = 5.3, SE = 0.22) was greater than those captured in segment one ($p = 0.03$) and segment three ($p < 0.01$). The mean back-calculated length-at-age in segment three were greater than segment one at age-3 (ANOVA: $F_{1,47} = 5.76$, $p = 0.02$) and age-6 (ANOVA: $F_{1,34} = 13.93$, $p < 0.01$) (Figure 3b). Length at age for fish >10 years in age did not significantly vary among gears across the study area (ANOVA: $F_{2,19} = 1.0.461$, $p = 0.638$). Mean back calculated length for segment two overlapped with both segment one and three for all age groups examined.

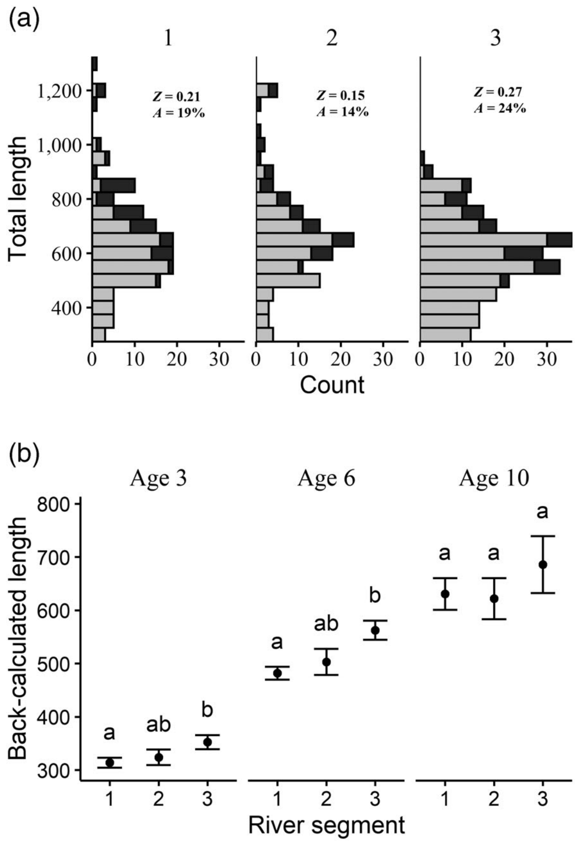

FIGURE 3 (a) Total length (mm) frequency histograms, instantaneous mortality (Z) and annual mortality (a) and (b) mean back-calculated length (mm) at ages 3, 6 and 10 across three River Segments of the Kansas River, KS. Error bars indicate 95% confidence intervals derived from Tukey HSD test

Visual inspection of catch curves indicated fish were recruited to LFE at age six (the peak of the age-frequency histogram). Mortality was estimated as Z = 0.22 (SE = 0.04) and $A = 19\%$ (SE = 3.7) for the entire study area. Segment two (Z = 0.15 ± 0.07, $A = 14\% \pm 5.6$) had a lower mortality estimate than segment one (Z = 0.21 ± 0.07, $A = 19\% \pm 5.6$; ANCOVA: $F_{3,22} = 34.23$, $p = 0.329$) and a significantly lower estimate than segment three (Z = 0.27 ± 0.08, $A = 24\% \pm 5.8$; ANCOVA: $F_{3,21} = 38.38$, $p < 0.01$).

3.2 | Mark-recapture

A total of 588 Blue Catfish were tagged between June 2018 and October 2019, including 121 individuals tagged at catch and release tournaments in segment one. The mean total length of tagged juvenile fish was 257 mm ($n = 135$; range 190–396; SE = 4.7) and 698 mm ($n = 453$; range = 401–1,330; SE = 7.8) for adult fish. A total of 63 unique fish were recaptured, with two individuals recaptured twice. Some fish ($n = 17$) were recaptured during sampling however the majority of recaptured fish ($n = 48$) came from anglers. Seventeen recaptured individuals were originally tagged at tournament events, seven of which were recaptured in the Missouri River. Most fish (85%) were recaptured within 50 rkm of the tagging location, 57% were within 10 rkm and 31% were within 5 rkm of tagging location (Figure 4). The median distance between tagging and recapture location was 8.4 rkm with a mean of 33.0 rkm (SE = 9.8).

Anglers recaptured fish in five rivers: the Kansas River ($n = 24$), the Delaware River downstream of Perry Reservoir ($n = 10$), the Missouri River ($n = 12$), the Osage River, Missouri ($n = 1$) and the Platte River, Missouri ($n = 1$). The Johnson County Weir was the most traversed structure, with individuals navigating both downstream ($n = 4$) and upstream ($n = 2$). The Topeka Weir was navigated by a single individual in an upstream direction. One individual was recorded as

TABLE 1 Proportional size distribution (PSD) values for Kansas River Blue Catfish captured with low-frequency electrofishing and combined gears across sampling years and river segments

	Low-frequency electrofishing					Combined gears			
Segment	PSD-Q	PSD-P	PSD-M	PSD-T	Segment	PSD-Q	PSD-P	PSD-M	PSD-T
1	78	13	6	1	1	83	26	9	3
2	83	17	5	3	2	87	26	11	5
3**	69	14	2	0	3**	74	18	3	0
Overall	73	14	4	1		80	22	7	2

**Chi square test results indicate statistical significance ($p < 0.05$).

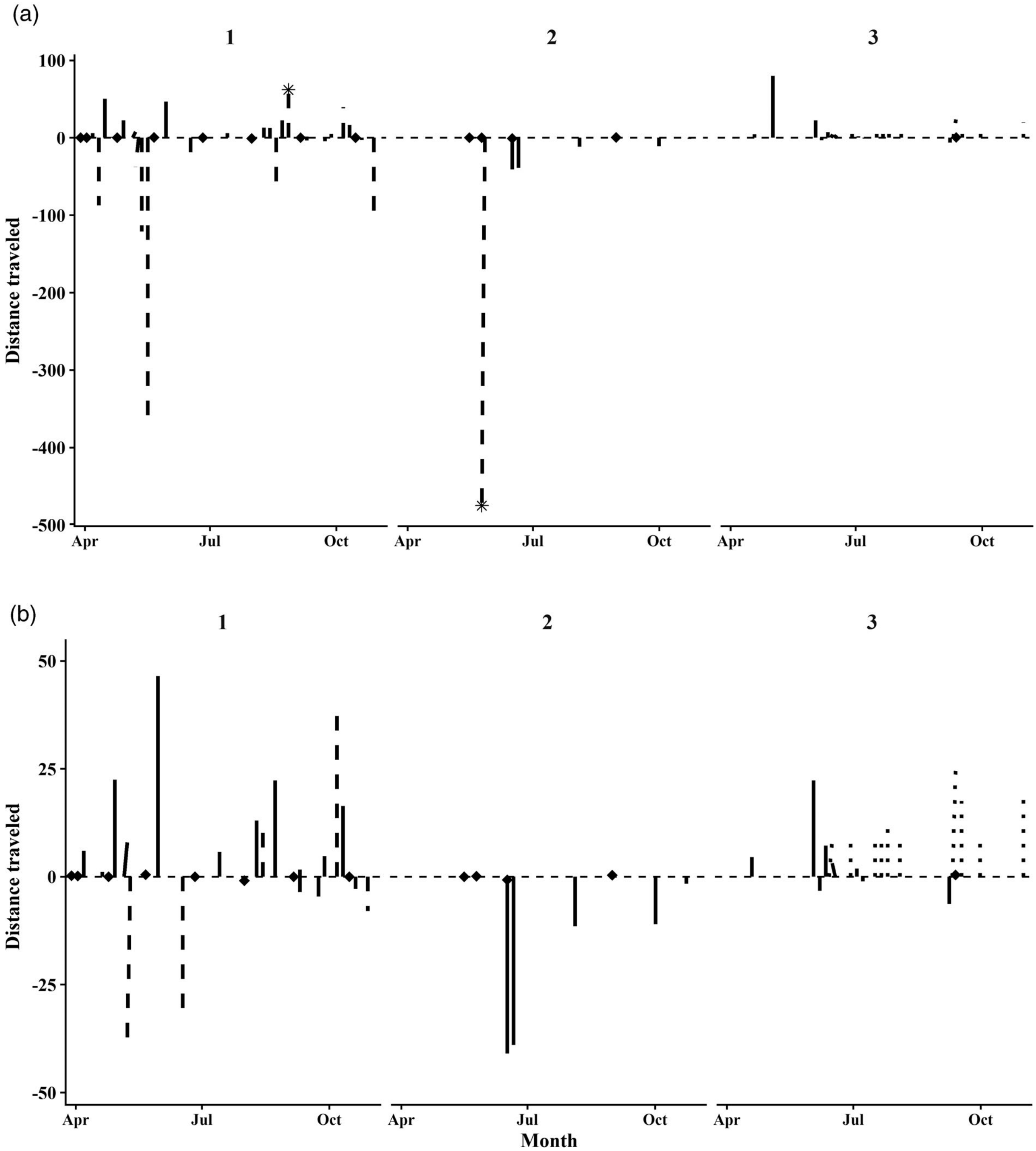

FIGURE 4 Distance traveled and orientation of (a) all individual movement events and (b) those less than 50 rkm for Blue Catfish tagged in the three river reaches of the Kansas River. Orientation of bars represent the direction a fish traveled within in Kansas River (solid), Delaware River (dotted) or the greater Missouri River system (dashed). Asterisks indicate an individual captured in a Missouri River tributary, excluding the Kansas River

moving downstream and none moved upstream through Bowersock Dam. No fish were reported traversing a dam structure during the low water conditions of 2018.

3.3 | Microchemistry

A total of 146 Kansas River otoliths were used for microchemistry analysis. The mean total length for juvenile fish used in microchemistry analysis was 226 mm (range 100–400 mm; SE = 8.8) and 674 mm (range = 424–1,208 mm; SE = 16.2) for adult fish. The mean water Sr:Ca differed among the water bodies sampled (ANOVA: $F_{5\ 66} = 29.37$, $p < 0.001$) (Figure 5a). The Kansas River had the highest water Sr:Ca (mean = 4.17 mmol/mol, SE = 0.08). Water Sr:Ca overlapped among Perry, Milford and Tuttle Creek reservoirs and the Missouri River. Clinton Reservoir exhibited the lowest water Sr:Ca (mean = 2.34 mmol/mol, SE = 0.1). The Sr:Ca signatures of Perry, Milford and Tuttle Creek

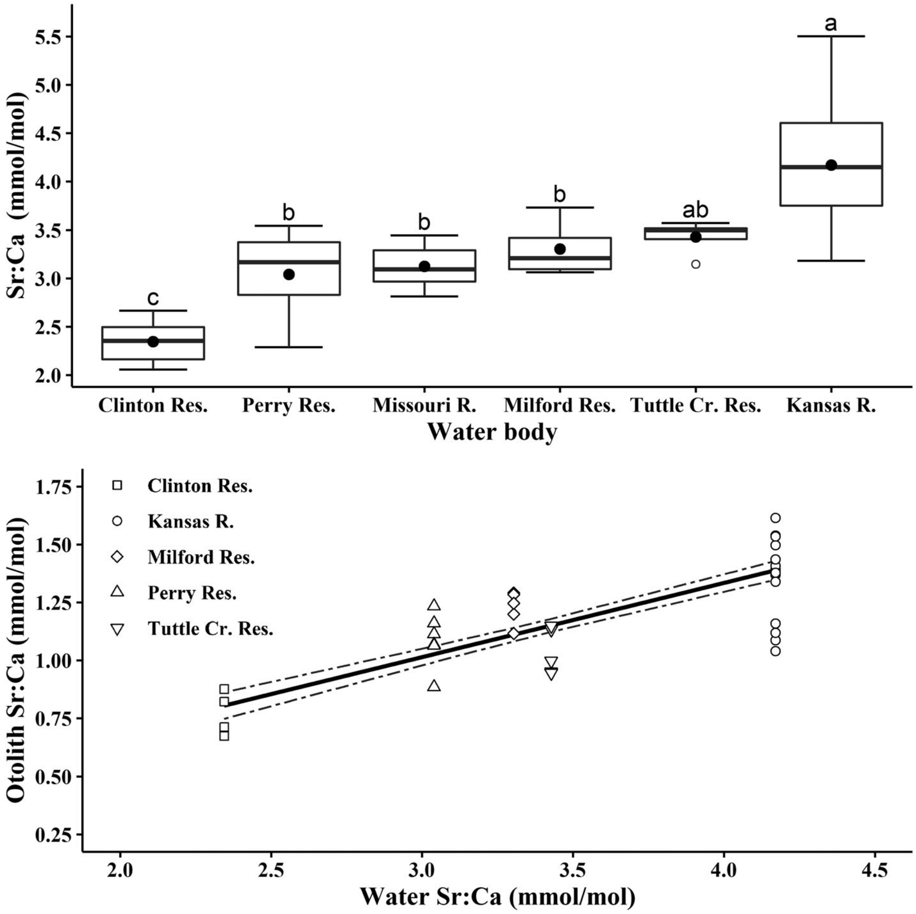

FIGURE 5 (a) Boxplots depicting the median, range, inter-quartile ranges and mean of water Sr:Ca (mmol/mol) from potential natal environments of Blue Catfish collected in the lower Kansas River. (b) Relationship between water Sr:Ca and otolith Sr:Ca for Blue Catfish from this study (solid line; y = 0.3195x–0.0559; $R^2 = 0.60$, $p < 0.001$) and associated standard error (dashed line)

overlapped considerably and were reclassified as reservoir signatures for further analysis.

The recent environmental history of otoliths collected within the Kansas River displayed substantial variation in Sr:Ca values (range = 0.70–1.93, SE = 0.02), indicating recent immigrants from other water bodies. However, otolith Sr:Ca values of known environments and juvenile fish collected in segment two was positively correlated to water Sr:Ca (y = 0.3195x–0.0559; $R^2 = 0.60$, $p < 0.001$) (Figure 5b).

We used four categories to assign natal environments based on the water Sr:Ca ratios and their relation to otolith signature information: the Kansas River, the Missouri River, Clinton Reservoir, and Reservoir (e.g., Milford/Perry/Tuttle Creek). Values representing regions of significant overlap among water bodies were classified as indistinguishable environments (i.e., Kansas R./Missouri R., Missouri R./Clinton Res., Kansas R./Reservoir). Movement patterns observed from mark-recapture events were used to distinguish Reservoir and Missouri River environments. For example, fish captured in segment three with signatures indicating Missouri River or Clinton Reservoir were classified as Reservoir signatures because upstream passage of Bowersock Dam was not observed. Additionally, fish with signatures representing the Reservoir classification but were captured in segments one or two were classified as Missouri River because downstream passage of Bowersock Dam was minimal.

Adult fish captured in segments one and two had relatively equal representation as being from the Kansas River or Missouri River (Figure 6a; Table 2). Reservoir environments contributed 50–75% of juveniles and 64–87% of adults collected upstream of Bowersock Dam. Collectively, a higher proportion of juvenile fish displayed Kansas River origins compared to adults of the same river segment, particularly in segment two. A high percentage (85%) of juvenile fish in segment two had natal origins indicating the Kansas River, with no contributions from other, distinguishable environments. Natal origins indicating Clinton Reservoir were not observed.

The percent of juvenile residents was relatively high for segments one (59%) and two (80%) compared to segment three (22%), however residents represented a small percentage of adult fish for all segments (Figure 6b; Table 2). Adult returning emigrants were absent in segment three, but the percent of returning emigrants were relatively similar among segment one (26%) and segment two (35%). Segment three contained a high percent of adult reservoir immigrants (75%) and segment two had the highest percentage of transient fish (52%). A higher percentage of immigrant fish were present in segment one (26%) compared to segment two (9%), however similar proportions were observed among other movement patterns for reaches below Bowersock Dam.

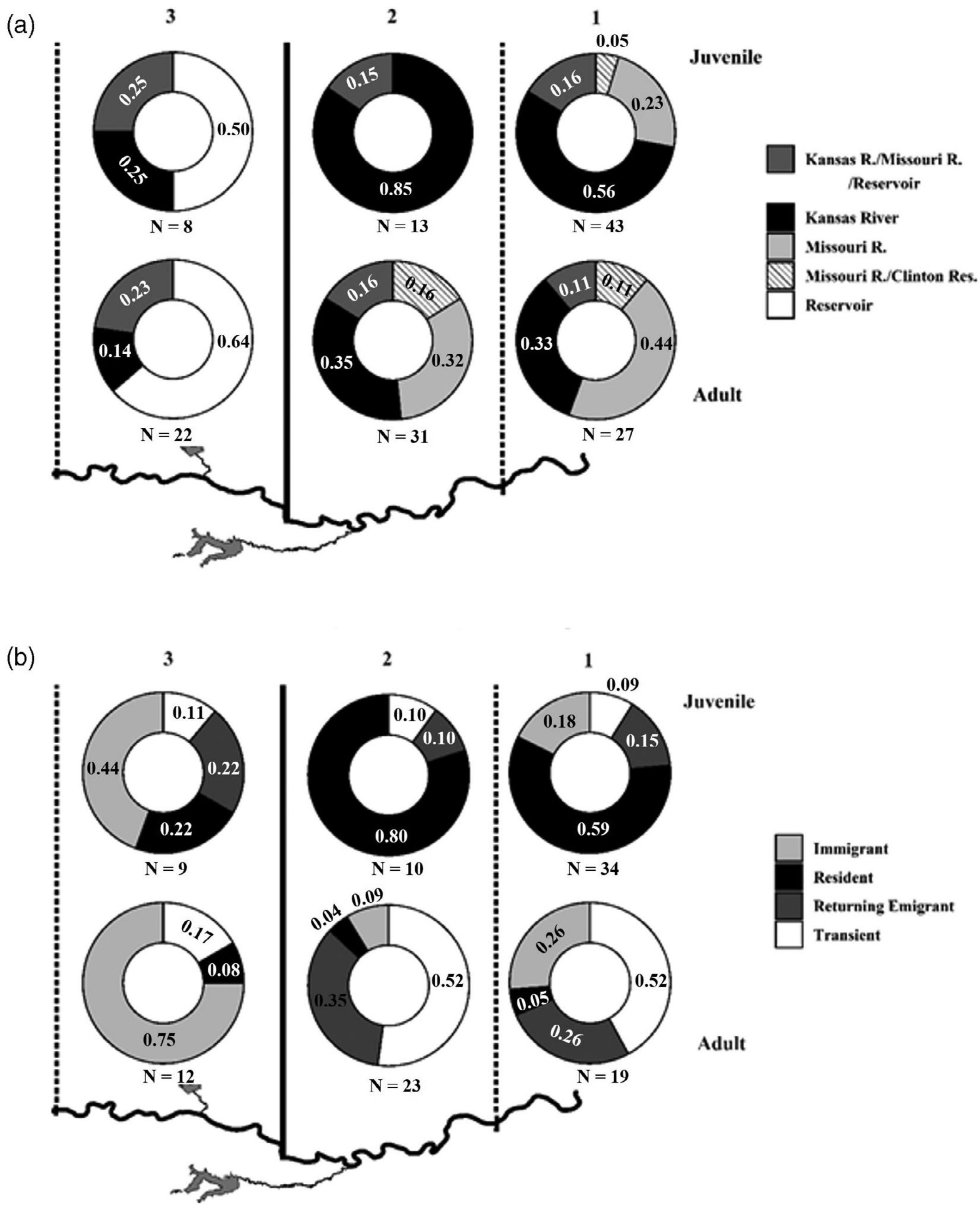

FIGURE 6 Proportional distribution of (a) natal environment and (b) environmental history movement patterns for juvenile (TL < 400 mm) and adult (TL > 400 mm) Blue Catfish captured in three reaches of the lower Kansas River. Vertical lines represent anthropogenic barriers that allow (dashed) or prohibit (solid) upstream passage of Blue Catfish

4 | DISCUSSION

Tributary habitats provide important recruitment contributions and habitat access for main-stem populations of various large-river fishes (Firehammer & Scarnecchia, 2006; Gorman & Stone, 1999; Humston, Priest, Hamilton, & Bugas Jr., 2010; Neely, Pegg, Mestl, & G. E., 2009; Pracheil, Lyons, Hamann, Short, & McIntyre, 2018; Pracheil, Pegg, & Mestl, 2009). Our observations provide additional support on the importance of river network connectivity for large-river fish occupying an intermediate tributary system. Contributions of Blue Catfish from the Missouri River to the lower Kansas River suggest that large-river habitats provide considerable influxes of adult stock to connected tributary systems and are an important source population. Additionally, a high proportion of fish within connected reaches of the Kansas River used multiple river systems throughout their lifetime and few were classified as Kansas River residents.

We anticipated the majority of fish collected upstream of Bowersock Dam (i.e., Segment 3) would be Kansas River residents due to restricted connectivity with the Missouri River network. However, our results suggest the majority of juvenile and adult fish in

TABLE 2 Proportional distribution of (a) natal environment and (b) environmental history movement patterns for juvenile (TL < 400 mm) and adult (TL > 400 mm) Blue Catfish captured in three reaches of the lower Kansas River

		Juvenile		Adult		Combined	
Segment	**Movement pattern**	***n***	**%**	***n***	**%**	***n***	**%**
1	Resident	20	59	1	5	21	40
	Transient	3	9	8	42	11	21
	Returning emigrant	5	15	5	26	10	19
	Immigrant	6	18	5	26	11	21
2	Resident	8	80	1	4	9	27
	Transient	1	10	12	52	13	39
	Returning emigrant	1	10	8	35	9	27
	Immigrant			2	9	2	6
3	Resident	2	22	1	8	3	14
	Transient	1	11	2	17	3	14
	Returning emigrant	2	22			2	10
	Immigrant	4	44	9	75	13	62
Natal environment							
1	Kansas River	24	56	9	33	33	47
	Missouri River	10	23	12	44	22	31
	Kansas R./Missouri R.	7	16	3	11	10	14
	Missouri R./Clinton res.	2	5	3	11	5	7
2	Kansas River	11	85	11	35	22	50
	Missouri River		0	10	32	10	23
	Kansas R./Missouri R.	2	15	5	16	7	16
	Missouri R./Clinton res.			5	16	5	11
3	Kansas River	2	25	3	14	5	17
	Kansas R./reservoir	2	25	5	23	7	23
	Reservoir	4	50	14	64	18	60

segment three originate from tributary reservoirs. In October 2020, approximately 34,000 kg of fish (~ 80% Blue Catfish) were salvaged from Tuttle Creek Reservoir stilling basin, providing anecdotal evidence of substantial reservoir contributions in this river system (Melissa Bean, Army Corp of Engineers, personal communication). We pose that reservoir contributions act as a surrogate source population for river reaches with diminished or absent main-stem habitat connectivity. Unlike large-river connectivity, stock contributions from reservoirs are unidirectional and may impact the abundance, size structure and vital rates of downstream populations (Jager, 2006; Pracheil, Mestl, & Pegg, 2015; Weber, Flammang, & Schultz, 2013). Unidirectional connectivity is also likely occurring at Bowersock dam, made evident by the absence of adult returning emigrants to segment three.

Blue Catfish population demographics and dynamics varied among the three Kansas River segments. This was surprising given that the narrow spatial area of our study (~141 km) experiences relatively similar environmental conditions and perceived angling effort. Although the specific mechanisms were not measured, our results support evidence that factors associated with connectivity were responsible for differentially structuring this Blue Catfish population. The population above Bowersock Dam exhibited higher mortality and a truncated size structure compared to downstream river reaches. These results suggest disconnection from main-stem environments, coupled with substantial inputs from reservoir populations may create a situation where density dependent factors are influential in structuring population characteristics. Contrary to this, open populations can distribute throughout and among other systems (e.g., metapopulation dynamics), possibly negating density-dependent effects on population dynamics.

Mark-recapture data provided interesting anecdotes about Blue Catfish movement. Two fish traveled over 300 km between capture events and several approached 100 km (Figure 4). Collectively, mark-recapture data were helpful as we were able to couple these data with our microchemistry analyses to assess likely locations of Blue Catfish across our study system. That coupling has inherent assumptions that should be considered. For example, a proportion of fish collected below Bowersock may have occupied reservoir environments but were classified as Missouri River fish based on our movement data. Additional analysis (i.e., stable oxygen isotopic composition) would likely refine our environmental assignments (Laughlin et al., 2016;

Spurgeon, Pegg, & Halden, 2018; Zeigler & Whitledge, 2011). This information would provide additional insight into the dispersal of reservoir fish within the entire Kansas River and alleviate concerns about density-dependent effects or ecological ramifications of reservoir contributions in upstream reaches.

The similarities observed in population characteristics, movement, and environmental history of Blue Catfish occupying river reaches below Bowersock Dam coupled with the limited, unidirectional connectivity this dam creates, supports differential management for Blue Catfish populations separated by this barrier. Effective management strategies below Bowersock dam would reflect those of other mobile, large-river fishes; adopting a spatial scale reflecting the species' use of a complex river network (Pracheil et al., 2012; Spurgeon, Pegg, Hamel, & Steffensen, 2018; Tripp et al., 2019) and utilizing inter-jurisdictional collaboration across the defined river network to achieve management objectives (Koehn, 2015; Pope et al., 2016; Siddons et al., 2017). Applying this approach to other systems offers the flexibility required to achieve both trophy-based objectives within Blue Catfish native range as well as population control and mitigation in non-native watersheds.

ACKNOWLEDGEMENTS

Funding for this research was provided by Kansas Department of Wildlife, Parks and Tourism. We thank Dr. Alan Shiller (Center for Trace Analysis, University of Southern Mississippi) for trace element analyses of water samples and Dr. Whitledge (Southern Illinois University Mass Spectrometry Facility) for technical support while processing otolith samples. We thank Katie Schrag, Charlie DeShazer, Andrew Karlin, Quade Brees, Luke Kowalewski, Ernesto Flores, Vanessa Salazar, Jeff Conley, and Jeff Koch for assisting various field collection efforts. We also thank Dr. Kevin Pope, Dr. Chris Chizinski and Ben Neely for comments on previous versions of this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Quintin J. Dean https://orcid.org/0000-0001-8324-0912
Jacob P. Werner https://orcid.org/0000-0003-4592-9983
Martin J. Hamel https://orcid.org/0000-0001-5013-2907

REFERENCES

Anderson, R. O., & Neumann, R. M. (1996). Length, weight, and associated structural indices. In B. R. Murphy & D. W. Willis (Eds.), *Fisheries Techniques* (2nd ed., pp. 447–482). Bethesda, Maryland: American Fisheries Society.

Arterburn, J. E., Kirby, D. J., & Berry, C. R. (2002). A survey of angler attitudes and biologist opinions regarding trophy catfish and their management. *Fisheries*, *27*(5), 10–21. https://doi.org/10.1577/1548-8446(2002)027<0010:ASOAAA>2.0.CO;2

Bonvechio, T. F., Bowen, B. R., Mitchell, J. S., & Bythwood, J. (2012). Non-indigenous range expansion of the blue catfish (Ictalurus furcatus) in the Satilla River, Georgia. *Southeastern Naturalist*, *11*(2), 355–358. https://doi.org/10.1656/058.011.0217

Ciepiela, L., & Walters, A. (2019). Life-history variation of two inland salmonids revealed through otolith microchemistry analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(11), 1971–1981. https://doi.org/10.1139/cjfas-2018-0087

Daugherty, D. J., & Buckmeier, D. L. (2009). Retention of passive integrated transponder tags in Flathead catfish. *North American Journal of Fisheries Management*, *29*(2), 343–345. https://doi.org/10.1577/M08-153.1

Dean, Q. J., Hamel, M. J., Werner, J. W., & Pegg, M. A. (2021). Efficacy and temporal capture patterns of bank poles in the Kansas River: A novel sampling tool for catfish managers. *North American Journal of Fisheries Management*, *41*, 379–387. https://doi.org/10.1002/nafm.10627

Duncan, M. B. (2019). Distributions, abundances and movements of small, nongame fishers in a large great plains river network. Doctoral dissertation. Montana State University.

Eitzmann, J. L., Makinster, A. S., & Paukert, C. P. (2007). Distribution and growth of blue sucker in a Great Plains river, USA. *Fisheries Management and Ecology*, *14*(4), 255–262.

Eitzmann, J. L., & Paukert, C. P. (2010). Longitudinal differences in habitat complexity and fish assemblage structure of a Great Plains river. *The American Midland Naturalist*, *163*(1), 14–32. https://doi.org/10.1674/0003-0031-163.1.14

Firehammer, J. A., & Scarnecchia, D. L. (2006). Spring migratory movements by paddlefish in natural and regulated river segments of the Missouri and Yellowstone rivers, North Dakota and Montana. *Transactions of the American Fisheries Society*, *135*(1), 200–217. https://doi.org/10.1577/T05-058.1

Gablehouse, D. W., Jr. (1984). A length-categorization system to assess fish stocks. *North American Journal of Fisheries Management*, *4*, 273–285. https://doi.org/10.1577/1548-8659(1984)4%3C273:ALSTAF%3E2.0.CO;2

Garrett, D. L., & Rabeni, C. F. (2011). Intra-annual movement and migration of flathead catfish and blue catfish in the lower Missouri River and tributaries. In P. H. Michaletz & V. H. Travnichek (Eds.), *Conservation, Ecology, and Management of Catfish: The Second International Symposium* (pp. 495–510). Bethesda, Maryland: American Fisheries Society, Symposium 77. https://doi.org/10.47886/9781934874257.ch41

Gorman, O. T., & Stone, D. M. (1999). Ecology of spawning humpback chub, Gila cypha, in the little Colorado River near grand canyon, Arizona. *Environmental Biology of Fishes*, *55*, 115–133. https://doi.org/10.1023/A:1007450826743

Graham, K. (1999). A review of the biology and management of blue catfish. In E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., & T. Coon (Eds.), *Catfish 2000: Proceedings of the International Ictalurid Symposium* (Vol. 24, pp. 37–50). Bethesda, Maryland: American Fisheries Society, Symposium.

Graham, K., & DeiSanti, K. (1999). The population and fishery of Blue Catfish and Channel Catfish in the Harry S. Truman Dam tailwater, Missouri. In E. R. Irwin, W. A. Huber, C. F. Rabeni, H. L. Schramm, Jr., & T. Coon (Eds.), *Catfish 2000: Proceedings of the International Ictalurid Symposium* (pp. 361–376). Bethesda, Maryland: American Fisheries Society, Symposium 24.

Guy, C. S., Neumann, R. M., Willis, D. W., & Anderson, R. O. (2007). Proportional size distribution (PSD): A further refinement of population size structure index terminology. *Fisheries*, *32*, 348.

Hamel, M. J., Spurgeon, J. J., &. Pegg, M. A. (2021). Catfish population characteristics among river segments with altered fluvial-geomorphic conditions in the Missouri River, NE, USA. *North American Journal of Fisheries Management*, *41*, S133-S145. https://doi.org/10.1002/NAFM.10478.

Hamel, M. J., Spurgeon, J. J., Steffensen, K. D., & Pegg, M. A. (2021). Uncovering unique plasticity in life history of an endangered centenarian fish. *Scientific Reports*, *10*, 12866. https://www.nature.com/articles/s41598-020-69911-1

Homer, M. D., & Jennings, C. A. (2011). Historical catch, age and size structure, and relative growth for an introduced population of blue catfish (Ictalurus furcatus) in Lake Oconee, Georgia. In P. H. Michaletz & V. H. Travnichek (Eds.), *Conservation, Ecology, and Management of Catfish: The Second International Symposium* (pp. 383–394). Bethesda, Maryland: American Fisheries Society, Symposium 77.

Humston, R., Priest, B. M., Hamilton, W. C., & Bugas, P. E., Jr. (2010). Dispersal between tributary and main-stem rivers by juvenile smallmouth bass evaluated using otolith microchemistry. *Transactions of the American Fisheries Society*, *139*(1), 171–184. https://doi.org/10.1577/T08-192.1

Isely, J. J., & Grabowski, T. B. (2007). Age and growth. In C. S. Guy & M. R. Brown (Eds.), *Analysis and Interpretation of Freshwater Fisheries Data* (pp. 187–228). Bethesda, Maryland: American Fisheries Society.

Isermann, D. A., & Knight, C. T. (2005). A computer program for age–length keys incorporating age assignment to individual fish. *North American Journal of Fisheries Management*, *25*(3), 1153–1160. https://doi.org/10.1577/M04-130.1

Jager, H. I. (2006). Chutes and ladders and other games we play with rivers. II. Simulated effects of translocation on white sturgeon. *Canadian Journal of Fisheries and Aquatic Sciences*, *63*(1), 176–185. https://doi.org/10.1139/f05-225

Jennings, C. A., & Zigler, S. J. (2009). Biology and life history of the paddlefish: An update. In C. P. Paukert & G. D. Scholten (Eds.), *Paddlefish Management, Propagation, and Conservation in the 21st Century: Building from 20 years of Research and Management* (pp. 1–22). Bethesda, Maryland: American Fisheries Society, Symposium 66.

Koehn, J. D. (2015). Managing people, water, food and fish in the Murray–Darling basin, South-Eastern Australia. *Fisheries Management and Ecology*, *22*(1), 25–32. https://doi.org/10.1111/fme.12035

Laughlin, T. W., Whitledge, G. W., Oliver, D. C., & Rude, N. P. (2016). Recruitment sources of channel and blue catfishes inhabiting the middle Mississippi River. *River Research and Applications*, *32*(8), 1808–1818. https://doi.org/10.1002/rra.3015

Miranda, L. E., & Bettoli, P. W. (2007). Mortality. In C. S. Guy & M. R. Brown (Eds.), *Analysis and Interpretation of Freshwater Fisheries Data* (pp. 229–277). Bethesda, Maryland: American fisheries society.

Neely, B. C., Pegg, M. A., &. Mestl, G. E. (2009). Seasonal use distributions and migrations of blue sucker in the middle Missouri River. *Ecology of Freshwater Fish*, *18*(3): 437–444. https://doi.org/10.1111/j.1600-0633.2009.00360.x.

Ogle, D. H. (2016). *Introductory Fisheries Analyses with R*. Florida: CRC Press.

Paukert, C. P., & Galat, D. L. (2010). Large warmwater rivers. In W. A. Hubert & M. C. Quist (Eds.), *Inland Fisheries Management in North America* (3rd ed., pp. 699–730). Bethesda, Maryland: American Fisheries Society.

Paukert, C. P., & Makinster, A. S. (2009). Longitudinal patterns in flathead catfish relative abundance and length at age within a large river: Effects of an urban gradient. *River Research and Applications*, *25*(7), 861–873. https://doi.org/10.1002/rra.1089

Pegg, M. A., Pierce, C. L., & Roy, A. (2003). Hydrological alteration along the Missouri River basin: A time series approach. *Aquatic Sciences*, *65*, 63–72. https://doi.org/10.1007/s000270300005

Peterson, J. T., & Dunham, J. (2010). Scale and fisheries management. In W. A. Hubert & M. C. Quist (Eds.), *Inland Fisheries Management in North America* (3rd ed., pp. 43–77). Bethesda, Maryland: American Fisheries Society.

Pope, K. L., Pegg, M. A., Cole, N. W., Siddons, S. F., Fedele, A. D., Harmon, B. S., … Uerling, C. C. (2016). Fishing for ecosystem services. *Journal of Environmental Management*, *183*(2), 408–417. https://doi.org/10.1016/j.jenvman.2016.04.024

Porath, M. T., Kwak, T. J., Neely, B. C., & Shoup, D. E. (2021). Catfish 2020, A clear vision of the future. *North American Journal of Fisheries Management*, *41*, S1–S10. https://doi.org/10.1002/nafm

Porreca, A. P., Hintz, W. D., Whitledge, G. W., Rude, N. P., Heist, E. J., & Garvey, J. E. (2016). Establishing ecologically relevant management boundaries: Inking movement ecology with the conservation of Scaphirhynchus sturgeon. *Canadian Journal of Fisheries and Aquatic Sciences*, *73*, 877–884. https://doi.org/10.1139/cjfas-2015-0352

Pracheil, B. M., Lyons, J., Hamann, E. J., Short, P. H., & McIntyre, P. B. (2018). Lifelong population connectivity between large rivers and their tributaries: A case study of shovelnose sturgeon from the Mississippi and Wisconsin rivers. *Ecology of Freshwater Fish*, *28*, 20–32. https://doi.org/10.1111/eff.12423

Pracheil, B. M., Mestl, G. E., & Pegg, M. A. (2015). Movement through dams facilitates population connectivity in a large river. *River Research and Applications*, *31*, 517–525. https://doi.org/10.1002/rra.2751

Pracheil, B. M., Pegg, M. A., & Mestl, G. E. (2009). Tributaries influence recruitment of fish in large rivers. *Ecology of Freshwater Fish*, *18*(4), 603–609. https://doi.org/10.1111/j.1600-0633.2009.00376.x

Pracheil, B. M., Pegg, M. A., Powell, L. A., & Mestl, G. E. (2012). Swimways: Protecting paddlefish through movement-centered management. *Fisheries*, *37*, 449–457. https://doi.org/10.1080/03632415.2012.722877

Pugh, L. L., & Schramm, H. L., Jr. (1999). Movement of tagged catfishes in the lower Mississippi River. In E. R. Irwin, W. A. Hubert, C. F. Rabeni, H. L. Schramm, Jr., & T. Coon (Eds.), *Catfish 2000: Proceedings of the International Ictalurid Symposium* (pp. 193–197). Bethesda, Maryland: American Fisheries Society, Symposium 24.

R Core Team. (2018). *R: A Language and Environment For Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Ricker, W. E. (1975). Computation and interpretation of biological statistics of fish populations. *Bulletin of the Fisheries Research Board of Canada*, *191*, 1-38.

Sanders, R. M., Jr., Higgins, D. G., & Cross, F. B. (1993). The Kansas River system and its biota. In L. W. Hesse, C. B. Stalnaker, N. G. Benson, & J. R. Zuboy (Eds.), *Proceedings of the Symposium on Restoration Planning for the Rivers of the Mississippi and Missouri River Ecosystem* (pp. 295–326). Washington, D.C., USA: U.S. National Biological Survey, Biological Report 19.

Shiller, A. M. (2003). Syringe filtration methods for examining dissolved and colloidal trace element distributions in remote field locations. *Environmental Science and Technology*, *37*, 3953–3957. https://doi.org/10.1021/es0341182

Siddons, S. F., Pegg, M. A., & Klein, G. M. (2017). Borders and barriers: Challenges of fisheries management and conservation in open systems. *River Research and Applications*, *33*(4), 578–585. https://doi.org/10.1002/rra.3118

Spurgeon, J. J., Pegg, M. A., & Halden, N. M. (2018). Mixed-origins of channel catfish in a large-river tributary. *Fisheries Research*, *198*, 195–202. https://doi.org/10.1016/j.fishres.2017.09.001

Spurgeon, J. J., Pegg, M. A., Hamel, M. J., & Steffensen, K. D. (2018). Spatial structure of large-river fish populations across main-stem and tributary habitats. *River Research and Applications*, *34*, 807–815. https://doi.org/10.1002/rra.3289

Stanford, J. A., & Ward, J. V. (2001). Revisiting the serial discontinuity concept. *Regulated Rivers: Research & Management*, *17*(4–5), 303–310. https://doi.org/10.1002/rrr.659

Tripp, S. J., Hill, M. J., Calkins, H. A., Brooks, R. C., Herzog, D. P., Ostendorf, D. E., … Garvey, J. E. (2011). Blue catfish movement in the upper Mississippi River. In P. H. Michaletz & V. H. Travnichek (Eds.), *Conservation, Ecology, and Management of Catfish: The Second International Symposium* (pp. 511–520). Bethesda, Maryland: American Fisheries Society, Symposium 77. https://doi.org/10.47886/9781934874257.ch42

Tripp, S. J., Phelps, Q. E., Hupfeld, R. N., Herzog, D. P., Ostendorf, D. E., Moore, T. L., … Garvey, J. E. (2019). Sturgeon and paddlefish migration:

Evidence to support the need for interjurisdictional management. *Fisheries*, *44*, 183–193. https://doi.org/10.1002/fsh.10215

Weber, M. J., Flammang, M., & Schultz, R. (2013). Estimating and evaluating mechanisms related to walleye escapement from Rathbun Lake, Iowa. *North American Journal of Fisheries Management*, *33*, 642–651. https://doi.org/10.1080/02755947.2013.788588

Zeigler, J. M., & Whitledge, G. W. (2010). Assessment of otoliths chemistry for identifying source environment of fishes in the lower Illinois River, Illinois. *Hyrobiologia*, *638*, 109–119. https://doi.org/10.1007/s10750-009-0033-1

Zeigler, J. M., & Whitledge, G. W. (2011). Otolith trace element and stable isotopic compositions differentiate fishes from the middle Mississippi River, its tributaries, and floodplain lakes. *Hydrobiologia*, *661*, 289–302. https://doi.org/10.1007/s10750-010-0538-7

How to cite this article: Dean, Q. J., Werner, J. P., Pegg, M. A., & Hamel, M. J. (2022). Blue catfish population characteristics and dispersal along a Great Plains river gradient. *River Research and Applications*, *38*(6), 1179–1191. https://doi.org/10.1002/rra.3985