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Research Article

GIS-based rapid-assessment of bighead carp *Hypophthalmichthys nobilis* (Richardson, 1845) suitability in reservoirs

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Abstract

Broad-scale niche models are good for examining the potential for invasive species occurrences, but can fall short in providing managers with site-specific locations for monitoring. Using Oklahoma as an example, where invasive bighead carp (*Hypophthalmichthys nobilis*) are established in certain reservoirs, but predicted to be widely distributed based on broad-scale niche models, we cast bighead carp reproductive ecology in a site-specific geospatial framework to determine their potential establishment in additional reservoirs. Because bighead carp require large, long free-flowing rivers with suitable hydrology for reproduction but can persist in reservoirs, we considered reservoir tributaries with mean annual daily discharge ≥8.5 cubic meters per second (m^3/s) and quantified the length of their unimpeded portions. In contrast to published broad-scale niche models that identified nearly the entire state as susceptible to invasion, our site-specific models showed that few reservoirs in Oklahoma (N = 9) were suitable for bighead carp establishment. Moreover, this method was rapid and identified sites that could be prioritized for increased study or scrutiny. Our results highlight the importance of considering the environmental characteristics of individual sites, which is often the level at which management efforts are implemented when assessing susceptibility to invasion.

Key words: invasive species, hydrology, dams, discharge, Asian carp, Oklahoma, risk assessment

Introduction

Bighead carp *Hypophthalmichthys nobilis* (Richardson, 1845), a fish species native to China that was brought to the United States for aquaculture, now occurs in 23 states (Jennings 1988; Kolar et al. 2007; Nico and Fuller 2013). Bighead carp are planktivorous, compete with native fishes for food (Burr et al. 1996; Tucker et al. 1996; Schrank et al. 2003; Irons et al. 2007), and are considered harmful in their invaded environment. Most research in the United States has focused on the invasion in the Mississippi River basin as bighead carp have moved upstream and into larger tributaries (e.g., Missouri River, Illinois River) toward the Great Lakes, where they are feared to become established and cause irrevocable changes (Kolar et al. 2007; Chapman and Hoff 2011). Though escapement from aquaculture ponds in Arkansas is widely cited as the source of invasion (e.g., Jennings 1988; Kolar et al. 2007; Nico and Fuller 2013), the pathway for bighead carp invasion is more varied than escape and expansion from this single point (Kelly et al. 2011). For example, in California, completely segregated from the Mississippi River basin, bighead carp were introduced illegally, brought into the state in 1989 in a hidden container with black bass *Micropterus* spp. Lacepède, 1802 for stocking into commercial aquaculture ponds (Dill and Cordone 1997). Other locations within the United States and outside of the Mississippi River basin where bighead carp have been introduced include parts of the Mobile River basin in Alabama, Lake Okeechobee, Florida, Kirby Lake and Phantom Hill reservoirs in Texas, and ponds in Franklin Township, New Jersey (Nico and Fuller 2013). In the California instance, the source of fish was cited as either Oklahoma or Arkansas. Interestingly, this corresponds closely to discovery of wild bighead carp in Oklahoma in 1992 (Pigg et al. 1993), also considered to be a separate point of introduction.

Ecological niche models developed for North America predicted that nearly everywhere east of the 100th meridian was highly suitable for bighead carp establishment (Herborg et al. 2007; Kolar et al. 2007), suggesting high vulnerability. However, managers cannot be vigilant to every water body under their supervision without infinite resources. Moreover, the biology of the species suggests that not all water bodies in a state are equally vulnerable to invasion. Bighead carp reportedly have specific requirements for completing their life cycle, such as large rivers at least 100-km long where current velocities exceed 0.8 m/sec (Jennings 1988; DeGrandchamp et al. 2007). Although these requirements have not been validated in U.S. waters, they provide a starting point for rapidly conducting site-specific risk analyses. However, defining a “large river” is problematic and there is no consensus or database of such (Gupta 2007). Moreover, current velocities exceeding 0.8 m/sec can occur in nearly any lotic water body given sufficient precipitation or upland runoff. In practice, the current velocity criterion relates to the ability of water turbulence to entrain bighead carp eggs for their development, so incorporating this measure into a broad-scale spatial model would require additional information including temperature and time typically not available from current monitoring networks (e.g., USGS stream gages). Furthermore, numerous upstream dams and other water diversion structures exist that may limit the extent of free-flowing habitat and, thus, the potential areas for bighead carp establishment.

Reservoirs may be particularly important because they can facilitate further invasions (Havel et al. 2005; Johnson et al. 2008), but few studies have considered reservoirs when conducting risk assessments for bighead carp. Thus, these systems have largely been ignored. However, recent reports of large bighead carp from reservoirs, such as a 48-kg specimen from Lake of the Ozarks, Missouri in 2011 (Nico and Fuller 2013) indicate that reservoirs can be suitable for invasion. Moreover, recurring reports of bighead carp from reservoirs such as Grand Lake O’ the Cherokees, Oklahoma (Long and Nealis 2011) indicate potentially suitable reproductive conditions. Taken together, illegal introductions of bighead carp into reservoirs represent a currently underappreciated, yet unquantified, method of establishment for this invasive species.

In Oklahoma, bighead carp were first discovered in 1992 in two locations of the Neosho River, above and below Grand Lake (Pigg et al. 1993), which was speculated to have come from a private fish farm in Kansas, near Wichita in the Arkansas River drainage, in 1987 (Nico and Fuller 2013). If the fish from Kansas escaped, they would have had to travel downstream through several reservoirs in the Arkansas River then upstream through several more reservoirs in the Neosho River to be captured by anglers at Miami, Oklahoma as described by Pigg et al. (1993). This scenario seems highly unlikely because there are no reports of bighead carp between these areas (Figure 1). The alternative that fish migrated from a source in Arkansas, upstream through the Arkansas River, also seems unlikely because there are no contemporaneous or earlier reports of bighead carp between that earliest reported instance (1992) and the ones in Oklahoma. As a result, it is logical to conclude that an unknown introduction accounted for the bighead carp collected in the Neosho River, Oklahoma and that these fish migrated downstream through dams to at least below Hudson Lake (Pigg et al. 1997) and upstream through unimpounded Neosho River into Kansas (Nico and Fuller 2013). Continued reports of bighead carp from this area suggest that this species has become established even though no reports of reproduction have been verified (Pigg et al. 1997; Foster et al. 2009; Long and Nealis 2011; Nico and Fuller 2013). Coupled with the knowledge that other point-sources of introductions have occurred throughout the United States, there exists a real likelihood of additional introductions. Because managers have limited fiscal and logistical resources, but nearly unlimited sites that are vulnerable to introductions, a tool that could assess site-specific risks of introduction would be useful to help curb these potential impacts. As a result, we sought to refine previous models using factors associated with their

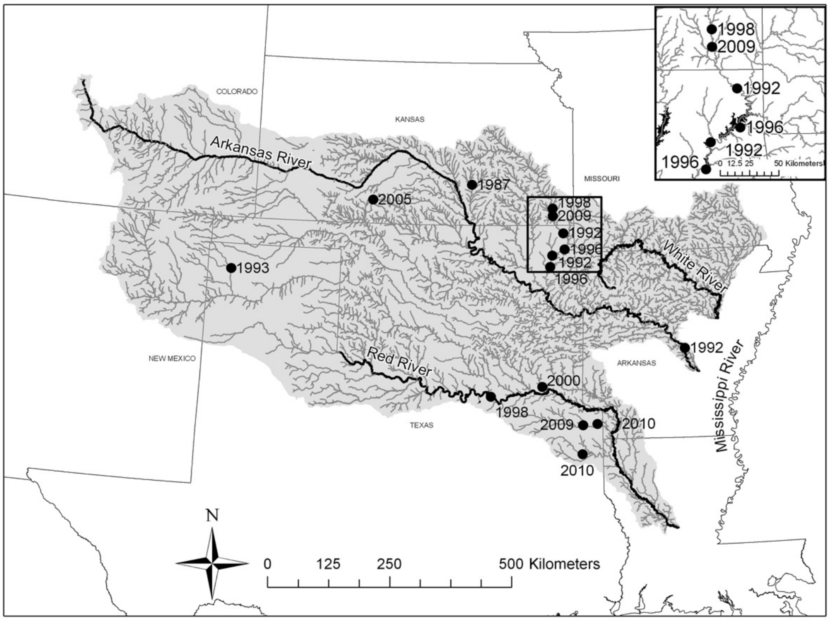

Figure 1. Locations and timing of bighead carp reports in relation to streams in the Arkansas-Red-White river basin surrounding Oklahoma (Nico and Fuller 2013). River flow is generally from west to east, toward the Mississippi River. The inset shows the reports of bighead carp in the Neosho River basin in more detail. Three separate reports in Grand Lake from 1996 are shown as one for simplicity.

reproductive requirements and assess site-specific susceptibility to invasion by bighead carp, but over a broad scale. As noted by Papes et al. (2011), management efforts are often designed and initiated at individual sites (or individual states), which is the approach we used to develop a rapid, geographic information systems- (GIS) based approach to assess the risk of bighead carp introductions in reservoirs in Oklahoma.

Methods

We specifically focused on reservoirs within state borders because states represent a real political boundary in the United States where decisions and management actions occur. In Oklahoma, reservoirs are prevalent, represent most of the locations for reports of bighead carp in the state (e.g., Pigg et al. 1993; Pigg et al. 1997), and provide useful starting places from which to determine suitable hydrologic conditions for reproduction. Our method proceeded in a linear fashion by ultimately determining 1) reservoirs connected to “large” rivers flowing into Oklahoma, and 2) length of unimpeded “large” river tributaries inflowing to these reservoirs (Figure 2).

To determine which rivers flowing into Oklahoma were large enough for bighead carp reproduction, we identified rivers in the encompassing drainage basin flowing into the state (Arkansas-Red-White basin) that had mean annual daily discharge greater than or equal to the smallest known to support bighead carp reproduction in the United States (Cache River, Illinois; 8.5 m^3/s; Burr et al. 1996; USACOE 2007; Nico and Fuller 2013; Deters et al. 2013; Coulter et al. 2013). Geospatial data on rivers and streams came from the National Hydrography Dataset Plus (NHDPlus) and mean annual daily discharge of individual river segments were obtained by overlaying USGS gage locations (part of NHDPlus) that met the discharge criteria. We then intersected those systems with locations of reservoirs in Oklahoma, which were obtained from the Oklahoma Water Resources Board (OWRB 2013), producing a candidate set of reservoirs from which to further evaluate bighead carp establishment suitability.

Reportedly, bighead carp require 100 km of free-flowing “large river” habitat for successful reproduction (Jennings 1988; Kolar et al. 2007; DeGrandchamp et al. 2007), although recent evidence suggests shorter river segments in their invaded range have sufficed (Coulter et al. 2013; Murphy and Jackson 2013). To identify the free-flowing portions of inflowing tributaries, we intersected the location of dams (USACOE 2009) on the river segments identified above and calculated the length of the segments between the reservoirs and the dams.

The resulting dataset identified reservoirs suitable for bighead carp establishment as a function of mean annual daily discharge and free-flowing length of

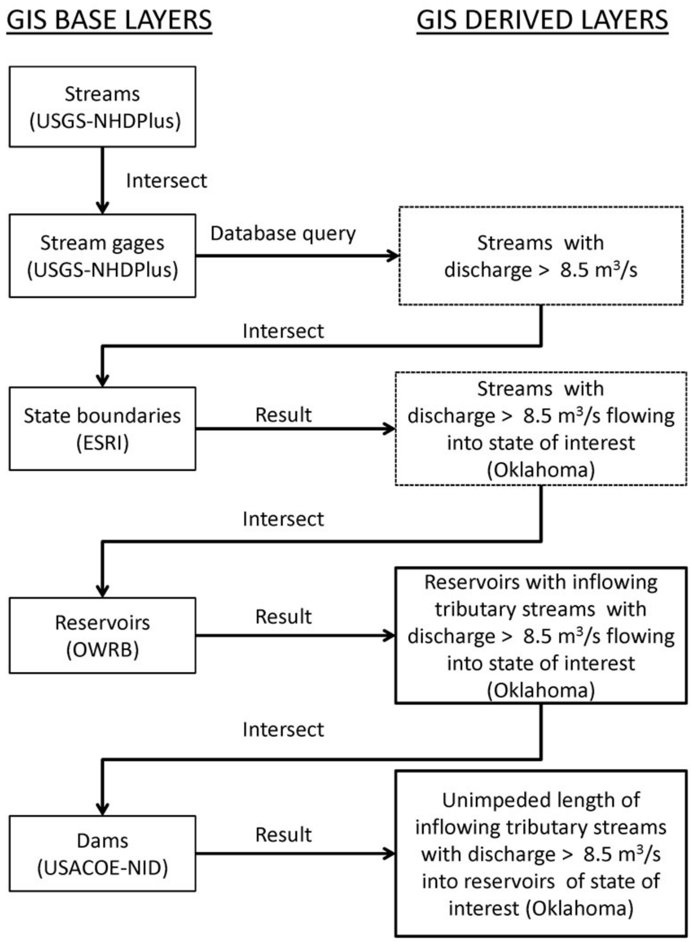

Figure 2. Flow-chart diagram of process used to identify reservoirs and tributaries potentially suitable for bighead carp reproduction in Oklahoma. Base GIS layers are identified with thin solid lines, derived GIS layers intermediate to the final products are identified with thin dashed lines, and the two derived GIS layers that formed the final set of products (reservoirs and unimpeded length of large inflowing tributaries) are identified with thick solid lines. Arrows indicate GIS processes used to derive layers.

inflowing tributaries. The reservoirs that impounded large rivers (mean annual daily discharge ≥8.5 m^3/s) were the primary locations of interest. At these reservoirs, secondary locations of interest were the inflowing tributaries that not only met the "large" definition, but also exhibited sufficient free-flowing length to support bighead carp reproduction (i.e., "long"). Suitability of reservoirs to sustain bighead carp was thus a function of their inflowing tributaries (i.e., large and long). To illustrate, consider two rivers with mean annual daily discharge >8.5 m^3/s flowing separately into one reservoir (i.e., two "large" tributary streams). The reservoir would be a candidate for further consideration and the two tributaries would be further examined for the presence of dams upstream of the candidate reservoir (i.e., unimpeded length). If one tributary was less than 100 km from dam to reservoir, it would be considered "unsuitable" for bighead carp reproduction. If the other tributary was greater than 100 km from dam to reservoir, it would be considered "suitable" for bighead carp reproduction. The reservoir itself would thus be considered "suitable" for bighead carp reproduction because at least one tributary was considered "suitable".

Results

Bighead carp are known from two reservoirs and two river systems in Oklahoma as well as river and reservoir systems outside the state, but within the encompassing watershed (Figure 1). Fourteen reservoirs in the state were identified downstream from river systems with mean annual daily discharge ≥8.5 m^3/s (Table 1, Figure 3). All remaining reservoirs in the state impounded streams with mean annual daily discharge < 8.5m^3/s, and were thus deemed unsuitable for bighead carp reproduction. The reservoirs on "large" rivers were

Table 1. Name, size, and presence of bighead carp (*Hypopthalmichthys nobilis*) in reservoirs of Oklahoma that were assessed for bighead carp establishment suitability.

Reservoir Name	Surface area (ha)	Rank size in state (ascending)	Bighead carp present	Bighead carp suitability
Broken Bow	5,714	9	No	Unsuitable
Eufaula	40,454	1	No	Suitable
Fort Gibson	7,473	7	No	Unsuitable
Grand	15,553	4	Yes	Suitable
Great Salt Plains	3,355	18	No	Unsuitable
Hudson	4,278	14	Yes	Unsuitable
Hugo	4,674	12	No	Suitable
Kaw	6,709	8	No	Suitable
Keystone	10,131	6	No	Suitable
Oologah	11,714	5	No	Suitable
Robert S. Kerr	16,789	3	No	Unsuitable
Tenkiller Ferry	5,494	11	No	Suitable
Texoma	34,018	2	No	Suitable
Webbers Falls	4,338	13	No	Suitable

Table 2. Discharge regime (mean annual daily discharge, maximum discharge) and upstream limitation to bighead carp (*Hypopthalmichthys nobilis*) reproduction in large tributaries (≥ 8.5 m^3/s mean annual daily discharge) inflowing to Oklahoma reservoirs. No USGS gage above indicates that an upstream limitation based on mean annual daily discharge could not be established.

Reservoir	Tributary	Distance (km)	Most upstream USGS gage	Mean annual daily discharge (m^3/s)	Maximum discharge (m^3/s)	Upstream limitation
Broken Bow	Mountain Fork	15	07338750	16.4	954.3	Dam & no USGS gage above
Eufaula	Canadian River	366	07228500	10.5	1,192.1	Dam & < 8.5m^3/s above
Eufaula	North Canadian River	360	07241500	10.7	413.4	Dam & < 8.5m^3/s above
Eufaula	Little River	160	07230597	8.9	275.2	< 8.5m^3/s above
Eufaula	Deep Fork	80	07243500	26.6	1,574.4	< 8.5m^3/s above
Ft. Gibson	Neosho River	0.1	07191500	249.4	10,392.3	Dam above
Grand	Neosho River	321	07182510	45.5	676.8	Dam above
Grand	Spring River	39	07188000	61.6	5,946.5	Dam above
Grand	Elk River	9	07189000	23.3	1,942.6	No USGS gage above
Great Salt Plains	Salt Fork Arkansas River	21	07149500	11.1	744.7	No USGS gage above
Hudson	Big Cabin Creek	22	07191000	9.9	1,311.1	< 8.5m^3/s above
Hudson	Neosho River	0.1	07190500	213.6	8,126.9	Dam above
Hugo	Kiamichi River	108	07335790	29.4	1,042.1	< 8.5m^3/s above
Kaw	Arkansas River	786	07130500	9.0	945.8	Dam above
Kaw	Little Arkansas River	168	07144100	10.7	498.4	< 8.5m^3/s above
Kaw	Ninnescah River	125	07145500	14.9	954.3	< 8.5m^3/s above
Kaw	Walnut River	64	07147800	25.1	2,412.6	< 8.5m^3/s above
Keystone	Salt Fork Arkansas River	292	07150500	11.2	560.7	Dam above
Keystone	Arkansas River	152	07152500	151.8	5,493.5	Dam above
Keystone	Chikaskia River	209	07152000	16.9	1,968.0	Dam & < 8.5m^3/s above
Keystone	Cimarron River	220	07159100	25.4	2,271.0	< 8.5m^3/s above
Oologah	Elk River	143	07170000	8.7	1,591.4	< 8.5m^3/s above
Oologah	Fall River	224	07168500	10.4	1,529.1	Dam above
Oologah	Verdigris River	221	07166000	14.2	1,682.0	Dam above
Robert S. Kerr	Canadian River	35	07245000	170.4	6,767.7	Dam above
Robert S. Kerr	Illinois River	16	07198000	44.7	4,162.6	Dam above
Tenkiller	Illinois River	112	07195400	10.6	719.2	< 8.5m^3/s above
Tenkiller	Baron Fork River	15	07197000	9.3	971.3	< 8.5m^3/s above
Texoma	North Fork Red River	472	07305000	9.8	1,178.0	< 8.5m^3/s above
Texoma	Washita River	495	07325500	10.3	999.6	< 8.5m^3/s above
Webbers Falls	Arkansas River	124	07164500	216.8	7,390.7	Dam above

among the largest in the state, exceeding 3,000 ha surface area (OWRB 2013). Of these fourteen reservoirs, five (Broken Bow, Fort Gibson, Great Salt Plains, Hudson, and Robert S. Kerr) appear to be unsuitable for bighead carp reproduction based on unimpeded length of inflowing tributaries, although the length of unimpeded tributaries inflowing to Broken Bow and Great Salt Plains was based on limited USGS gaging stations (Table 2; Figure 3) and additional length of these rivers with suitable discharge could exist. Except for Hugo and Webbers Falls reservoirs, which had one suitable tributary, all the remaining suitable reservoirs had multiple inflowing tributaries with suitable mean annual daily discharge, but varying lengths of unimpeded habitat. Many of these

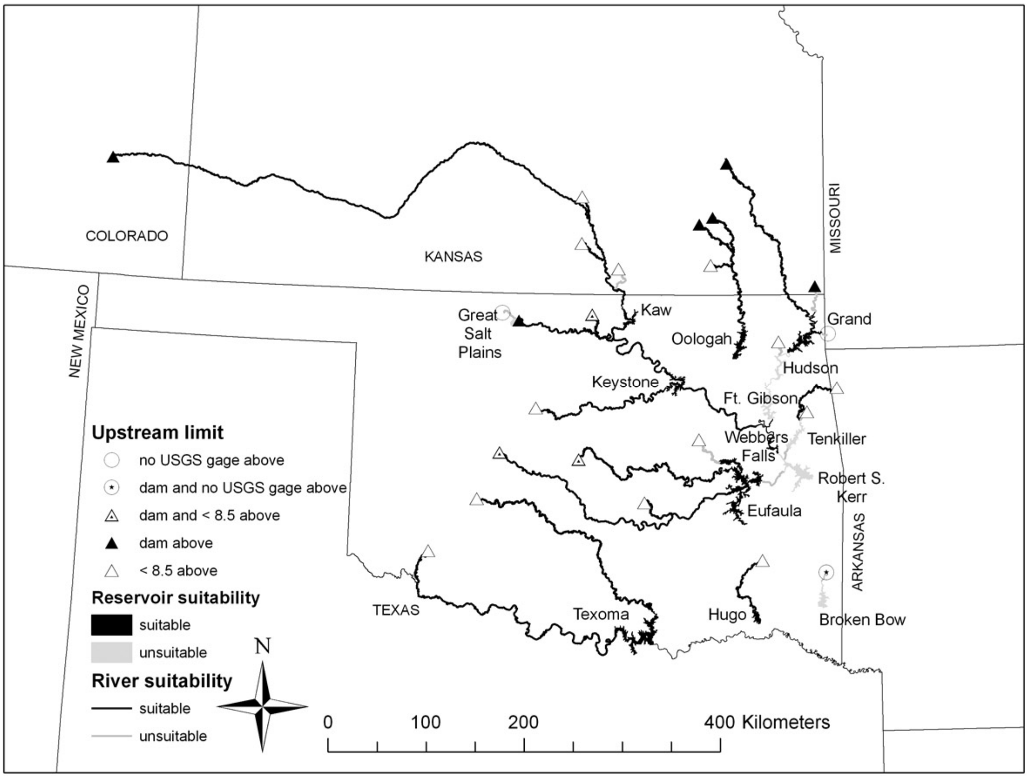

Figure 3. Map of potentially-suitable reservoir habitat for bighead carp reproduction in Oklahoma based on mean annual daily discharge (≥8.5 m^3/s) and length of unimpeded river.

tributaries terminated upstream to either a dam or USGS gage where mean annual daily discharge was <8.5 m^3/s, except for the Elk River inflowing into Grand Lake where no USGS gage existed upstream of the terminus.

Discussion

Previous modeling efforts (Chen et al. 2007; Herborg et al. 2007) have shown that most of Oklahoma (east of the panhandle) is susceptible to invasion by bighead carp, but these models were based on entire landscapes and did not differentiate among water bodies specifically. More recent efforts (e.g., Coulter et al. 2013; Deters et al. 2013) have sought to determine suitable sites for Asian carp establishment by sampling for eggs in streams connected to known invaded sites, which is impractical in non-invaded sites. From a management perspective with the goal to prevent invasion, these results are difficult to use because they do not enable managers to identify or prioritize areas for monitoring *a priori*. With over 9,000 records in the OWRB GIS database of reservoirs in the state, such a task would be overwhelming. The methods we employed in this study are rapid, can be scaled as new research methods become available, and provide managers with specific areas (rivers and reservoirs) to be prioritized and monitored. For example, sampling for eggs could be prioritized in the Neosho River, Spring River, and Elk River inflowing to Grand Lake because this reservoir has a known population of adult bighead carp that has persisted for nearly 20 years. To document spawning in this system, these tributaries appear to be the most likely areas to search compared to searching indiscriminately. Moreover, because these rivers were the only ones entering Grand Lake that met the mean annual daily discharge ≥8.5 m^3/s criteria, yet differed in terms of unimpeded length and hydrology regime, they could be used for testing hypotheses about environmental factors important for bighead carp reproduction (*sensu* Deters et al. 2013).

Our assessment was in agreement with the limited existing invasion records. For example, although no one has yet documented bighead carp reproduction in Oklahoma, a few adult fish are caught each year by anglers in Grand Lake (ODWC 2008; Foster et al. 2009). This is the reservoir where carp were first observed and one of three identified by our methods as suitable for establishment. One large specimen (~40 kg) recently acquired from Grand Lake was estimated to be 9 years old (Long and Nealis 2011), suggesting that reproduction or additional invasion has occurred since the first sighting in 1992 (Pigg et al. 1993). Moreover, there are also reports of bighead carp from the Neosho River, which is the one tributary of Grand Lake that was identified as suitable for bighead carp reproduction. We found no evidence of suitable reproductive habitat for bighead carp in Hudson Lake, although they have been reported there. This discrepancy is likely the result of emigration from Grand Lake, which is situated above Hudson Lake. In their report of bighead carp in Hudson Lake, Pigg et al. (1997) concluded similarly. Our assessment did not take into account migration from other suitable systems and suggests that if bighead carp were eradicated from Grand Lake, the population in Hudson Lake would not persist due to lack of suitable spawning habitat. Although, our results also suggest that if these fish were to continue a downstream trajectory, suitable habitat may exist and allow for increased spread from those reservoirs.

Our approach is similar to that used for identifying Lake Erie tributaries suitable for Asian carp spawning (Kocovsky et al. 2012), except we did not use temperature as a criterion because of the largely suitable temperatures for bighead carp spawning throughout Oklahoma and we did not use velocity measurements. Initially, we sought to use velocity because it is the variable most often reported in the literature as a limitation for bighead carp establishment (e.g., Jennings 1988; Kolar et al. 2007), but we could find no suitable predictive equation based on discharge, which is the variable monitored at the USGS gaging stations. We speculate that the rivers in Oklahoma may differ in geomorphology from those feeding Lake Erie, thus accounting for our inability to find suitable flow-discharge relationships to use in our suitability assessment.

There is a need for validation of the factors related to bighead carp reproduction in their invaded habitat in the United States. For example, there is no evidence from the primary literature to support the assertion that a threshold of 100 km of free flowing river is required for bighead carp, although it has been often-stated (e.g., Jennings 1988; Kolar et al. 2007; Kocosvky et al. 2012). In fact, recent studies have indicated that reaches shorter than 100 km can support reproduction by Asian carp in North America (Coulter et al. 2013; Murphy and Jackson 2013; Chapman et al. 2013). Our methods take this information into account though because we report the extent of unimpeded length, allowing for alternative thresholds to be examined for suitability assessment. In the Great Plains, however, 100 km appears to be a reasonable approximate lower threshold. There, native pelagic-spawning minnows that share a similar reproductive strategy as bighead carp have persisted mainly in streams with fragmented lengths greater than 100 km (Perkin and Gido 2011). Interestingly, many Great Plains minnows have declined because of damming in the region, and this may reduce the potential for bighead carp establishment (Jackson and Pringle 2010). Potentially more important is that recent evidence suggests interactive effects of temperature, flow, substrate, and channel sinuosity may be more important than distance, especially in non-native environments where phenotypic plasticity may allow bighead carps to persist (Coulter et al. 2013). Our work thus identifies areas in Oklahoma that could be prioritized for this type of additional research that is more time and labor intensive.

In summary, bighead carp have the potential to spread in Oklahoma, and our research suggests some logical places to conduct education campaigns to prevent their introduction; specifically those places where this species is absent but has potential for establishment. Furthermore, this strategy could be easily adapted to other geopolitical boundaries (e.g., states, countries) where similar GIS base layers exist. In contrast to the published broad-based models, the site-specific methodology we employed should provide information that is more useful to local managers who initiate and implement management strategies.

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