

Rapid Communication

Occurrence of bigheaded carps (*Hypophthalmichthys* spp.) in the Pearl River Drainage, Louisiana and Mississippi, USA

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Abstract

Two *Hypophthalmichthys molitrix* (silver carp) were collected in the Pearl River on 6 September 2012 during a natural fish kill in the decommissioned lock chamber of Lock-and-Dam No. 1 located at river kilometer (RKM) 47.5 in St. Tammany Parish, 9.4 km NW of the city of Pearl River, LA. Fish were a male 987 mm TL, 10.9 kg, and a female 1042 mm TL, 12.2 kg. Both fish were age 5. Eight additional silver carp (930–1054 mm TL, 9.1–14.1 kg) and one bighead carp (*H. nobilis*) (1065 mm TL, 15.9 kg) were collected in the West Middle Pearl River 29 September – 1 October 2015 (RKM 18.9–20.8), 10.5 km E of Slidell, LA (St. Tammany Parish). All specimens were male and ranged 6–9 years in age. A silver carp (age = 7) was collected by a recreational fisher 19 November 2015 in the Pearl River below the Ross Barnett Reservoir (RKM 480) near Jackson, MS. These three collections are believed to represent nonindigenous silver and bighead carp dispersal from the Mississippi River Basin during floods.

Key words: Pearl River, Louisiana, Mississippi, introduction, flood dispersal, Mississippi River basin

Introduction

Non-native species introduced into a new ecosystem pose a major threat to biodiversity. Once exotic species are established they become invasive and usually outcompete the native fauna that occupy that same niche (Miller et al. 1989; Parker et al. 1999; Sampson et al. 2009). Bigheaded carps are large planktivorous carp native to East Asia and include silver carp (*Hypophthalmichthys molitrix* Valenciennes, 1844), bighead carp (*H. nobilis* Richardson, 1845) and largescale silver carp (*H. harmandi* Sauvage, 1884) (Kolar et al. 2007). Because they are hardy with the capabilities to filter contaminated water, these species have been used in fish aquaculture facilities worldwide (88 countries) for food and to control plankton in aquaculture ponds (Kolar et al. 2007). In 1973, a private fish farmer in Arkansas

obtained silver and bighead carp to improve water quality in aquaculture facilities (Henderson 1976, 1979). During the mid-1970s numerous fish hatcheries (e.g., state, federal and private facilities) were raising silver and bighead carp in Arkansas and subsequently stocked them in four municipal sewage lagoons (Robison and Buchanan 1988). Hatchery-produced silver carp were collected in streams outside the aquaculture facilities in January 1980 (Freeze and Henderson 1982) signaling the beginning of the expansion of bigheaded carps within U.S. waters. For example, in 1994, during a high water year, > 1,600 larvae (*Hypophthalmichthys* spp.) were collected from a backwater outlet of the Black River in Louisiana (Hoover et al. 1995; Douglas and Jordan 2002). Since the introduction of silver and bighead carp, they have established themselves throughout the Mississippi River Basin including all

of its major tributaries and waterways (Schofield et al. 2005); however, successful establishment of these species outside the Mississippi River Basin into another drainage through flood water dispersal is unknown (Nico et al. 2016a, 2016b). Herein we report on the observation and occurrence of nonindigenous bigheaded carps within the Pearl River drainage of Louisiana and Mississippi.

Methods

The Pearl River watershed is a northern Gulf of Mexico drainage that begins in Winston and Choctaw counties approximately 170 km NE of Jackson, MS. The drainage consists of 6 major river systems (Ross 2001) and drains approximately 22,688 km² of central Mississippi and eastern Louisiana (Lang 1972). The main Pearl River is 585 river kilometers (RKM) in length and splits into two distributaries (Pearl and West Pearl River) approximately 77.3 and 70.8 RKM, respectively, from the coast where they empty into the Mississippi Sound and Lake Borgne (Lang 1972). The West Pearl River flows directly into the lower reach of the Rigolets near its confluence with Lake Borgne. The Rigolets is a major strait connecting Lake Pontchartrain and Lake Borgne (Sikora and Kjerfve 1985). In addition, the West Pearl River system includes a manmade lateral navigation canal consisting of three lock and dams that parallels the natural channel downstream of Bogalusa, LA to RKM 45.9 where it joins the West Pearl River at the junction with Holmes Bayou. The West Pearl River Navigation Project was authorized in 1935 and completed in 1956. The project consists of 93.3 km of waterways and was officially placed in caretaker status in 1995 (USACE 2013). The lower 98.2 RKM of the Pearl River forms the boundary between Louisiana and Mississippi. Most of the streams in lower Pearl River sub-basins are gravel bedded with fast, deep base flow. Near the Gulf Coast, the Pearl River becomes estuarine where it is bounded by salt marsh and is tidally influenced (Mississippi Department of Environmental Quality 2000).

Observations of bigheaded carps within the Pearl River drainage were compiled from personal observations noted by the authors and specimens collected during field outings within the drainage (Figure 1). Pectoral fin rays and post-cleithra were retained when possible as aging structures (e.g., Kamilov and Komrakova 1999; Johal et al. 2000; Williamson and Garvey 2005). Fin rays were sectioned along the basal portion of the ray and post-cleithra were sectioned in the middle of the extracted bone. Both were cut to a thickness of approximately 0.70 mm using a Buehler Isomet[®] saw with a diamond wafering



Figure 1. Map depicting location of bigheaded carp specimens (solid circles) in the Pearl River drainage, Mississippi and Louisiana. Specific details for catch at each location are described in the corresponding account in the text. The location of the Bonnet Carré Spillway is near LaPlace, LA (red asterisk). The inset (upper right) illustrates the geographic location of the Pearl River drainage within the southeastern United States.

blade. Annuli were viewed with transmitted light using an Olympus SZX16[®] zoom stereomicroscope equipped with an Olympus DP72[®] camera system and cellSens[®] imaging software. Two researchers agreed in advance what constituted an annular mark and independently estimated age by counting annual marks; a final age was determined by consensus. Assignment of gender and reproductive condition were based on prior classification schemes of Bruch et al. (2001), Colombo et al. (2007), and Chebanov and Galich (2009), and modified for use in field assessments of river sturgeon populations (Divers et al. 2009, 2013). Although sturgeon and carp are taxonomically and anatomically disparate, gonadal development cycles and peak fat development prior to maturation are comparable. Specimens were photo-vouchered or retained as museum voucher material.

Potential pathways were identified and evaluated using procedures adapted from invasive species risk assessment techniques (ANSTF 1996; Pathways Work Team 2007). For each pathway, or group of pathways, likelihood of use was scored and uncertainty



Figure 2. Location of bigheaded carp sampling stations (A–F) in the lower Pearl River drainage. The red asterisk represents the location of the Bonnet Carré Spillway and the downstream floodway extending to Lake Pontchartrain. A hypothesized path of dispersal of bigheaded carp from the Bonnet Carré Spillway to the West Pearl River is depicted by the red line.

of that score was assessed (as low, medium, or high) based on availability of supporting data (e.g., local fishing practices, state regulations, hydrographic data, etc.). Scores were not developed formally or iteratively, based on independent input from outside experts, but rather internally among the co-authors, who collectively have more than 50 years working experience with bigheaded carps in the lower Mississippi River basin.

Results

Dates, localities, and circumstances of collections were:

6–8 September 2012. — Complaints by the public were received by US Army Corps of Engineers (USACE), Vicksburg District and by Louisiana Department of Wildlife and Fisheries (LDWF) of moribund and dead fish observed in the closed lock chamber at Lock-and-Dam No. 1 (RKM 47.5) on the lateral navigation canal of the West Pearl River, 9.4 km NW of the city of Pearl River, LA (St. Tammany Parish, LA; 30.45633, –89.77902; Figure 2, Location C). The closed lock chamber was nearly stagnant with some water seepage through the junction of the upstream gate. The downstream gates

were also closed but the culvert below permitted leakage and fish passage. Water inside the lock chamber was hypoxic <1.0 mg/L (Table S1). Twenty-three species of fishes were observed within the lock chamber; eighteen species consisted entirely of dead individuals including two silver carp (male: 987 mm TL, 10.9 kg; female: 1042 mm TL, 12.2 kg). A necropsy showed the female contained well-developed eggs (Figure 3), the male had developing testes (stage 3) and both possessed 80% gonadal fat. Both individuals were 5 years old.

29 September 2015. — West Middle Pearl River upstream from confluence of Fridays Ditch (RKM 18.9) (St. Tammany Parish, LA; 30.26589, –89.67380; Figure 2, Location D). This sampled river reach is approximately 10.5 km E of Slidell, LA. Surface and bottom salinities were 0.4 and 9.6 ppt, turbidity 10 NTU (surface), and depth 11.6 m. Three silver carp (930–943 mm TL, 9.1–11.8 kg) were captured in anchored gillnets (12.7 cm bar mesh) by ERDC (U.S. Army Engineer Research and Development Center) personnel while sampling for gulf sturgeon (*Acipenser oxyrinchus desotoi*). All specimens were male with ages ranging 6–8 years. Associated river conditions for the samples are listed in Table S1.



Figure 3. Co-author (JJH) holding the first silver carp collected during the 2012 fish kill in the West Pearl River Navigation Canal Lock-and-Dam No. 1. Silver carp contained eggs (inset) and could have spawned next year (photo by S.G. George).

30 September 2015. — West Middle Pearl River, 2.0 RKM upstream of Fridays Ditch (RKM 20.8) (St. Tammany Parish, LA; 30.27885, -89.66734; Figure 2, Location E). Surface and bottom salinities were 0.8 and 8.8 ppt, turbidity 11.3 NTU (surface), and depth 11.1 m. One silver carp (953 mm TL, 10.9 kg) was captured in an anchored gillnet similar to efforts on 29 September. The specimen was male and 8 years old.

1 October 2015. — West Middle Pearl River upstream from confluence of Fridays Ditch (RKM 18.9) (St. Tammany Parish, LA; 30.26561, -89.67365; Figure 2, Location F). Surface and bottom salinities were 0.2 and 10.2 ppt, turbidity 14.7 NTU (surface), and depth 10.2 m. Four silver carp (1003–1054 mm TL, 10.7–14.1 kg; age = 8–9 years) and one bighead carp (1064 mm TL, 15.9 kg, age = 8) (Figure 4) were captured in anchored gillnets similar to efforts on 29 September. All specimens were male. In addition, all male fish processed 29 September – 1 October 2015 possessed small testes with a high degree of gonadal fat (80–95%).

19 November 2015. — Pearl River below Ross Barnett Reservoir Spillway (RKM 480.0) (Rankin County, MS; 32.39695, -90.06548; Figure 1, Location G). An angler reportedly caught a silver carp in the spillway tailwater and posted the photograph on social media (Figure 5). Afterwards, the fish was filleted and the carcass discarded. The head and remainder of the carcass were later recovered by Mississippi Department of Wildlife, Fisheries and Parks (MDWFP) fisheries biologists following the

internet posting and archived at the Mississippi Museum of Natural Science as a voucher (MMNS 64511). Pectoral rays were removed at MMNS and provided for aging. Data on length, weight and gender were not available due to condition of the carcass but head length was 190 mm. Based on head length (i.e., tip of upper jaw to posterior margin of opercle) and our unpublished data on morphometry of silver carp in the lower Mississippi River Basin (J. J. Hoover, unpublished data), we estimated total length as 915 mm. The specimen was 7 years old.

Introduction to the Pearl River drainage could have occurred through 11 different pathways (*sensu* Pathways Work Team 2007): 4 from living industries, 3 from transportation, and 4 from miscellaneous sources (Table 1). Any are possible, either individually or in combination with each other, but only one is high in likelihood and certainty: entrainment through a water diversion.

Discussion

These specimens represent the first confirmed occurrence of bigheaded carps in the Pearl River drainage of Louisiana and Mississippi, and furthermore document the early stages of the introduction event. Few reports involving the introduction of non-native aquatic species have been successful in providing documentation of occurrence following the initial introduction event; most documentation generally occurs long after populations are well established (Fuller et al. 1999).



Figure 4. Silver and bighead carp collected 1 October 2015 from West Middle Pearl River (St. Tammany Parish, LA). Lateral (upper image) and ventral (lower image) views of the two species illustrate diagnostic taxonomic differences for eye position, head size, pectoral fin size length and ventral keel length (photo by W.T. Slack).



Figure 5. Silver carp collected by an angler 19 November 2015 from the Pearl River (Rankin Co., MS) at tailwaters of the Ross Barnett Reservoir (photo by B. Nguyen).



Table 1. Introduction pathways for the occurrence of bigheaded carps in the Pearl River drainage.

Pathway	Evaluation	Likelihood	Uncertainty
Living Industries: i) Bait ii) Aquarium Trade iii) Aquaculture iv) Non-Pet Animals	i) Bait bucket introductions are possible, but commercial and recreational fishermen in the area do not commonly use locally collected fishes as bait. ii) Bigheaded carps lack ornamentation or striking appearance and have limited appeal to aquarists and are not maintained by suppliers or hobbyists. iii) No aquaculture facilities have been permitted for bigheaded carps within the Pearl Basin in LA or MS (T. Ruth, LDWF pers. comm., 19 January 2016; G. Robertson, Mississippi Department of Agriculture and Commerce pers. comm., 5 February 2016). iv) Because they are universally recognized as undesirable and a nuisance, intentional releases for stocking are improbable.	Low	Low
Transportation: i) Hull/Surface Fouling ii) Stowaways iii) Organisms Transported for Entertainment	i, ii) The distance between closest public boat ramps in the Mississippi River and the Pearl River (70 km: Lakeshore Park [Lake Pontchartrain] at Seabrook Bridge to Mississippi River at RM 92.5 via Inner Harbor Navigation Canal; Lakeshore Park to Hwy 90 launch on Middle Pearl River, SE of Slidell, LA) makes survival of bigheaded carps propagules on boat hulls, propellers, bilges, etc. highly improbable. Also, Silver Carp are not hardy when transported in containers (Kolar et al. 2007). iii) It is possible that large fish brought back by anglers as a novelty or for display could be subsequently released, but this seems unlikely since carp do not typically bite a baited hook.	Low	Medium
Unusual Weather/Hydrographic Events	Excluding Spring 2008 and Spring-Summer 2011, Mississippi River hydrographs for 2007–2015 do not indicate unusually high water (RiverGages.com: Carrollton gage – station 01300, RM 102.8, LDB, New Orleans, LA). This gauge is used by USACE for basing decision to open the Bonnet Carré Spillway. Flood stage is 17', overbank stage is 11'; river stage ranged 1.37–17.05' between 1 January 2007 and 31 December 2015 with 14 overbank events (mean stage = 13.10'; range = 11.26–16.49') excluding the 2008 and 2011 spillway openings. Fish surveys in principal connections between the lower Mississippi River and the Pearl River drainage include no records of bigheaded carps prior to 2011 (Ross 2001; Douglas and Jordan 2002; O'Connell et al. 2004; O'Connell et al. 2014).	Low	Low
Natural Dispersal	Salinities of the Mississippi Sound vary seasonally and spatially (mean monthly range 1.0–29.4 ppt; Christmas and Eleuterius 1973; Eleuterius 1976); Lake Pontchartrain mean monthly levels range 1.4–5.4 ppt (Sikora and Kjerfve 1985). Fry and juvenile bigheaded carps experience a greater salinity tolerance than adults (Kolar et al. 2007) and may be able to use estuarine areas as bridges to colonize neighboring watersheds (Garcia et al. 2004) similar to hypothesized range expansion of Nile tilapia in coastal Mississippi watersheds (Lowe et al. 2012).	Medium	High
Bio-Control	There are no records of intentional stockings of bigheaded carps within the Pearl basin in LA or MS and neither state has permitted the culture of either species for aquaculture (see Pathway iii). The possibility exists of unauthorized culture or transport but this seems remote due to local animosity towards these species.	Medium	Medium
Interconnected waterways and interbasin transfers	Observed chronology and age structure of captured bigheaded carps are consistent with a single (2008 or 2011) or multiple (2008 and 2011) entrainment events at the Bonnet Carré Spillway. A single event in 2008 is less probable due to the high water volume diverted in 2011, and the requirement that 2008-entrained fish are successfully reproducing and recruiting in the Pearl River (for which there is no evidence).	High	Low

Of the described introduction pathways, natural dispersal from proximal watersheds (e.g., Lake Pontchartrain, Tchefuncte River or Pascagoula River) during periods of elevated river stage has the greatest likelihood of occurrence. Bigheaded carps do not have established populations or have not been previously reported in the Tchefuncte or Pascagoula rivers (USGS 2015). However, Lake Pontchartrain via the Mississippi River offers a viable option for introduction of bigheaded carps into the Pearl River drainage. Lake Pontchartrain is a 1630 km² brackish-water lagoon located directly north of New Orleans, LA and drains primarily east through the Rigolets into Lake Borgne and then into the Mississippi Sound (Sikora and Kjerfve 1985). This shallow estuary receives freshwater inputs from larger rivers (e.g., Amite, Tickfaw, Tangipahoa and Tchefuncte rivers) and bayous primarily along its north shore and from the Mississippi River during periodic leakage or prolonged openings of the Bonnet Carré Spillway during high water stages (Brammer et al. 2007).

The Bonnet Carré Spillway is a controllable crevasse providing an additional outlet for the Mississippi River to reduce flooding in downstream communities including New Orleans, LA (White et al. 2009). Built as part of the Mississippi River and Tributaries Project, a USACE multi-state management plan addressing flood risk damage in the Lower Mississippi Valley, construction started following the Great Mississippi Flood of 1927 (USACE 2016a). The spillway was first opened in 1937 and ten times thereafter including the Spring flood of 2016 (USACE 2014, 2016b). The length of opening has ranged 13–75 days with a mean opening of 39.72 days (± 9.98 , 95% CI). The facility consists of two basic components: a control structure located along the east bank of the Mississippi River 53.1 RKM upstream of New Orleans and a floodway that transfers diverted water to Lake Pontchartrain and then into the Gulf of Mexico (USACE 2014). The overall spillway structure is 2.35 km wide; the actual weir opening is 2.1 km wide and consists of 350 flood gates which can divert up to 7000 m³ s⁻¹ from the river during the flood stage (Lane et al. 2001). Diverted floodwaters flow downstream through a 9.2 km floodway (3238 hectares) emptying directly into Lake Pontchartrain along its south shoreline. During the 2011 Mississippi River flood, 330 of the flood gates were opened for 42 days. The previous opening in 2008 extended for 28 days during which 160 flood gates were open (Day et al. 2012).

Bigheaded carps could have entered the Lake Pontchartrain system and subsequently the Pearl River drainage during either event: in 2011 as adults or in 2008 as young-of-year. The age structure of the

examined specimens supports either of these scenarios (Table 2 and Table S2). During the 2008 and 2011 flood, we (ERDC and LDWF) collected both silver and bighead carp on the Bonnet Carré Spillway floodway. Following the 2008 flood, we collected silver carp from the floodway during summer 2009. These fish were 141–380 mm TL and would have been yearlings at the time of capture and likely represent age 0–1 individuals entrained during the 2008 event. The proposed age distribution of those individuals is similar to the ages reported for the 2012 and 2015 Pearl River specimens. In addition, ERDC personnel processed 43 silver carp specimens from the 2011 Bonnet Carré Spillway opening for age and growth assessments. Ages of the examined specimens ranged 3–7 years with a modal age of 3 years and 70% of the examined specimens were ≤ 4 years old (ERDC unpublished data). These data provide support for a 2011 introduction event of bigheaded carps into the Lake Pontchartrain and Pearl River systems.

The length of opening of the Bonnet Carré Spillway structure in 2011 was 14 days longer than 2008 and with more than twice the number of gates open. In addition, a larger volume of freshwater was diverted into Lake Pontchartrain during 2011 compared to 2008 (22.1 vs. 8.0 billion m³, Mize et al. 2012) thereby providing a greater probability of entrainment and subsequent dispersal.

Silver carp were observed in Lake Pontchartrain and in the Pearl River within a year of the 2011 opening (T. Ruth, pers. obs). Jumping fish, presumed to be silver carp, were observed in a small canal on the Northshore of Lake Pontchartrain near Mandeville, LA on 19 July 2011 (30.36817, -90.10867). Personnel from LDWF observed several silver carp jumping behind their boat on 18 April 2012, in the West Pearl River at a canal north of I-59 (RKM 38.1) (St. Tammany Parish, LA; 30.39358, -89.73455; Figure 2, Location A). On 30 July 2012, LDWF observed several silver carp jumping in English Bayou, a tributary of the East Pearl River, E of John C. Stennis Space Center (RKM 34.8) (St. Tammany Parish, LA; 30.35021, -89.66316; Figure 2, Location B) with one landing directly in the boat. No measurements or photographs were taken of the specimen. Additional observations of potential sightings in the Lake Pontchartrain system were reported to LDWF from April 2012 through June 2013 (USGS 2015). These include sightings in Lake Pontchartrain and smaller water bodies near Slidell and Lacombe, LA (USGS 2015).

There were no anecdotal observations reported following the 2008 opening. Similar reports have been noted for the coastal region east of Lake Pontchartrain. An adult silver carp was hooked by an

Table 2. Summary of catch data for bigheaded carp specimens processed at the Bonnet Carré Spillway and Pearl River 2008–2015. Abbreviations include: Silver Carp = SC; Bighead Carp = BH; Spillway = Bonnet Carré Spillway.

Collection Year	Species	Number	Observed Age	Predicted Age 2008 flood	Predicted Age 2011 flood	Location
2008	SC	4	Adult (910–933 mm TL)	NA	NA	Spillway
2008	BH	1	Adult (1230 mm TL)	NA	NA	Spillway
2009	SC	91	141–380 mm TL ^a	NA ^b	3–4	Spillway
2009	BH	1	Large adult	1+	4+	Spillway
2011	SC	43	3–7	YOY-4	3–7	Spillway
2011	BH	4	3–6	YOY-3	3–6	Spillway
2012	SC	Several	Adult (not captured)	NA	NA	A
2012	SC	Several	Adult (not captured)	NA	NA	B
2012	SC	2	5	1	4	C
2015	SC	3	6–8	YOY-1	2–4	D
2015	SC	1	8	1	4	E
2015	SC	4	8–9	1–2	4–5	F
2015	BH	1	8	1–2	4–5	F
2015	SC	1	7	YOY	3	G ^c

^aBased on ERDC field data and subsequent aging efforts we consider silver carp < 738 mm TL to be ≤ 1 year old (\bar{x} = 566.72 mm TL).

^bThese individuals would have been too small to have been entrained as YOY during the 2008 opening. They could have passed from the Mississippi River through gaps between the pins in the Bonnet Carré Spillway structure at a later date following the closure of the structure in 2008 or they may have been spawned in the floodway following the 2008 opening.

^cDuring the review period for this manuscript, MDWFP officials reported the capture of an adult bighead carp on 14 April 2016 by a local angler in the Ross Barnett Spillway tailwater. The fish was not retained; length and weight measurements were not obtained nor were ageing structures removed.

angler on 19 April 2014 off a pier at Bay St. Louis (Hancock Co, MS) (USGS 2016), and jumping carp have been observed in nearby marshes in Hancock County (M. Pursley, Mississippi Department of Marine Resources, pers. comm. 12 May 2016). These observations further support the concerns that both species may disperse through coastal estuarine conditions to neighboring watersheds.

The modal age of the 2015 West Middle Pearl silver carp specimens was 8 while the age of the 2012 lock-and-dam specimens was 5. The three year difference between observations and the age difference of the specimens between the two events (e.g., 3 years) supports a single dispersal event with the majority of the fish being from the same cohort.

Historically, freshwater input from the Mississippi River into Lake Pontchartrain has been sporadic and a natural event. Between 1849 and 1892, the Mississippi River breached levees and flowed into Lake Pontchartrain on an average of once every four years (Sikora and Kjerfve 1985). Following the completion of the Bonnet Carré Spillway in 1931, Mississippi River waters have been diverted into Lake Pontchartrain 11 times (USACE 2014, 2016b). However, compilations of fish distribution records have yet to document any endemic Mississippi River

basin fish (e.g., river sturgeon [*Scaphirhynchus* spp.] and goldeye [*Hiodon alosoides*]) establishing new populations in Lake Pontchartrain or the Pearl River drainage (Douglas 1974; Ross 2001). The presence of bigheaded carps in the Pearl River drainage suggests opportunism in exploring a new ecosystem by a non-native species. The distribution and abundance of bigheaded carps in the Pearl River is as yet unknown, and we can only speculate if or when these species will become established.

There is an immediate and critical need for monitoring and population modeling of bigheaded carps in the Pearl River. If the 12 fish documented herein represent non-recruiting, senescing survivors of one or two entrainment events, then long-term impacts are minor and will diminish with attrition, so that management actions are unnecessary. Assuming maximum life spans of 15–20 years for both species (Kolar et al. 2007), most of the entrained fish will have died out within 10 years. If, however, these fish represent viable colonists and their offspring, then long-term impacts will be substantial and will increase with population growth, so that management actions, to be effective, must be swift and absolute. Older, larger individuals exhibit disproportionately high fecundity and, as a result,

greater reproductive potential than younger smaller fish (Jennings 1988; Williamson and Garvey 2005). Control (or elimination) through harvest is more likely in the early stages of population growth than in later stages when a population is approaching carrying capacity. For example, a recent meta-analysis of bigheaded carps indicated that for established populations in North America, 50–70% of the fish would have to be harvested for effective suppression of current population levels (Tsehaye et al. 2013). Whether senescing or recruiting in the Pearl River, synoptic assessments of bigheaded carps distribution, abundance, population structure and reproductive status are needed now to develop contingency-based management plans. Population models indicate that large populations of bigheaded carps can be established from very small numbers (< 20) of colonists (Cuddington et al. 2014). Consequently, proactive monitoring and management of the Pearl River cannot be considered an over-reaction.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Water quality parameters associated with bigheaded carps sampling event.

Table S2. Records of silver carp and bighead carp in the Bonnet Carré Spillway and Pearl River in 2008–2015.

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