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Swimming Performance of Bighead Carp and Silver Carp: Methodology, Metrics, and Management Applications

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PURPOSE: This study summarizes laboratory swim studies of two species of Asian carp, 36-334 mm total length, and suggests ways that swimming performance data can be used to contain these invasive species.

CARP MOVEMENTS: Bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*H. molitrix*) are native to China but are now established and spreading throughout North America. Following their introduction in the Lower Mississippi River in the 1980s, both species have dispersed upriver towards the Great Lakes and laterally into floodplain wetlands and tributaries (Kolar et al. 2007). Their diets overlap highly with those of native planktivorous fishes (Sampson et al. 2009). Because they consume large quantities of food representing a wide variety of taxa (Jennings 1988), selectively digesting and egesting viable algae (Pongruktham et al. 2010), they can alter food webs and increase trophic competition (Pegg et al. 2009), reducing the robustness (condition) of native fishes like gizzard shad (*Dorosoma cepedianum*), bigmouth buffalo (*Ictiobus cyprinellus*) (Irons et al. 2007), and possibly paddlefish (*Polyodon spathula*) (Varble et al. 2007). Predicting rates and likelihood of carp dispersal and containing populations with hydraulic barriers (or other types of barriers) are options for managers, but quantitative data are required on swimming performance of carp.

Both species of carp have fusiform flexible bodies, narrow peduncles, and moderately high forked caudal fins (Figure 1). This "cruiser" morphology (sensu Webb 1988) suggests extended high-speed movements, but previous studies suggest that bighead and silver carp are comparatively slow swimmers. Telemetry indicates that swim speeds of sub-adults (360-460 mm total length [TL]) of both species occasionally exceed 300 cm/s but average < 35 cm/s (Konagaya and Cai 1987; 1989). A single unpublished laboratory study indicates that large juveniles (93.3 mm TL mean $\pm$ 19.5 SD) are displaced by water velocities averaging only 25 cm/s $\pm$ 3.8 SD (Layher and Ralston 1997). High activity levels of two enzymes associated with anaerobic metabolism (phosphofructokinase and pyruvate kinase), though, suggest that both species should be capable of substantially greater levels of high-speed burst swimming than common carp (*Cyprinus carpio*) and grass carp (*Ctenopharyngodon idella*) (Shenouda 1996), both of which have extensive geographic distributions in North America (Schofield et al. 2005). No empirical data, however, have been published on the swimming capabilities of bighead carp or silver carp in controlled laboratory conditions.

METHODOLOGY FOR QUANTIFYING SWIMMING PERFORMANCE: Swimming performance of carp is evaluated using the same methodology and test chambers as other fish species, such as native minnows (Adams et al. 2003), paddlefish (Hoover et al. 2009), and sturgeon (Adams et al. 1999, Hoover et. al. 2011a, 2011b). Fish are collected in the field or at aquaculture facilities by seining, moved

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into aerated tanks on trucks, and driven directly to the laboratory. On arrival, water temperature of the transport tank is equilibrated with that of the holding tanks (transferring holding tank water to transport tank for larger fish, and floating containers of the transport water in holding tanks for smaller fish).

Figure 1. Adult bighead carp (upper) and silver carp (lower) collected from Forest Home Chute, a backwater of the lower Mississippi River. Note differences in size of head and pectoral fin.

Fish are maintained in large static holding tanks that permit unimpeded natural movement and behavior (including schooling). Holding tanks are 2800-L aquaculture tubs, half- to three-quarters full, circulated with a Little Giant Water Wizard Model 5 MSP submersible water pump, filtered with a 200-L canister containing carbon, ammonia-absorbing resin chips, and foam (Figure 2). The system provides mechanical, chemical, and biological filtration with minimal fluctuations in water quality. Holding tanks are established two to six weeks prior to receiving fish. Fish are fed commercial dry fish foods ad libitum two to four times daily: slow-sinking granules and/or floating flakes. Because wild-caught carp are reluctant to feed in captivity (Hogue and Pegg 2009), sub-adult fish are housed with domestic goldfish (*Carassius auratus*), which provide carp with visual cues that stimulate and reinforce feeding (Figure 3). Water quality is monitored weekly and partial water changes are made semi-monthly or as needed. Individual fish of both species have been successfully maintained using this protocol for more than 2 years in captivity. Fish facility and protocol are inspected and evaluated every six months by the U.S. Army Engineer Research and Development Center (ERDC) Institutional Animal Care and Use Committee (IACUC).

Each individual fish is tested only once in freshly drawn water that is dechlorinated and aerated. Tests are conducted at 20-27 °C, a range that includes temperatures preferred by carp (Bettoli et al. 1985), associated with greatest activity of the fish (Negonovskaya 1980, cited by Jennings 1988), and believed optimal for feeding and growth (Jingsong and Honglu 1989). Juveniles are tested in a 100-L Blazka swim tunnel (Figure 4). Sub-adults are tested in a 1200-L Brett swim tunnel (Figure 5). Both tunnels

Figure 2. Holding tanks used to maintain bighead carp and silver carp in the laboratory. Water is pumped by submerged pumps into overhead filters supported on fiberglass grids. Water passes through ammonia-removing resin chips, carbon, and foam pads and then showers back into the tank. Net skirts attached to grids prevent silver carp from jumping out of the tanks.

Figure 3. Bighead carp surfacing for food pellets. Goldfish provide feeding cues to carp, which are accustomed to feeding on plankton.

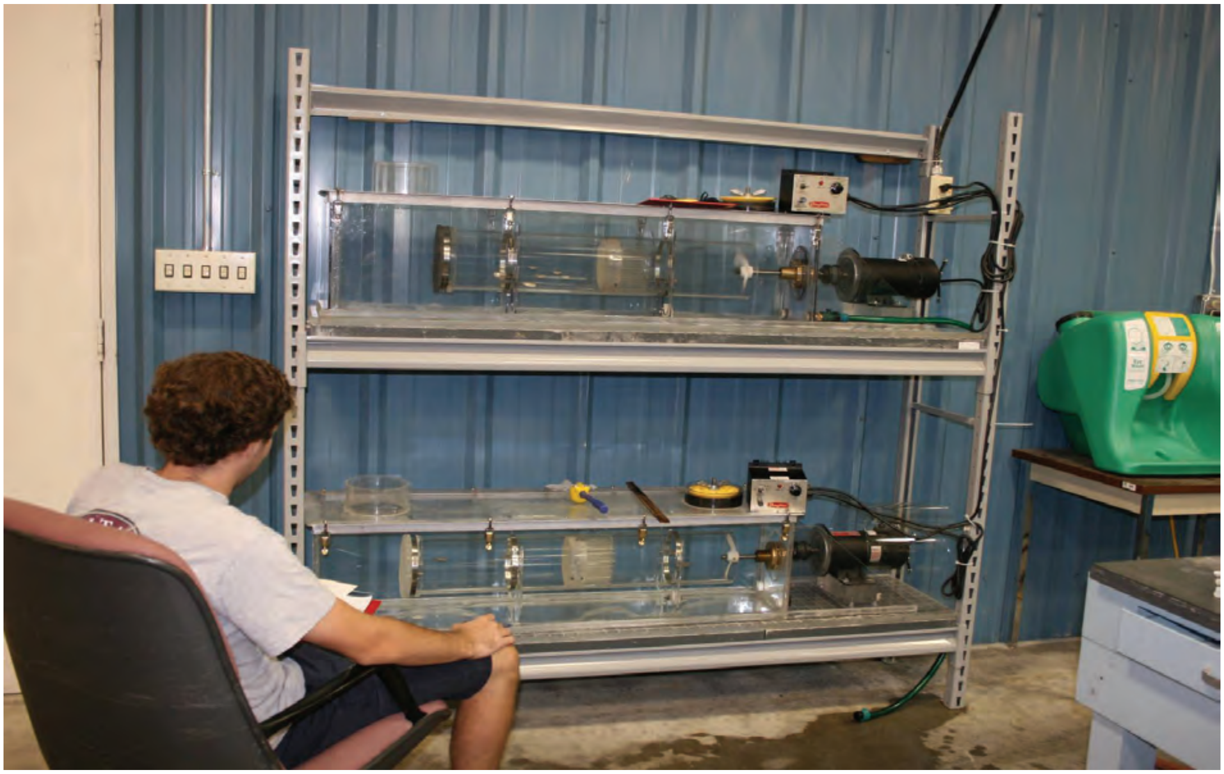

Figure 4. Blazka swim tunnels. Paired tunnels allow acclimation of one fish while another fish is being tested.

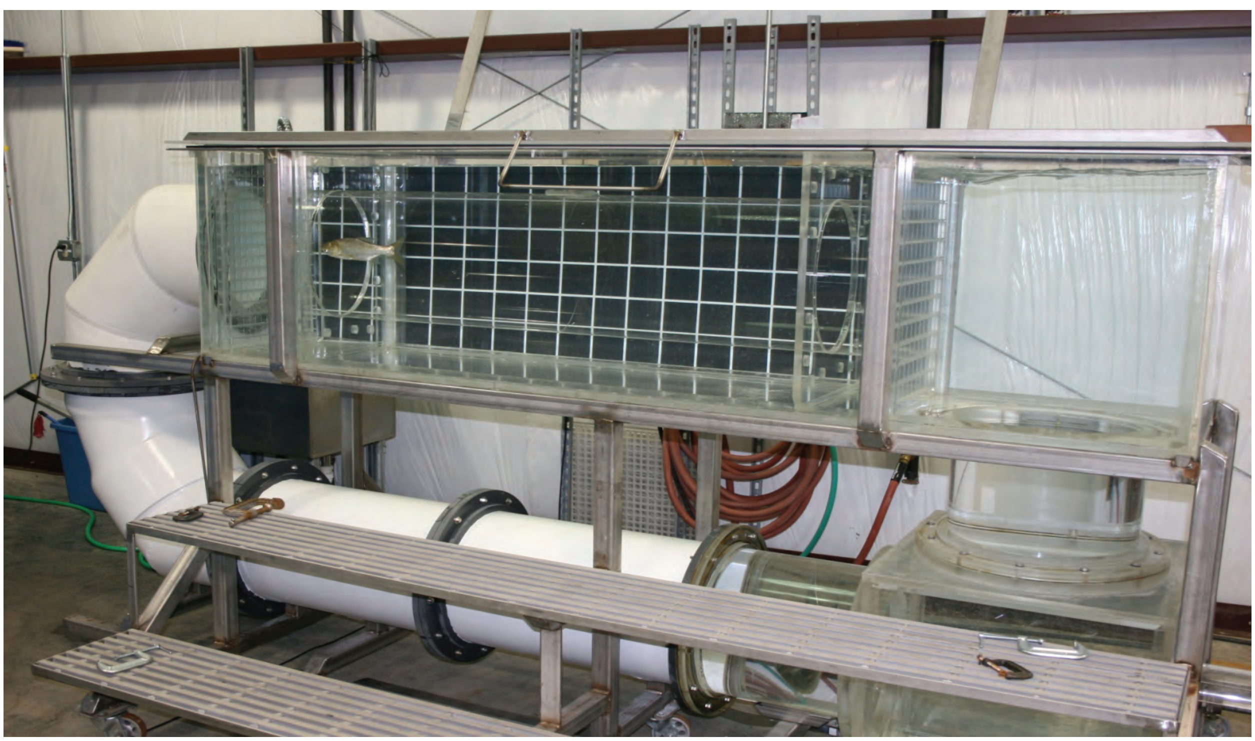

Figure 5. Brett swim tunnel with bighead carp undergoing swimming trial. Front and rear grids at either end of the tunnel are exchangeable with others of different pore size. They can contain fish of various sizes and also act as collimators, providing rectilinear flow.

provide a wide range of water velocities and uniform, rectilinear flow (Hoover et al. 2011a, 2011b). Fish are acclimated in the tunnel for approximately 1 hour, initially at no-flow and subsequently at slow-flow conditions, before each timed trial is conducted at a pre-determined water velocity. Head-first orientation into flow, called positive rheotaxis, categorizes a fish as a "performer," and endurance and behaviors are recorded until the fish fatigues or until > 200 minutes have elapsed. Failure to orient head-first into flow categorizes a fish as a non-performer and the trial is ended. Following trials, fish are measured to the nearest millimeter for total length before being placed in a recovery tank to monitor post-experiment behavior and survival.

Three parameters are used to quantify swimming performance: rheotaxis (i.e., the percentage of fish that performed under experimental conditions by orienting head-first into flow); endurance (i.e., time to fatigue at a test water velocity); and behavior (i.e., modes of locomotion exhibited by the fish). Rhoetaxis is quantified as the percentage of all fish tested who performed under experimental conditions. Endurance data are analyzed using regression models that describe linear or curvilinear relationships between water velocity (independent or predictor variable) and endurance (dependent or response variable). Models developed with these data are highly predictive ($R^2 > 0.41$, $p < 0.001$). Three endurance-based metrics are listed: 1) highest water velocity tested at which a fish swan for 200 minutes (maximum sustained speed); 2) regression-predicted water velocities at which fish can swim for 1 minute (a prolonged swim speed); 3) regression-predicted water velocity at which a fish swam for 0.1 minute (a burst speed). Behavior is described qualitatively as any of seven discrete locomotor behaviors observed in stream fishes: free-swimming (in open water), skimming, hunkering, creeping (on horizontal substrates), wedging, oral-grasping, and tail-bracing (at vertical surfaces) (Adams et al. 2003; Hoover et al. 2011a).

CARP SWIMMING PERFORMANCE: Both species of carp were strongly rheotactic and moderately strong swimmers, but performance metrics for larger fish were greater than smaller fish and those for bighead carp were consistently greater than those of silver carp (Table 1). More than 90% of fish tested were rheotactic. Disparity between bighead and silver carp was greater in large juveniles (97 vs. 85%, respectively) than in sub-adults (100 vs. 93%). Maximum sustained swim speeds were generally 50-60 cm/s except in small juvenile bigheads, which could sustain speeds only of 20 cm/s, and sub-adult bigheads, which could sustain speeds of 80 cm/s. Regression-predicted 1-min prolonged swim speeds were less than 5 cm/s greater than maximum sustained speeds for large juveniles of both species, and 14-30 cm/s greater for small juvenile bighead carp and sub-adults of both species. Similarly, regression-predicted 0.1-min burst swim speeds were 15-22 cm/s higher than prolonged swim speeds for small juvenile bighead and large juveniles of both species. Burst speeds of sub-adults, however, were more than 50 cm/s greater than prolonged swim speeds. Prolonged and burst speeds of sub-adult bighead carp were almost 40 cm/s greater than those of silver carp. Behavior of fish consisted almost exclusively of mid-water free-swimming (Figure 6) and tail-bracing at the rear of the chamber (Figure 7). Tests were non-injurious to fish. All survived and behaved normally for a minimum of 24 hours following tests and most were alive and healthy weeks and months later.

APPLICATIONS OF CARP SWIMMING PERFORMANCE DATA:

<u>Risk Assessment</u> – Results are consistent with previous field studies indicating that bighead carp have higher burst speeds and routine swim speeds (sustained and prolonged) than silver carp (Konagaya and Cai 1987; 1989). This seems at first counter-intuitive, since bighead carp appear less hydrodynamic

than silver carp. Bighead carp have a larger head, a wider body, and a shorter ventral keel than silver carp (Schofield et al. 2005). They can have larger pectoral fins, however, as adults (Figure 1) and as fingerlings and larvae (Soin and Sukhanova 1972), which may compensate for greater drag experienced by fishes having a less streamlined body.

Table 1. Metrics of swimming performance for bighead and silver carp.[1]

Life stage Species (Numbers tested)	Total Length (mm)	Water Temperature (°C)	Positive Rheotaxis (% tested)	Sustained Swimming, 200 min (cm/s)	Prolonged Swimming, 1-min (cm/s)	Burst Swimming, 0.1-min (cm/s)
Small juveniles						
Bighead carp (56)	36-69	22-23	89	20	34	56
Large juveniles						
Bighead carp (32)	72-106	19-25	97	60	64	86
Silver carp (33)	85-116	20-26	85	60	62	77
Sub-adults						
Bighead carp (48)	250-334	23-27	100	80	110	166
Silver carp (45)	141-288	21-24	93	50	73	128

[1] Rheotaxis is the percentage of all fish tested that oriented headfirst into flow at test water velocities. Sustained swimming speed is the maximum observed water velocity at which any individual fish tested was able to swim more than 200 minutes. Prolonged and burst swim speeds correspond to 1-min and 0.1-min endurance times, respectively, as predicted by regression models.

Figure 6. Sub-adult bighead carp free-swimming in Brett swim tunnel.

Figure 7. Sub-adult silver carp tail-bracing in Brett swim tunnel.

Carp swimming performance metrics are useful tools for managers and planners. They enable estimates of passage time across given combinations of distances and water velocities. As a result, representative swim speeds have been used to estimate duration of exposure to electrical fields and to develop operational guidelines for the electrical barrier in the Chicago Ship and Sanitary Canal (Holliman 2010). Swim speeds can also be used to evaluate dispersal along various pathways (e.g., time required to travel a given distance) and to evaluate the likelihood of establishment based on bioenergetics models (e.g., suitability of available plankton resources to support carp growth). A recent model suggested that the threat of carp establishment and food web disruption was small in oligotrophic portions of the Great Lakes but that some productive regions, such as Green Bay in Lake Michigan and the West Basin in Lake Erie, provided sufficient plankton for the energetic needs of the fish (Cooke and Hill 2010). This model, however, assumed swim speeds of < 5 cm/s. Because energy requirements increased logarithmically within the range evaluated (0-4 cm/s), use of higher documented sustained swim speeds (20-80 cm/s) could have indicated lower likelihoods of sustainability.

Risk management – Swimming performance data can also be used to evaluate potential for swift-water containment of carp populations. Non-negotiable combinations of water velocity and distance, for functional containment of invasive fishes, can be determined using the same methodology as determining negotiable conditions, for functional passage of endangered fishes (e.g., Peake et al. 1997; Adams et al. 2000). The following equation is used:

$$V_f = V_s - (D / E_{vs}) \quad (1)$$

in which V_f is ambient water velocity, V_s is swimming speed of fish, D is distance traveled, and E_{vs} is endurance at that V_s (Peake et al. 1997). This equation predicts the maximum velocity that can be traversed by fish moving various distances through culverts, channels, canals, or any other waterway. Conversely, it can be used to establish water velocities that will block movements of fish (those greater than V_f).

This relationship was used to predict maximum water velocities traversable by silver carp for distances ranging from 0.1 to 100 m. A range of swim speeds (0.3-1.5 m/s) and endurance (predicted by regression of empirical data) was substituted iteratively into this equation to determine maximum velocity traversable at each distance. Results indicated that short distances (< 5 m) of high flow (1.1 to 1.5 m/s), intermediate distances (5-15 m) of moderate flow (0.85 to 1.1 m/s), and long distances (> 19 m/s) of lower flows (> 80 cm/s) will exceed swimming capabilities of sub-adult bighead carp (Figure 8). Barriers engineered for containment of sub-adult bighead carp would be effective for silver carp and for juvenile bighead carp as well, since those groups have lower swim speeds (Table 1). Barriers could be created by modifying channels topographically (e.g., shoreline constrictions), structurally (e.g., small diameter culverts), or hydrologically (e.g., drawdowns) to elevate flow, at least during some hydrologic conditions to deter fish from moving upstream. "Accelerated Water Velocity" is under consideration as a control for aquatic nuisance species in the Great Lakes-Mississippi River Interbasin Study or GLMRIS (Cornish et al. 2011).

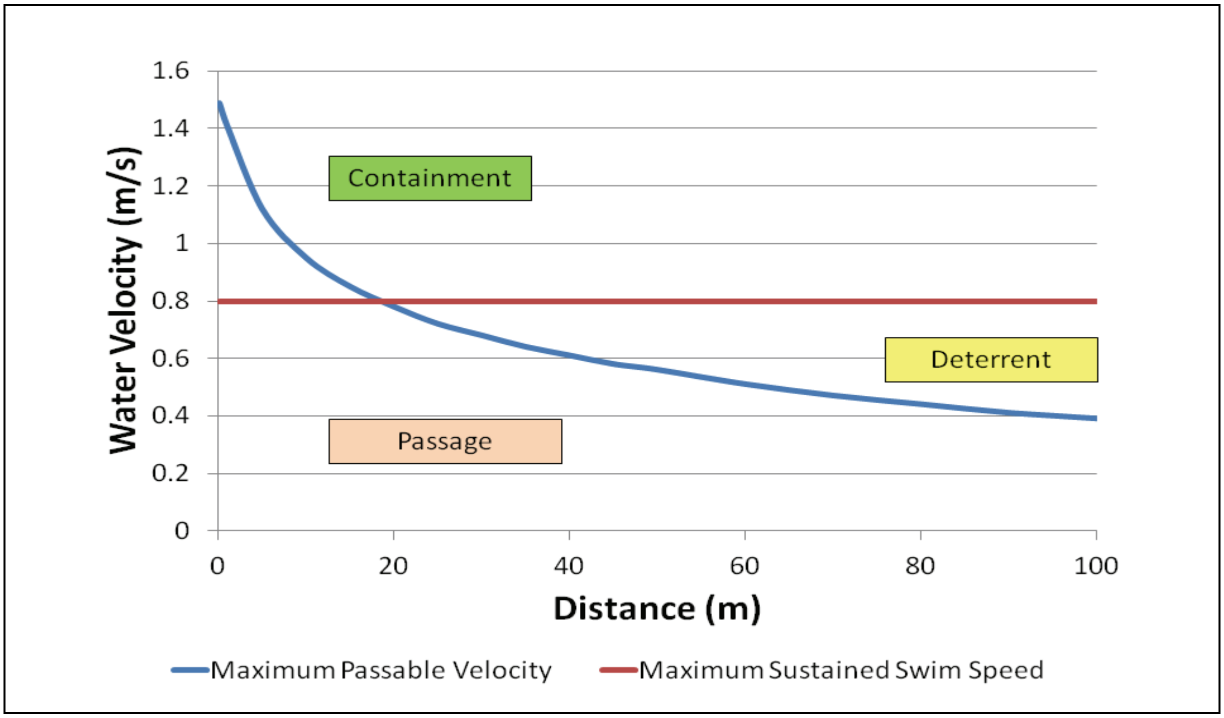

Figure 8. Maximum passable water velocities for sub-adult bighead carp swimming at maximum sustained speeds (red line) and at prolonged and burst speeds (blue line). For distances < 19 m, water velocities above the blue line will exceed swimming capabilities of fish and can provide containment. For distances ≥ 19 m, water velocities greater than 80 cm/s will exceed swimming capabilities of fish. Water velocities below the blue line are within the swimming capabilities of fish and will enable fish passage. For distances ≥ 19 m, water velocities between the blue and red line will exceed swimming abilities for prolonged and burst swimmers, but not for sustained swimmers.

Examples above are simplistic, because they are based on hypothetical or average fish. There are many factors that can influence descriptors of "average" swimming performance. Some carp tested were underperformers – swimming for a few seconds when other individuals of the same species, size, and history swam hours. Of representative swimmers at any given water velocity, disparities existed between endurance of typical swimmers (or regression predicted endurance of an "average" swimmer) and the best individual swimmer. Even the best individual swimmer, however, may not be the best representation of performance since bighead carp and silver carp are strong schooling species and individuals tested in isolation are deprived of behavioral and physical benefits of swimming in formation. Lastly – hybridization and introgression of Asian carp is extensive (Lamer et al. 2010) – and the effects of genotypic and phenotypic variation have not been assessed. To best apply laboratory swimming performance data to real-world problems like dispersal, establishment, and containment, intraspecific variation in swimming performance must be accurately and fully understood.

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