Understanding invasion risk to more effectively allocate monitoring and management

Lead Agency and Author: Emily Pherigo (emily_pherigo@fws.gov), USFWS Columbia Fish and Wildlife Conservation Office

Cooperating Agencies:
Nebraska Game and Parks Commission (NGPC), Kirk Steffensen, kirk.steffensen@nebraska.gov; University of Nebraska – Lincoln, School of Natural Resources, Mark Pegg, mpegg2@unl.edu; U.S. Geological Survey—Nebraska Cooperative Fisheries and Wildlife Research Unit, and School of Natural Resources, University of Nebraska-Lincoln, Jonathan Spurgeon, jspurgeon2@unl.edu

South Dakota Game, Fish, & Parks (SDGFP), Tanner Davis (tanner.davis@state.sd.us) and BJ Schall (benjamin.schall@state.sd.us); South Dakota State University (SDSU), Alison Coulter (alison.coulter@sdstate.edu), Dave Coulter (david.coulter@sdstate.edu), and Steve Chipps (steven.chipps@sdstate.edu)

USFWS – Columbia FWCO, Jason Goeckler (jason_goeckler@fws.gov), Emily Pherigo (emily_pherigo@fws.gov), and Pablo Oleiro (pablo_oleiro@fws.gov)

USFWS – Missouri River FWCO, Tait Ronningen (tait_ronningen@fws.gov)

USGS South Dakota Water Sciences Center, Ryan Thompson (rcthomps@usgs.gov)

Statement of Need:

Minimizing the risk of invasive carp from spreading to new areas in the Missouri River basin requires an understanding of which sites are most vulnerable to invasion. This knowledge will allow limited management resources (e.g., prevention efforts, surveillance, removal) to be prioritized to the most at-risk locations and can aid in the development of proactive response plans. A site's vulnerability to invasive carp depends on a suite of factors. Permanent or temporary connectivity to systems where invasive carp occur increases a site's invasion risk due to the potential for movement or dispersal. The Missouri River basin has a diverse network of rivers, streams, and diversion canals which connect river systems, yet information is lacking regarding the hydrological connectivity that could allow invasive carp to move among these systems, especially during high-water events. A site's invasion risk also depends on whether habitat conditions (e.g., thermal conditions, flow regime, prey availability) are suitable to allow invasive carp to grow and survive once they have become introduced, regardless of the mechanism of introduction. Past habitat suitability assessments have been conducted over a broad spatial scale using climate matching approaches (e.g., Herborg et al. 2007). Instead, fine-scale habitat suitability predictions are needed so sites can be compared and ranked based onrelative risk. Additionally, understanding whether site conditions are suitable only for certain sizes or life stages can refine site relative risk comparisons and inform gears needed for surveillance efforts. Finally, a site's invasion risk depends on whether conditions are suitable for spawning. The ability of invasive carp to capitalize on environmental conditions conducive to spawning greatly contribute to their ability to invade an area and become the dominant fish species (Kolar et al. 2007; Irons et al. 2007). Applying previously developed models (e.g., Garcia et al. 2015) to quantify spawning potential will be an essential component for determining invasion risk in uninvaded rivers.

The primary goal of this work is to limit the spread of invasive carp in the Missouri River basin. The tasks described here will develop quantitative risk assessments that will identify site vulnerability to invasive carp in the Missouri River basin. These results will allow for the efficient use of management resources by identifying locations where movement deterrents can be placed, determining locations and life stages (eggs, juveniles, adult size classes) monitoring efforts should target and appropriate sampling gears to use, and informing or developing response plans if invasive carp are observed in new locations.

Objectives:

1. Assess hydrologic connectivity in the Missouri River Basin to identify locations at risk of Silver and Bighead carp movement into new areas.
2. Define relative risk based on habitat suitability for Silver and Bighead Carp invasion in uninvaded areas of the Missouri River Basin.
3. Define relative risk based on the system's ability to support spawning, drift, and hatch of Silver and Bighead Carp in uninvaded areas of the Missouri River Basin.

Agency: Nebraska Game and Parks Commission, Kirk Steffensen,
kirk.steffensen@nebraska.gov

Cooperating agencies:
University of Nebraska – Lincoln, School of Natural Resources
Mark Pegg
mpegg2@unl.edu

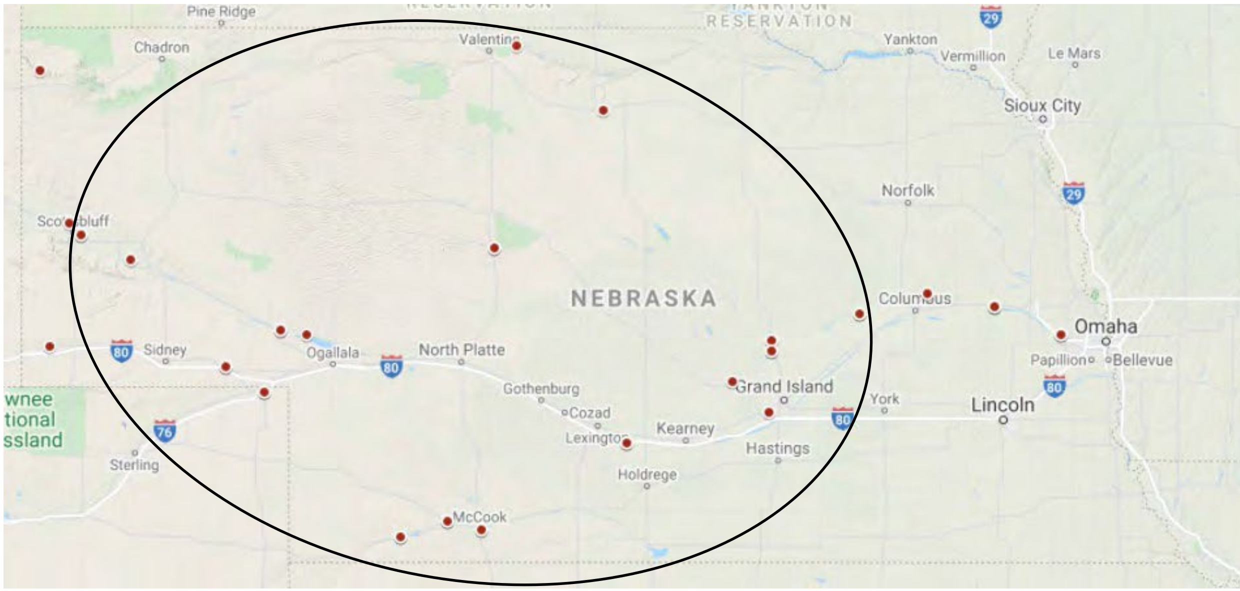
U.S. Geological Survey—Nebraska Cooperative Fisheries and Wildlife Research Unit, and
School of Natural Resources, University of Nebraska-Lincoln
Jonathan Spurgeon
jspurgeon2@unl.edu

Activities and Methods:

Objective 1. Nebraska has a diverse network of rivers, streams, and diversion canals which connect river systems and impoundments throughout the State as well as among states within the Missouri River basin. The current distributions of Silver Carp and Bighead Carp in Nebraska are being investigated through a combination of eDNA and traditional fish sampling. However, an understanding is lacking regarding the hydrological connectivity among systems where Silver Carp and Bighead Carp currently occur as well as in locations along and beyond the leading edge of their distributions. Such information will benefit understanding regarding potential dispersal pathways of invasive carp and highlight areas susceptible to ecological and economic threats posed by Silver Carp and Bighead Carp.

We will employ a GIS based assessment to detail the current invasive carp distribution and document barriers for upstream movement. The connectivity of the canal network throughout Nebraska will be extensively mapped to identify the "risk" of further invasive carp range expansion and then identify discharge levels that provide connectivity between systems, which may allow further invasive carp upstream movement and determine risk of range expansion. Areas containing sufficient habitats for all life-stages of Silver Carp and Bighead Carp will also be mapped. Additional field assessments of population sizes near potential access points will also be assessed to gauge the propagule pressure (i.e. greater numbers = greater risk) as part of the risk assessment. We will designate areas where management actions to control certain life-stages of carp (i.e., recruitment) could be feasible. For instance, if carp are determined to use canal networks there may be opportunities for water management to limit expansion.

Map of Project Area:



Map of the state of Nebraska. Red dots indicate potential locations of invasive carps. Black circle highlights the area where most of the assessment of movement capacity and propagule pressure will be assessed (i.e., the leading edge of expansion into new waters).

Project Highlights:

- Data collection and acquisition of spatial coverages have largely been completed during 2023. Incorporating the connection of these coverages (namely waterway connections at varying water elevations) with past and ongoing data collection efforts is continuing to assist in locating spatial "weak points" in the river and canal network across Nebraska.

Results and Discussion:

Spatial data, in the form of georeferenced material, is ongoing, but we have compiled information on the locations and lengths of the canals (Figure 1), intersection points of those canals with rivers or streams (Figure 2), and an overlay of dams across the landscape (Figure 3). The dams in Figure three represent an additional layer of complexity in the analyses as these may or may not form physical barriers depending on a number of factors. However, there are 2,959 dams in Nebraska, classified by the Nebraska Department of Natural Resources as being either 7.62 m high or greater than 6.1 ha-m in capacity, that may provide additional stoppage in movement of the invasive carps. We are incorporating the dams into our assessment as appropriate. In addition to these data, we have gathered information on flow characteristics at or near the intersection points to gauge if and when water levels will be able to facilitate connectivity. Actual elevations of many of the canals requires on-the-ground verification and are ongoing.

Nebraska has an extensive canal system connected to many of the major river systems across the state (Figure 1). There are 8,118 distinct segments of canals (i.e., object ID for operation and maintenance purposes) that span 10,559 km. Further, there are 485 intersection points where canals join rivers and streams (Figure 2) representing the most likely path for the carp species to broaden their range. However, not all of these canals are currently in operation and as such, confirmation of their status is ongoing.

We are continuing to compile water elevation, water quality, and biological data throughout the state to complete the assessment of potential access to new areas by the target invasive carp species. Part of that process will establish general guidelines on conditions conducive for the carp to move out of their current distributional locations. For example, Figure 4 highlights a hypothetical water elevation threshold that would allow invasive carps further access to canals or other areas in the Little Blue River in and around Deweese, Nebraska. If the hypothetical threshold were an actual threshold, water elevations would likely support fish movement during most seasons and years as drawn and may suggest a high risk zone.

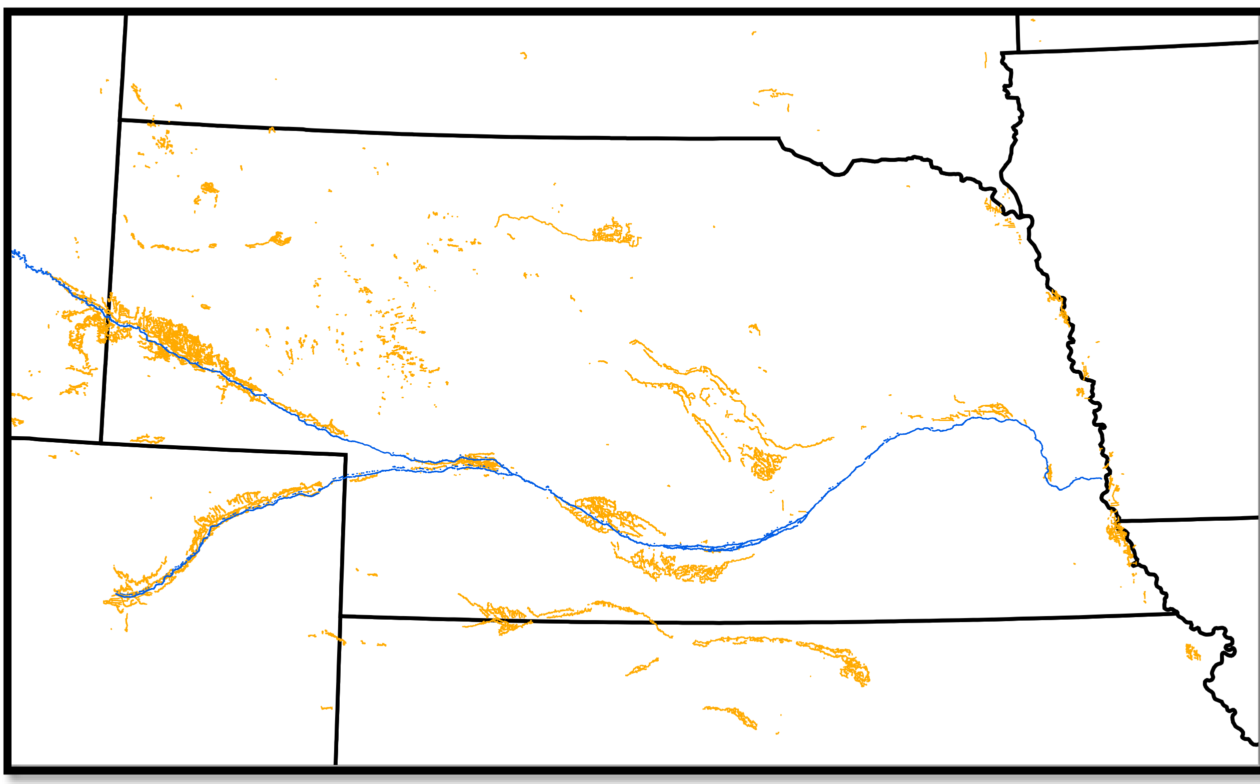


Figure 1. Locations of irrigation and power canals in Nebraska. Orange lines indicate locations.

Figure 2. Intersection points of canals with rivers and streams in Nebraska. Orange lines indicate locations of canals. Red plus signs (N = 485) represent location of intersection points.

Figure 3. Location of canals (orange lines), canal-stream intersection points (red plus sign) and dams (black dots) across Nebraska highlighting the complexity of inter and intra-basin connectivity.

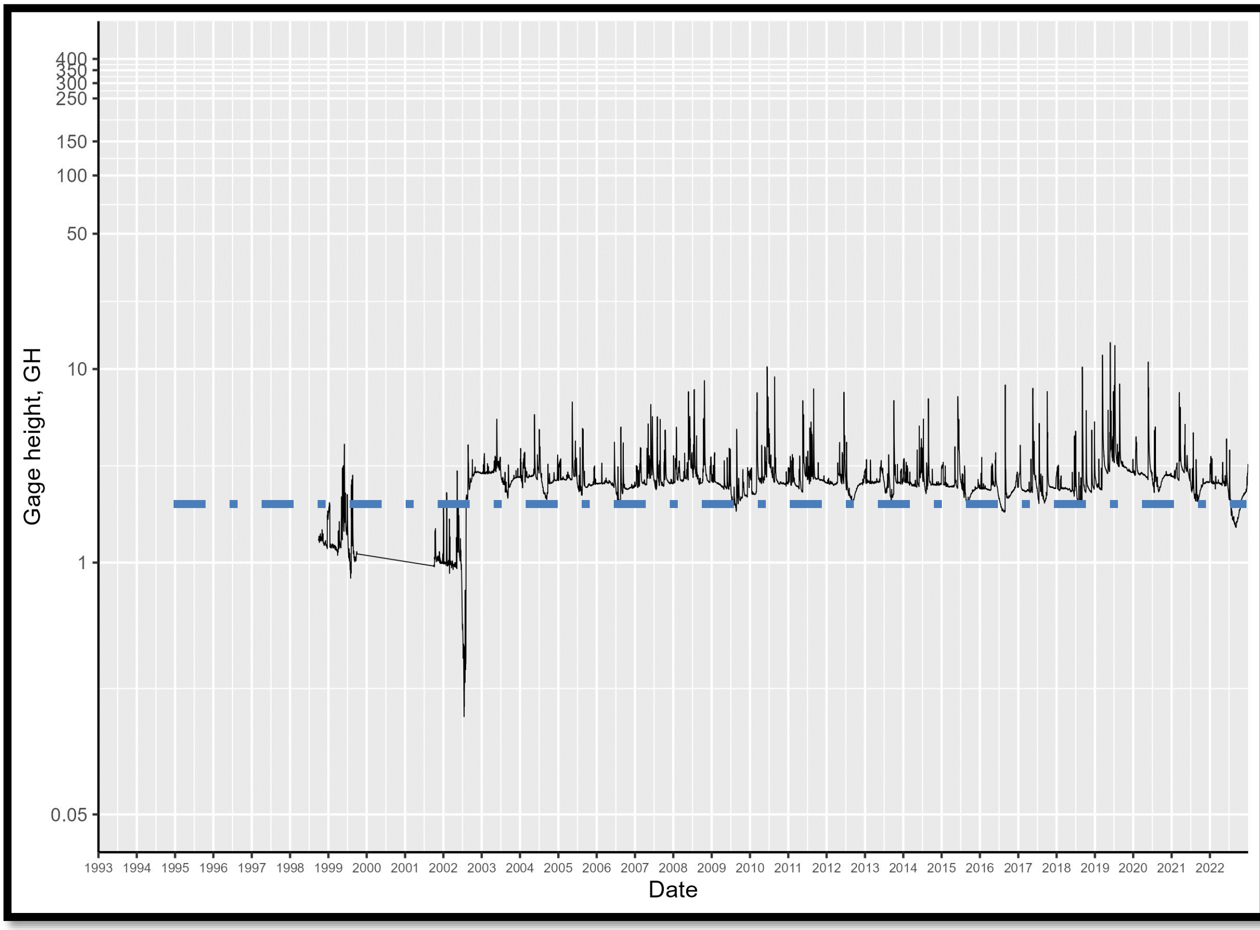


Figure 4. Water level elevation (USGS gage 6883000; elevation determined in feet by USGS) for Little Blue River near Deweese, Nebraska 1999-2023. Blue dashed line is a *hypothetical* threshold of what elevation may be required for invasive carps to access canals or other novel environments in this area. **NOTE:** actual thresholds are forthcoming.

Estimated Timetable for Activities:

Activity	Time Period (season, month/year)
Hire Postdoctoral Researcher	October – December 2022
Compile data currently available and GIS coverage information	January – March 2023
Stakeholder Meetings	April-June 2023
GIS analyses and modelling	July –December 2023
Annual Report	January-February 2024
GIS analyses and final report writing	March– Sept 2024
Final report and manuscript development	October -December 2024

Agency: South Dakota Game, Fish, & Parks (SDGFP), Tanner Davis (tanner.davis@state.sd.us) and BJ Schall (benjamin.schall@state.sd.us); South Dakota State University (SDSU), Alison Coulter (alison.coulter@sdstate.edu), Dave Coulter (david.coulter@sdstate.edu), and Steve Chipps (steven.chipps@sdstate.edu); USGS South Dakota Water Sciences Center, Ryan Thompson (rcthomps@usgs.gov)

Activities and Methods:

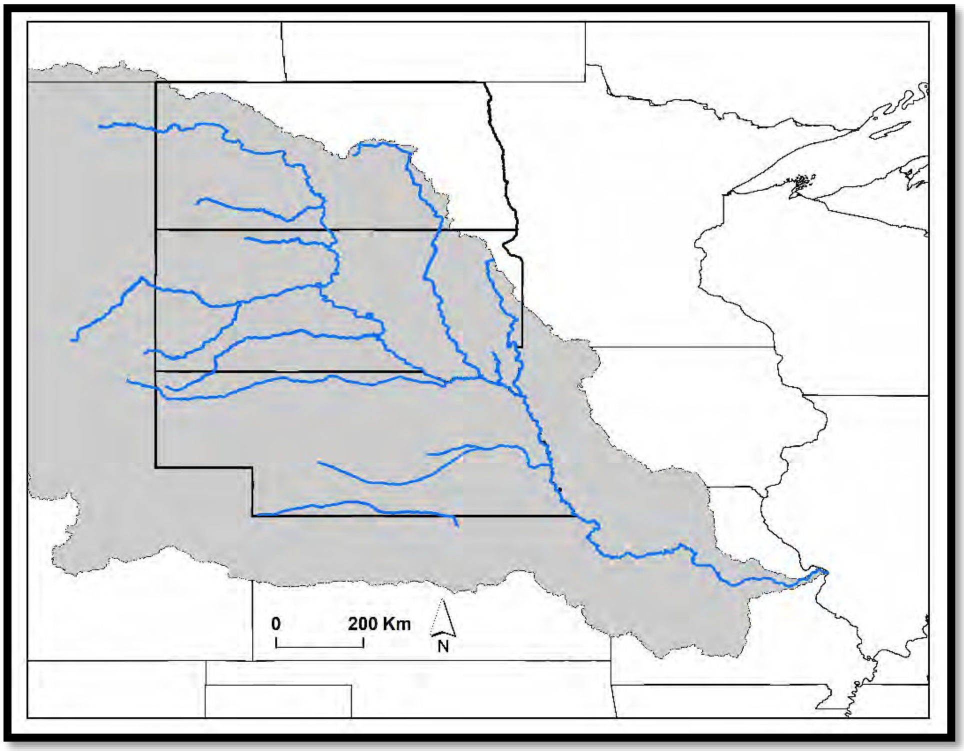
Objective 1. This project will be a collaborative effort between SDGFP, North Dakota Game and Fish, and the USGS Dakota Water science Center to assess the potential for interconnectivity of these eastern North Dakota and South Dakota tributaries to the Missouri River. Hydrological connectivity between uninvaded waterbodies with currently invaded locations in South Dakota and North Dakota will be identified using past remote sensing data. The current location of invasive carp will be determined from the USGS Nonindigenous Aquatic Species database and via the Missouri River Basin invasive carp partnership. Years representing typical and extreme water levels will be determined from the USGS stream gaging network for the Missouri River Basin. Remotely sensed imagery, such as digital elevation models (LIDAR based) and USGS's Dynamic Surface Water Extent products, will be obtained for typical and extreme water level years. GIS analyses will be used to identify the spatial extent of surface water that is connected to reaches currently harboring invasive carp. Deliverables from this work will include maps and GIS layers identifying waterbodies that are hydrologically connected to invaded habitats under 1) typical water levels, and 2) extreme low- and high-water levels.

This study has conducted an initial examination of potential hydrologic connectivity between the James River Basin (SD and ND) and the Missouri and Red river basins. Additionally, this study examined potential hydrological connectivity that could allow invasive carp to pass upstream of the Mitchell Dam or Jamestown Dam. We first assigned locations along the watershed boundaries a value (hereafter termed 'Point Selection Index') indicating the likelihood of surface water presence during high-water events following a precipitation event. Next, we subsampled locations along the watershed boundaries to obtain a feasible number of locations for subsequent analyses that represented a gradient of Point Selection Index values. Using these subsampled locations, we developed a statistical model predicting surface water presence (observed via remote sensing) from environmental conditions (e.g., precipitation and elevation data). This model was then applied to entire watershed boundaries to identify specific areas where hydrologic connectivity occurs during high-water events.

Objective 2. This project will assess invasion risk of Bighead and Silver Carp in the Missouri River Basin by quantifying habitat suitability. High invasion risk will be assigned to locations where adult and young-of-year (YOY) carp can grow and survive, whereas sites with low invasion risk will be characterized by poorly suited habitat for growth and survival of adult and/or YOY. Site-specific risk will be evaluated across all sizes of fish (YOY – adults) that could become introduced, thereby assessing risk regardless of the mechanism of introduction (e.g., live bait dumping, dispersal of adults, or spawning). Long-term growth and survival will be quantified using a bioenergetics-based approach based on reach-specific observations of water temperature, velocity, and plankton density. This study will initially target mid-order tributaries (e.g., 3^{rd} to 5^{th} order streams) to the Missouri River that lack established invasive carp populations. Water temperature, velocity, and plankton density will be collected from river reaches where historical data are unavailable and used as model input to evaluate carp growth. Growth predictions will be validated by modeling growth at locations where carps are present and comparing predicted long-term growth rates to observed carp length-at-age data (using existing data or capturing and aging fish if data are unavailable). Model output will include a database listing for each river and species: percent of individuals surviving, minimum size capable of surviving, growth of surviving individuals, and YOY introduction dates resulting in survival. Deliverables will include maps and GIS layers indicating relative invasion risk for Bighead and Silver Carp in Missouri River tributaries. Results from this project will provide stakeholders the information they need to (1) allocate signage or outreach to prevent bait dumping in areas where YOY can survive, (2) develop monitoring plans that prioritize locations based on relative risk and focus sampling gears on the size of fish expected to survive, and (3) inform actions when a Bighead or Silver Carp is observed (e.g., support for no action if individuals are found in a low risk area). This risk assessment will be valuable for identifying suitable areas that can be prioritized for management actions and for identifying areas where low survival and negative fish growth lead to a population sink that reduce risk priority. Elements of this risk assessment are additive to ongoing risk assessments focused on hydrologic connections or spawning potential in the basin.

Sampling of environmental conditions at 32 sites in the Missouri River Basin in North and South Dakota occurred monthly from May – October 2023 (Figure 2). These sites consisted of the Missouri River (Lewis and Clark Lake, Lake Francis Case), the James River, Big Sioux River, Vermillion River, and adjacent lakes and wetlands. At each site, five replicate zooplankton samples were collected from surface water samples using 56 and 18 µm mesh to assess zooplankton prey densities. Three replicate surface water samples were also collected for later measurement of chlorophyll-a concentrations, which will be used for estimating phytoplankton densities. Water samples were collected and stored on ice until filtered in the lab and frozen. Water temperature, dissolved oxygen concentration, and water velocity were also measured as abiotic characteristics of environmental conditions.

Map of Project Area:



Hydrological connectivity and habitat suitability risk assessments will be conducted in large tributaries of the Missouri River Basin.

Project Highlights:
Objective 1

- Points of potential hydrologic connection between invaded and uninvaded watersheds have been identified in portions of South and North Dakota. The next step is to determine the frequency and duration of these connections to identify if they could act as a novel route for invasive carp to pass into other watersheds or beyond dams. (Figure 1)

Objective 2

- Habitat conditions were sampled monthly at 32 locations for modeling of invasive carp habitat suitability. (Figure 2)

Results and Discussion:

Objective 1. Initial work on this project identified 21 areas of potential hydrologic connectivity (Figure 1). Many of these areas were located in a region with a low elevation gradient in the northern James River Basin adjacent to the Red River Basin which spans nearly 400 km. Areas of likely connectivity which are of higher risk for invasive carp spread were predicted in narrower low-elevation areas with the neighboring Missouri River basin. These initial results were presented at the 2023 annual meeting of the Dakota Chapter of the American Fisheries Society and at the

2023 Annual Meeting of the American Fisheries Society conference. The next steps in this project involve hydrologic modeling at identified connection points to determine the frequency, depth, and duration of surface water connection across watersheds.

Objective 2. Sample processing began in late 2023. By the end of 2023, 60 replicate zooplankton samples had been fully analyzed and most chlorophyll samples had been processed for chlorophyll-*a* concentration. Information from this project was disseminated at two scientific conferences. A poster presentation outlining the study was presented at the Dakota Chapter of the American Fisheries Society in January 2023. The second poster presentation was presented at the National American Fisheries Society meeting in August 2023 in Grand Rapids, MI. Additional field sampling will occur during 2024 to expand the spatial extent of the project. Modeling of sites sampled during 2023 will also commence to quantify carp habitat suitability based on estimated site-specific growth and survival. (Figure 2)

Recommendation:
Objective 1

- Managers should be cautious of areas with frequent and widespread flooding which may allow invasive carp to circumvent typical barriers (i.e., watershed boundaries, dams).

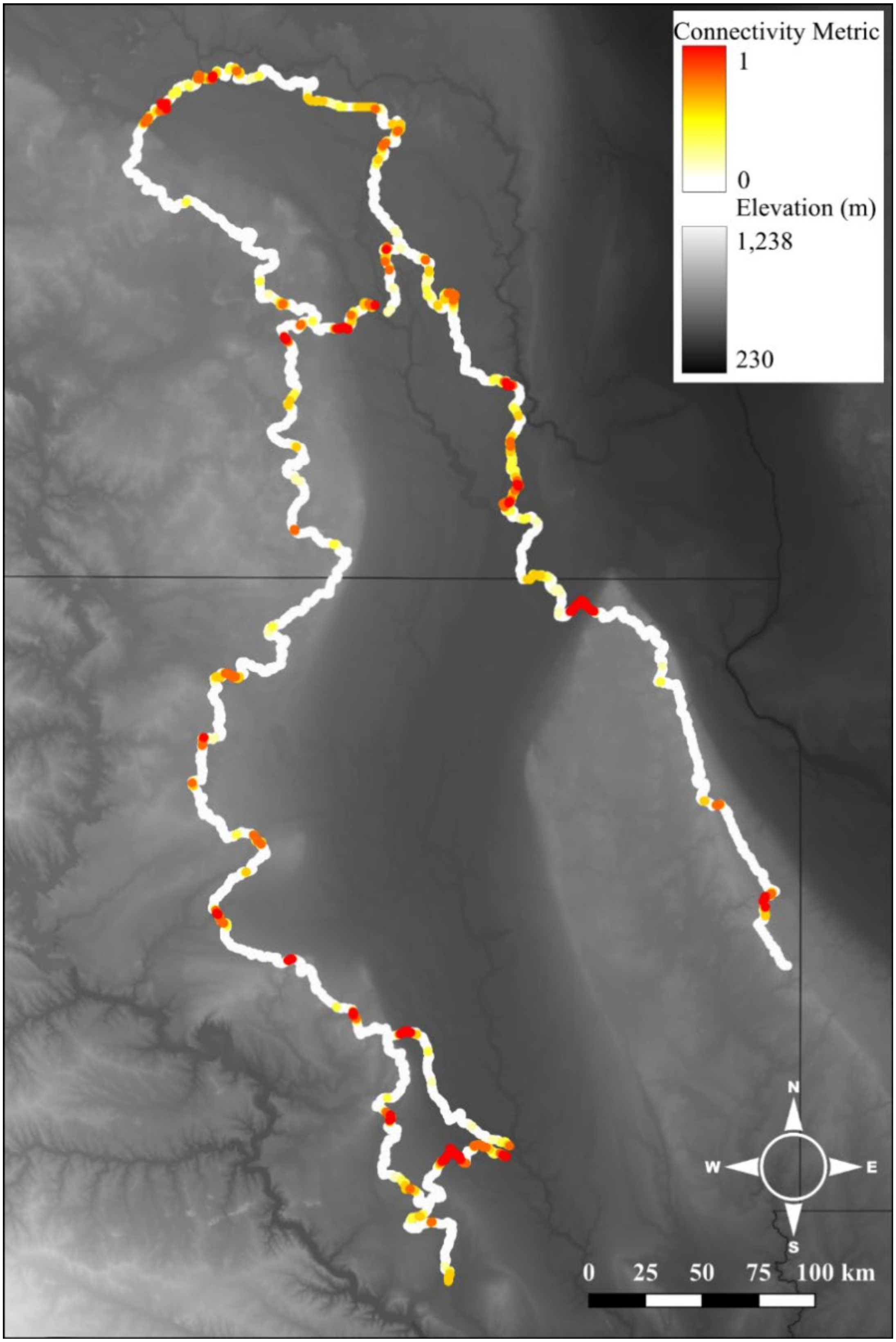


Figure 1. Predicted estimates of water presence along the James River watershed boundary in northeast South Dakota and southeast North Dakota. White points indicate low or no chance of water presence while yellow to red represents an increasing likelihood of water presence.

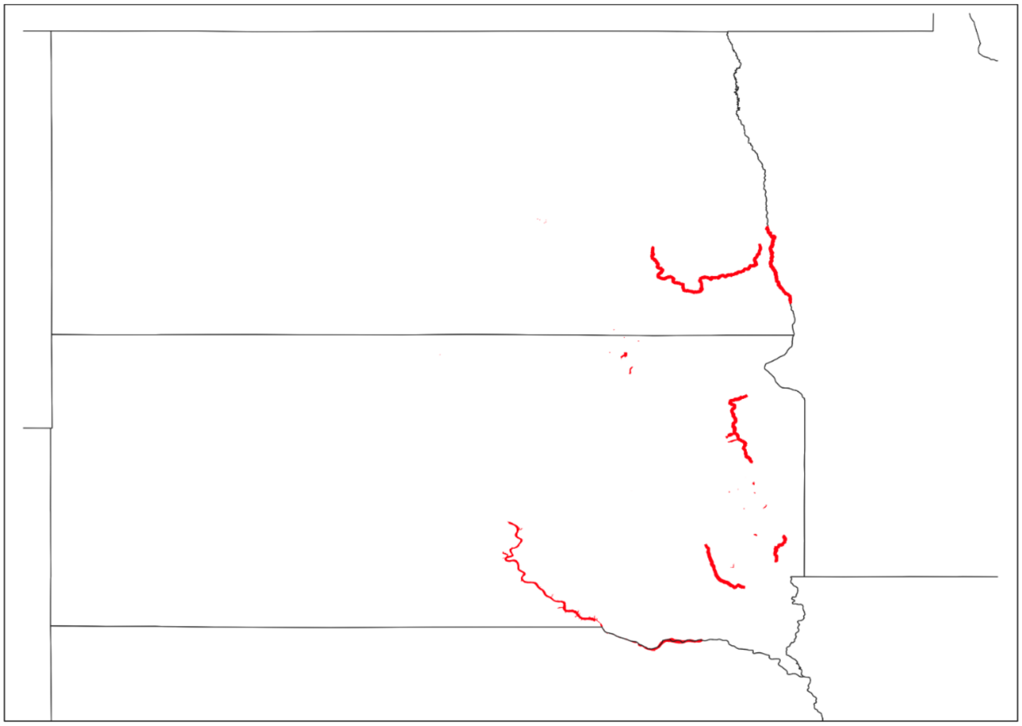


Figure 2. Study sites (n = 32) sampled monthly from May – October 2023 for environmental conditions that will be used to model invasive carp habitat suitability.

Estimated Timetable for activities

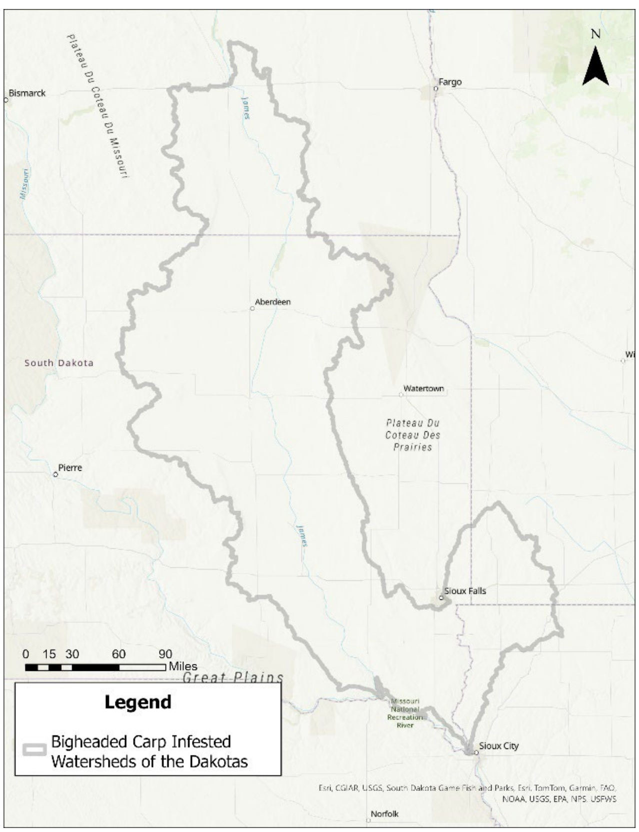
Activity	Time Period (Season, month/year)
Hire graduate student	January 2023
Meet with stakeholder groups	Spring 2023
Compile historical environmental data / collect field observations	Spring, Summer 2023
Develop habitat suitability model for MO River tributaries	Summer 2023 – Fall 2024
Validate model growth predictions	Summer – Fall 2024
Annual report	January – February 2024
Final report	Fall 2024

Agency: USFWS- Missouri River FWCO, Tait Ronningen (tait_ronningen@fws.gov)

Activities and Methods:

Objective 1. To assess hydrologic connectivity between bigheaded carp infested and uninfested waters in the Missouri River Basin I'll utilize the USGS NAS bigheaded carp distribution data, NHD watershed boundary dataset, NHD High Resolution Flowlines, and Google Earth 3D imagery to identify drainage pathways that may contain hydrophytes, hydrologic signatures, or both. These pathways will be mapped in ArcGIS Online as a polyline feature class. This effort focuses on identifying all potential connection paths of concern along the bigheaded carp infested watershed boundary of the James, Vermillion, and Big Sioux watersheds of North Dakota, South Dakota, Minnesota, and Iowa. It does not account for temporal risk of connectivity, such as hydrological permanence, slope, velocity, or water depth.

Map of Project Area:



Map of the bigheaded carp infested watersheds of the Dakotas. The infested watershed boundary encompasses the bigheaded carp infested watersheds of the James, Vermillion, and Big Sioux watersheds of North Dakota, South Dakota, Minnesota, and Iowa as of March 2024.

Project Highlights:

- Approximately half of the bigheaded carp infested watershed boundary has been reviewed for potential pathways of concern. A total of 2,604 invasion risk polylines with a total length of 2,652 miles have been mapped. (Figure 1)

Results and Discussion:
Over the past year I've made much progress mapping invasive carps connection paths of concern resulting in over half of the bigheaded carp infested watersheds of the Dakotas boundary being reviewed. This has resulted in 2,605 invasion risk polylines being mapped with a total length of 2,652 miles of invasion risk paths of concern. (Figure 1)

This effort has identified the magnitude of the invasive carps connection paths of concern. Due to the magnitude of the invasive carps connection pathways of concern, it'll be imperative to incorporate a risk analysis, such as the one listed above done in partnership with SDGFP, North Dakota Game and Fish, and the USGS Dakota Water Science Center to hone in on high risk pathways of concern that'll help inform management actions that could mitigate invasion risk. It's also noteworthy that as partners identify new areas of bigheaded carp invaded waters the infested watershed boundary will be adjusted to reflect the new infested extent and mapping of invasive carps connections paths of concern will follow.

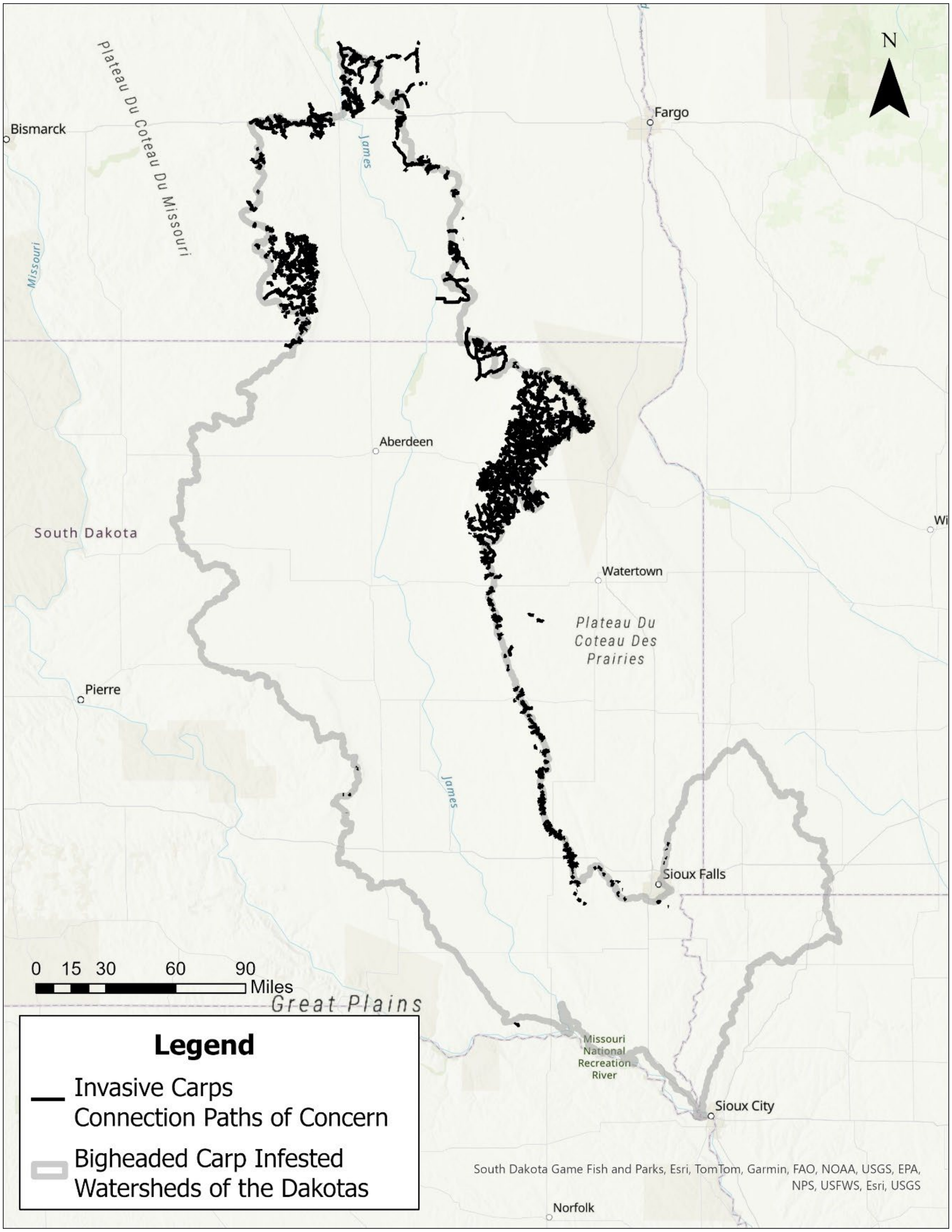


Figure 1. Map of bigheaded carp infested watersheds of the Dakotas and invasive carps connection paths of concern. These watersheds encompass the James, Vermillion, and Big Sioux watersheds of North Dakota, South Dakota, Minnesota, and Iowa as of March 2024.

Estimated Timetable for activities

Activity	Time Period (Season, month/year)
Compile spatial data and begin mapping	January 2023
Present preliminary results to Invasion Risk Team	Summer 2024
Complete mapping activities	Fall 2024
Final report	Fall 2024

Agency: USFWS – Columbia FWCO, Jason Goeckler (Jason_goeckler@fws.gov), Emily Pherigo (emily_pherigo@fws.gov), Pablo Oleiro (pablo_oleiro@fws.gov)

Project Objective:

1) Design a methodology to understand the relative risk based on a site's ability to support spawning, drift, and hatch of Silver and Bighead Carp in uninvaded areas of the Missouri River Basin.

Project Highlights:

- Methodology to assess a site's risk was developed where no special software is necessary with a short assessment time required.
- Approach was validated when applied to systems with colonized invasive carp populations and run for non-colonized example systems.
- Methodology has the possibility to work in conjunction with other projects in the Missouri River Basin Work Group (e.g., stream connectivity) to further aid in management decisions.

Methods:

Locations labeled as colonized systems were identified as being located within areas occupied by bigheaded and grass carp populations (USGS NAS). These colonized systems were used to inform determination of stream distance and duration of discharge events shown to support successful spawn, development, and hatch of invasive carp eggs and larvae (Figure 1).

Non-colonized reservoir-river systems evaluated were selected for their fisheries, recreational or economic importance, access to inland waters, and readily available thermal and hydrologic data (Table 1; Figure 1). These systems are located upstream of an impassable barrier and near the population leading edge of bigheaded carps. To assess the level of risk to these non-colonized systems, we selected key tributaries to investigate their available stream habitat and hydrologic conditions to support the spawning, development and hatch of bigheaded carps.

The available stream habitat for spawning, development, and hatch of young was defined for non-colonized and colonized systems by identifying the longest distance of free-flowing river between an upstream limit and a downstream limit. The upstream limits were impassable barriers or headwaters, while the downstream limits were impassable barriers, the confluence to a larger river, or where the stream flowed into a reservoir. We defined impassable barriers as high structures or dams greater than 8 feet in height, that given their characteristics, provided a physical or water velocity barrier (Hoover et. al 2017). The distance between upstream and downstream limits were considered the available distance for the system. Available distances for non-colonized and colonized systems were obtained from the National Hydrography Dataset PlusV2 (USGS 2020).

Defining spawning seasons for non-colonized systems

For each non-colonized system, all temperature data available from USGS gages was exported to identify the spawning season for each year. The first day of the spawning season was identified as the first day of a calendar year when the sum of mean daily temperatures for days above 15°C exceeded 655, hereafter referred to as 655 ADD15 (Gorbach and Krykhtin 1981). The last day of a spawning season was when mean daily water temperature fell to 18°C (Camacho 2016).

Identifying discharge events and calculating event duration and minimum stream distances

While shear velocity is the most accurate way to measure turbulence, most rivers lack shear velocity data because it requires extensive hydrology work and modelling to obtain it (Kokovsky et al. 2012, Camacho et al. 2023. Similar to Kokovsky et al. (2012), we used stream velocity as a surrogate for shear velocity.

For each non-colonized system, stream velocities were obtained by creating stream velocity-discharge relationships (Kokovsky et al. 2012). We used the best-fitting curve based on r-squared values to calculate stream velocities from USGS gage discharge values; our predicting curves were highly significant (P<0.001).

Following Kokovsky et al. (2012) approach, we identified when mean daily discharges reached or exceeded the minimum velocity threshold of 0.7 m/s for each system and identified a discharge event as consecutive days when mean daily discharge exceeded and did not fall below 0.7 m/s. We calculated the duration in number of days as well as the mean stream velocity and mean water temperature for each discharge event within the spawning season. These values were used to calculate the minimum distance needed for the incubation and hatch of bigheaded carps following the Kokovsky et al. (2012) formula:

$$D = V \; x \; I \; x \; 3.6$$

Where D represents minimum stream distance (km), V represents the stream velocity (m/s), and I represents the incubation time (h). Mean water temperature for each discharge event with stream velocities greater than 0.7 m/s was used to estimate egg incubation time using a temperature-time relationship created from Tsuchiya 1980 (Table 2). This relationship (r^2=0.9816) improved the precision of our calculations by allowing us to estimate the incubation for a larger range of values:

$$I = 0.3417 \times T^2 - 20.509 \times T + 323.7$$

The resulting minimum distance, D, was subtracted from the available stream distance to provide a spatial component indicative of the risk for each discharge event (Table 2).

For the colonized systems, we calculated the minimum distance (D) needed for spawning, incubation, and hatch of eggs (stage 31, hatching) and larvae (stage 32, pectoral fin bud present) captured in the Des Moines, Iowa-Cedar and Skunk rivers June 4 - 27, 2013 (Larson et al 2017; Table 3). Due to the inability to determine species of the eggs, we calculated the minimum distance for the eggs of Silver, Bighead and Grass carp. We obtained incubation time (I) in hours for Silver and Bighead carp combining Chapman and George (2011) life stages descriptions for high

(22.3°C) or low (20.1°C) water temperature and water temperatures recorded by Larson et al. (2017) when eggs and larvae were collected. Incubation time (*I*) for Grass carp were calculated using George and Chapman (2015). A logarithmic curve was fit to historical data to identify discharge – stream velocity relationship. Stream velocity (*V*) in the Des Moines and Iowa systems was then calculated using the discharge for the incubation period ending at noon on the collection day. Stream velocity (*V*) for the Skunk River was calculated averaging the discharge on the collection day and the previous day given that the USGS gage only provided mean daily discharge. The resulting minimum distance (*D*) for each specimen collected was subtracted from the available distance to provide the spatial component (Table 3). For each discharge event when eggs or larvae were collected, we calculated the event duration by enumerating the number of days when stream velocity reached 0.7 m/s in the respective river to the date of collection.

Results and Discussion:

The calculated spatial (stream distance) and temporal (discharge event duration) components for the eggs and larvae collected in the colonized systems were plotted along with the 58 discharge events in the five non-colonized systems (Figure 2). Discharge events with a negative spatial component indicate there is not enough available free-flowing stream to meet the needs for successful spawning, incubation, and hatch of young invasive carp. Discharge events with a positive spatial component indicate the available stream distance is longer than the required minimum stream distance; their X axis values indicate the length (km) of extra available stream distance. Half (30 of 58) of the discharge events in the five non-colonized systems identified during spawning seasons between 2011 and 2019 exhibited more available stream length than the calculated minimum distance necessary for the successful hatch of bigheaded carps (Figure 2). Of those thirty discharge events, the Nodaway had four while the Niobrara had eight events, Osage, and Republican rivers each had nine. While the available stream distance in the Niobrara (256 km), Osage (350 km), and Republican (358 km) rivers exceeded that which would be necessary in 100% of their identified discharge events, the 95 km of available stream in the Nodaway River only met this requirement in 14% of the discharge events while the 66 km of West Fancy Creek never did.

Despite not always having enough free-flowing stream habitat, every non-colonized system assessed had at least three discharge events. The duration of those discharge events varied among systems and years. Whereas the colonized systems displayed long durations of stream velocities exceeding the 0.7m/s minimum velocity. The average discharge event duration (number of days) in colonized systems was 93 days, ranging from 71 to 110 days, while the average discharge event duration for non-colonized systems was 16.25 days and varied among systems (e.g., Republican River average duration = 7.6 days, Niobrara River average duration = 80 days). Furthermore, duration of discharge events varied among years within systems (e.g., Osage 2017= average 4 days, 2019= average 21 days).

Tables and Figures:

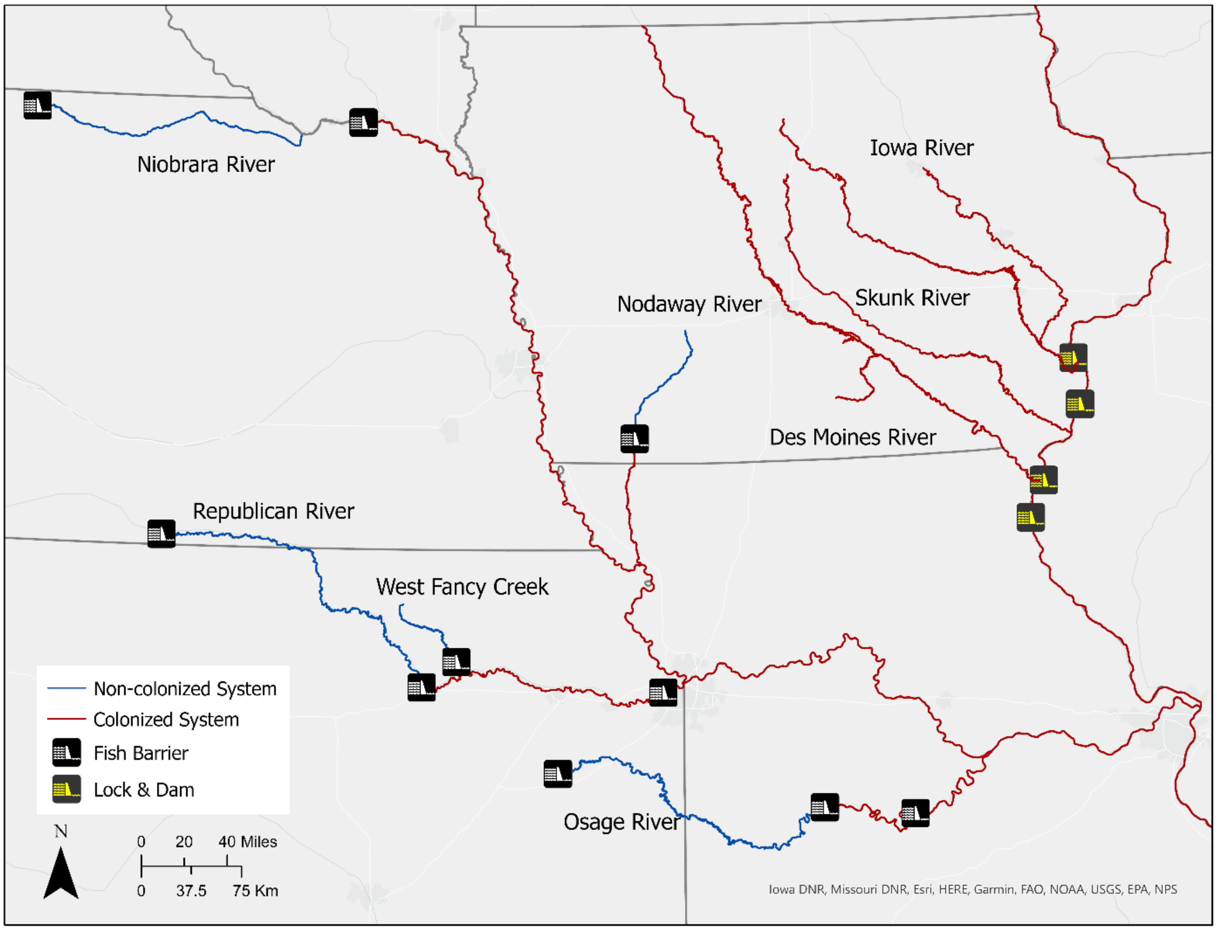


Figure 1. Colonized and non-colonized systems used to validate methodology investigating potential of Silver Carp establishment.

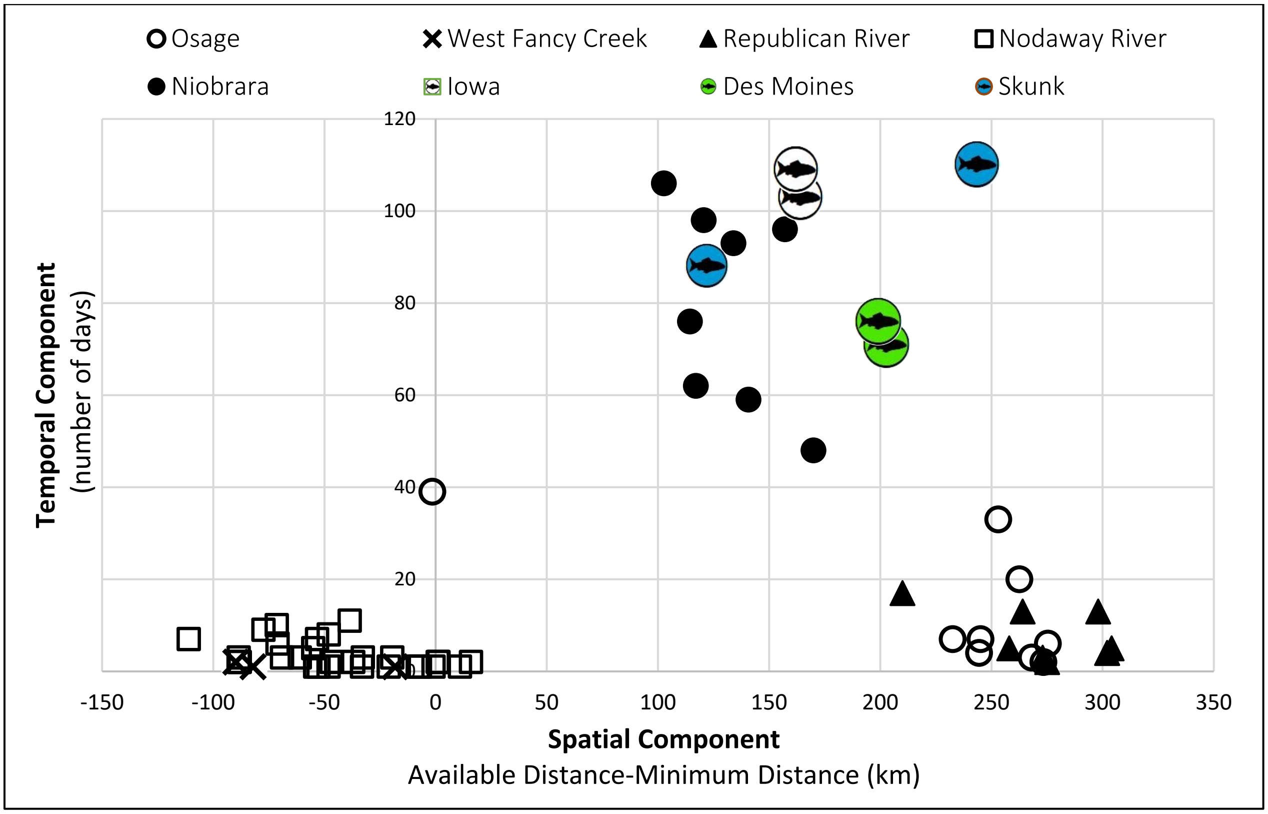


Figure 2. Spatial and temporal components of discharge events for non-colonized systems (Osage River, West Fancy Creek, Republican River, Nodaway River, and Niobrara River) plotted with events in colonized systems (Iowa, Des Moines, and Skunk rivers) that resulted in Silver Carp eggs and larvae to better understand the ability of these two characteristics to predict the successful spawning and development of Silver Carp.

Table 1. Non-colonized systems available distances used to compare with minimum distance needed for successful spawning and development of bigheaded carp eggs.

Reservoir	River	USGS Gage	Used Data Time Frame	Upstream Limit	Downstream Limit	Available Distance (km)
Truman Lake, MO	Osage-Marais De Cygnes River	6918250	6/2/17 to 12/31/19	Melvern Lake Dam	Truman Reservoir	340
Tuttle Creek Lake, KS	West Fancy Creek	6886500	9/20/18 to 12/31/19	Headwater	Tuttle Creek Lake	66
Milford Lake, KS	Republican River	6856600	7/24/18 to 12/31/19	Harlan County Lake Dam	Milford Lake	358
NA	Nodaway River	6817000	9/13/12 to 12/31/19	Headwater	Lowhead Dam	95
Lewis and Clark Lake, SD	Niobrara River	6465500	10/11/10 to 12/31/19	Cornell Dam	Lewis and Clark Lake	253

Table 2. Experimental incubation times for Silver Carp eggs at varying water temperatures (Tsuchiya 1980).

Temp (º C)	20	22	23	24	25	26	26.5	27	29.5	30	30.5
Time (h)	50	38	33	31	21	21	21	19.5	17	16	15.5

Table 3. Minimum distance needed to reach stages 31 and 32 for Silver, Bighead and Grass carp in three Mississippi tributaries.

River	Collection Stage	Collection Date	Event Duration (days)	***V*** (m/s)			***I*** (hrs)			***D*** (km)		
				Silver	*Big Head*	*Grass*	*Silver*	*Big Head*	*Grass*	*Silver*	*Big Head*	*Grass*
Iowa	31	Jun 20	103	1.068	1.067	1.070	38	39	29	111	130	112
Iowa	31	Jun 26	109	1.081	1.080	1.091	38	39	29	112	131	114
Des Moines	32	Jun 19	71	1.360	1.360	1.360	48	49	43	150	166	211
Des Moines	32	Jun 24	76	1.352	1.352	1.352	48	49	43	149	164	209
Skunk	31	Jun 4	88	1.394	1.394	1.394	38	39	29	228	226	146
Skunk	31	Jun 26	110	1.109	1.109	1.109	38	39	29	107	125	116

Recommendation:

The Missouri River Basin Invasive Carp Technical Committee has assigned priorities for inland state waters of high ecological and recreational value. Often, if the introduction and establishment of bigheaded carps occurs, these are reservoirs or inland lakes could have an impact on the native species (Freedman et al. 2012), and have consequences in the economic and social sectors (Ready et al. 2016). Therefore, this tool could be applied to those areas identified by partners to better understand the invasion risk. This study indicates that the Niobrara River has a high risk of supporting bigheaded carp establishment in Lewis and Clark Reservoir if the Gavins Point Dam barrier is breached. While the Osage and Republican rivers have the available distance to support successful hatches, this tool considers that they are at moderate risk since the duration of discharge events was highly variable (Osage River ranged from two to forty days and Republican River ranged from two to seventeen days) and the observation of colonized systems indicates that consistent discharge events sufficient to cue and support spawning events as well as maintain eggs in suspension during incubation. West Fancy Creek and Nodaway systems have the lowest priority since they do not meet the minimum distance for 85-100% of the discharge events and the discharge event durations averaged 1.3 and 3.1 days.

The application of this model could be used to inform study designs (e.g., larval sampling or detection of spawning adults). For example, if managers want to identify a population source to target management efforts or construct barriers, this tool can be applied using historical data to determine how often the stream meets the minimum hydrological conditions during the spawning season. Additionally, this tool can be used with real-time data to identify potential spawning conditions and deploy resources to detect spawning aggregations or implement ichthyoplankton sampling.

The non-colonized systems were selected because water temperature, discharge, and stream velocity data were readily available. Other systems of interest (e.g., Clinton Reservoir and Vermillion Reservoir) were identified and briefly investigated for potential evaluation but no temperature data was readily available. Modeling water temperature for the Missouri River Basin or specific areas of interest could be an effective tool to predict stream temperature (Loubna et al. 2007; Zhu et al. 2018,) and significantly increase the number of systems that can be studied. Additionally, air temperature to water temperature models could be used to estimate the spawning season for a system of interest (Zhu et al. 2018). Databases like DAYMET (https://daymet.ornl.gov/) or PRISM (http://www.prism.oregonstate.edu/) have readily available current and historical air temperature and climate data for the United States at a small spatial scale (1 x 1 km and 800 x

800 m). These models can be applied to estimate incubation times based on mean daily water temperatures during spawning seasons.

Given that large datasets, especially water temperature, are needed to use this approach, agencies and state partners should consider identifying areas of interest and plan to collect the necessary data. Having access to these data would allow managers and partners to identify resources in risk of establishment and therefore allocate the necessary resources to prevent the expansion of bigheaded carps.

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