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Swimming Performance of Adult Asian Carp: Field Assessment Using a Mobile Swim Tunnel

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PURPOSE: Empirical swim speed data are needed to manage invasive bigheaded or "Asian" carps (Figure 1). However, such data are limited within the scientific literature. The large size and active temperament of the carp combined with current legislative restrictions concerning transport, make them difficult to acclimatize and test in traditional laboratory swim tunnels. Biologists from the Engineer Research and Development Center (ERDC) Environmental Laboratory (EL), with funding from the EL and the Aquatic Nuisance Species Research Program (ANSRP), designed and constructed a mobile swim tunnel for use along shorelines, minimizing transport, and eliminating the need for acclimitization. This enables immediate evaluation and on-site measurements of swimming performance in carp and other species.

BACKGROUND: The swimming speeds of adult bigheaded carps (*Hypophthalmichthys* spp) are needed for management of these invasive species in North American waterways. Such data can be used to assess rates of movement (Konagaya and Cai 1987; 1989), the likelihood of hydraulic containment or displacement (Hoover et al. 2012), and the risk of establishment (Cooke and Hill 2010). Substantial obstacles to completing these studies are: their maximum size when mature (> 1 m and > 40 kg), their characteristic activity (powerful free-swimmers and leapers), and the Lacey Act restrictions concerning the interstate transport of the species (Kolar et al. 2005; USFWS 2007, 2011). These obstacles preclude traditional study approaches, including: collecting wild fish or using hatchery-produced fish; transport to and acclimatization in laboratory holding tanks; repeated testing of naïve individuals in controlled swim trials in laboratory swim tunnels (Brett, 1964; Hoover at al. 2012).

An alternative approach to laboratory-based testing is to collect and test fish immediately on site using a portable test chamber. This technique, although uncommon, has been used successfully several times over a 30-year period to measure swimming endurance, critical swim speeds (maximum speed for a given time interval), and the metabolic rates of more than 20 taxa of fish, ranging in mass from 0.5 g to > 5 kg (Table 1). This technique has not been used to determine the swimming performance of bigheaded carps of any size. However, our unpublished studies conducted with Paddlefish (*Polyodon spathula*) in a specially designed mobile swim tunnel indicated that it might be used effectively with other large, active, free-swimming planktivores, including bigheaded carps. Consequently, we conducted a feasibility study using Silver Carp (*H. molitrix*) as the principal test subjects.

Figure 1. Bighead Carp, *Hypophthalmichthys nobilis* (upper) and Silver Carp, *Hypophthalmichthys molitrix* (lower) as photographed during testing in the ERDC Mobile Swim Tunnel.

Table 1. Field studies of fish swimming performance using a mobile swim tunnel to determine the critical swim speed (U_{crit}), oxygen consumption (VO_2), and endurance at a single velocity.

Tunnel Type	Tunnel Size (L)	Type of Fish Tested, Size of Fish	Primary Data	Reference
Flow-through	< 77	Riverine (17 spp), 4–62 cm, 0.5 g–2.2 kg	U_{crit}	Jones et al. 1974
Re-circulating	87	Char 1.2 kg max	VO_2	Bårdgard et al. 1989
Re-circulating	2400	Sharks (2 spp), 35–121 cm,0.1–5.2 kg	U_{crit}	Graham et al. 1990
Re-circulating	215 and 471	Pacific salmon, 3.5 kg max	U_{crit}	Farrell et al. 2003
Re-circulating	272 and 471	Salmon (2 spp.), 58–64 cm, 2.0–3.0 kg	U_{crit}	Lee et al. 2003
Re-circulating	2935	Asian carp (2 spp.), 56–92 cm, 1.7–8.3 kg	Endurance	This study

OBJECTIVES: This study was designed to perform the following:

1. Evaluate the utility of the ERDC Mobile Swim Tunnel for bigheaded carp swim studies.
2. Measure swim speeds of Silver Carp and develop a preliminary swimming endurance model.
3. Identify potential confounding variables for refinement of future studies.

ERDC Mobile Swim Tunnel. Swimming performance of fishes is evaluated in a mobile Brett-type swim tunnel (Figure 2) modified from a basic design that has been in use for more than half a century (Brett 1964). The tunnel is mounted on a 5.5 m by 2.0 m trailer that is rated for a 4536 kg load. The trailer is equipped with four leveling jacks (one at each corner), each rated for 3629 kg loads. The jacks enable the vertical adjustment of the trailer and tunnel so that it remains level when used on uneven ground. Water flow is generated by a motor driven propeller and internal turbulence is reduced by grids (flow filters) placed at the front and rear of the tunnel. Water flow through the unmodified working section of the tunnel (between grids) is turbulent. Turbulence can be further reduced within the tunnel with the addition of a box or tube-shaped insert. However, the additional grids restrict the swimming space available to the fish and can influence results (see Results section). The lid of the tunnel has four removable plugs that enable the placement of water quality probes and air lines. This allows for the continual monitoring and adjustment of oxygen levels. Collapsible stairs and a platform constructed from stainless steel and fiberglass provide high-traction access to all working surfaces. Stairs, platform, and rails, which disassemble and fold up during transport, conform to Occupational Safety and Health Administration (OSHA) standards.

Figure 2. ERDC Mobile Swim Tunnel at Forest Home Chute, a backwater – channel of the Mississippi River near Vicksburg, Mississippi. Inflow is located on the left side, outflow is located on the right side. The collimator grid can be seen at right.

The mobile tunnel was newly designed and constructed by the Environmental Laboratory (EL) Fish Ecology Team with advice obtained from hydraulic engineer Stephen Maynord (retired) from the Coastal Hydraulics Laboratory (Figure 2). It was constructed by the Fish Ecology Team, U.S. Army Engineer Research and Development Center (ERDC) model shop and by Electro Mechanical Solutions Inc. located in Vicksburg, Mississippi. Electronic controls were manufactured by the Stuart C. Irby Company located in Vicksburg, Mississippi. The tunnel is similar in concept and design to a previous ERDC-EL constructed laboratory swim tunnel (Hoover et al. 2011) but is more than double the volume of the original (2935 L vs 1200 L total volume) and is completely portable. The mobile swim tunnel is slightly larger than the 2400 L ocean-going tunnel used by the Scripps Institute of Oceanography for shark studies (Graham et al. 1990). The working section of the tunnel (1525 L) is substantially larger than that of the Scripps tunnel (428 L), and therefore can accommodate fish of substantially larger sizes (> 35 kg vs < 10 kg) (Table 1).

A 10 horsepower Varidrive US electrical 220 volt AC motor, capable of 1740 revolutions per minute (rpm), drives a stainless steel shaft. Attached to the motor shaft is a 40 cm diameter (40 cm pitch), three blade propeller which provides thrust and drives the water in a vertically elliptical pattern. Electricity for the motor is supplied from conventional outlets (e.g., public and private boat ramps) or a small gasoline-powered generator. The tunnel is constructed from thermoplastic components, primarily polycarbonate (Lexan). The tunnel is reinforced with stainless steel frames and perimeters to maintain structural integrity. Tunnel components consist of a polycarbonate tank in which the fish is tested (2.4 m L x 0.9 m W x 0.9 m H, 2029 L) and a circulation tube which receives outflow from the rear of the tank and propels it back into the front of the tank as inflow (44 cm diameter, 907 L). The propeller is located inside the bottom of the circulation tube and can be viewed through a polycarbonate window. The lid is attached with a piano hinge running along the entire length of the tank and is supported by two gas-shocks located at each end of the tank. The lid swivels up, and when fully opened, rests against two 91 cm steel braces locking it in place 25 cm from the wall of the tank. When closed, the lid contains two pivoting aluminum lock-downs, one at each end of the tank. The lock downs are used to secure the lid after it is closed and when the tank is in operation. Additionally, c-clamps are used to tightly seal the lid against a gasket along the top edges of the tank, minimizing water loss during operation. Polycarbonate grids (variable pore size) contain the fish and function as collimators (flow filters), reducing turbulence within the tunnel. The grids are positioned against the inflow and outflow ports at the front and rear of the tank providing a > 2000 L working section. Slots positioned 25 cm from the inflow and outflow ports allow for additional collimators to be inserted. The addition of the collimators reduces turbulence within the tank further, but restricts the working section to approximately 1525 L. Grid pore sizes range from 1.3–5.0 cm. Grids with smaller pore sizes provide greater reduction of turbulence and are used to contain smaller fish. Grids with larger pore sizes provide greater absolute flow and effectively contain larger fish.

The working section of the tank can be used as is, or with one of two polycarbonate inserts. The inserts create rectilinear flow and form a box creating a boundary-layer flow along the bottom reducing waves at the surface. The diameter of the tube is 46 cm and it is 229 cm in length. The tube provides a swimmable working section with a volume of 375 L and has two 86 cm square "collars" at each end allowing it to fit snugly in tank when the lid is closed. The tube is cut into two sections so that one section may be lifted for entry of the fish being tested. The box is a double platform having the same footprint as the working section of the tank. Spacers attached to the lower platform elevate it 23 cm off the bottom. Two 44 cm struts connect the lower platform and the upper platform enabling the box to be locked tightly in place between the lid and the floor of the tank when the tank lid is closed. When this occurs, the upper platform is submersed 23 cm below the lid. Volume of the working section is 934L.

TUNNEL CALIBRATION: For this study, flow was measured in the tank (with no inserts) at center depth and center width along a 5 point longitudinal transect using a Marsh-McBirney Flo-Mate 2000 electromagnetic flow meter (Marsh-McBirney Inc., Frederick, MD) at 50 rpm increments ranging from 50–500 rpm. Relationship between shaft speed (independent or predictor variable) and water velocity (dependent or response variable) was linear. The resulting models were:

$$\text{Mean Velocity} = 0.2768(\text{RPM}) - 1.4533,\ R^2 = 0.994\ (N = 50)$$

$$\text{Maximum Velocity} = 0.419(\text{RPM}) - 3.933,\ R^2 = 0.996\ (N = 10)$$

Because of the tight relationships between independent and dependent variables (R2> 0.98), regressions were used to extrapolate slightly (550 rpm) beyond the measured values (500 rpm) and estimate mean and maximum water velocities which we judged to be upper prolonged and burst speeds of silver (Table 2). Overall, each 50 rpm increment corresponded to an increase in mean velocity of 14 cm/s and in maximum velocity of 21 cm/s. Differences between mean and maximum velocity over the 50–150 rpm acclimation range, and the 400–550 rpm test range, increase from 5–19 cm/s and from 54 to 76 cm/s respectively. These data demonstrate the greater ranges that occur between average and maximum velocities at higher motor speeds and suggest greater turbulence at higher speeds.

Table 2. Test velocities based on the relationship between shaft speed (rpm) and measured flow (cm/s). Estimates are regression predicted values of water velocities in tank.

Phase	RPM	Estimated Mean Velocity (N = 5 at each RPM)	Estimated Maximum Velocity (N = 1 at each RPM)	Difference
Acclimation	50	12.4	17.0	5.4
	100	26.2	38.0	11.8
	150	40.1	58.9	18.8
Testing	400	109.3	163.7	54.4
	450	123.1	184.6	61.51
	500	136.9	205.6	68.62
	550	150.8	226.5	75.73

Study Site. The study was conducted 24–26 September 2013 at Forest Home Chute, 32º 45.340’ N; 91º 01.440’ W, a backwater north of Vicksburg, Mississippi that functions as a flowing secondary channel to the Mississippi River during high river stages. The chute runs parallel to the main channel of the Mississippi River, just north at km 724–729. At one time the chute may have been part of the main channel. However, it is now a permanent backwater that is impounded in several locations by cross-sectional berms containing culverts and is only seasonally connected throughout its length. It is wooded on both shorelines. Bigheaded carp enter the chute during high water and remain for varying periods depending on the eventual reconnection of the chute with the river (Varble et al. 2007). The Silver Carp contained in the chute were abundant, large, and sexually mature.

Methods. The swim tunnel was filled with river water each morning, prior to collecting fish, using portable water pumps and garden hoses. Water was circulated through the tunnel (28 cm/s) and aerated (compressed 0_2 from ceramic diffusers) prior to each test for a minimum of 10 minutes so that oxygen levels at the onset were > 7.00 mg/L. Water quality was measured in the morning and in the afternoon prior to first and final swim trials for the day using YSI or Quanta multi-parameter water quality meters.

Water from the chute was warm (> 26 C), moderately conductive (0.574-0.597 S/cm), and slightly alkaline (7.00-7.94 pH). Some treatment of the water was necessary for observer effectiveness and fish well-being (Figure 3). During the initial four swim trials, water was turbid (> 40 NTU) hindering any observations of fish movements (i.e., swimming behaviors, ventilation, fin motion). It was also hypoxic (< 4 mg/L), possibly impacting the fish physiogically (i.e., prolonged swimming is a combination of aerobic and anaerobic metabolism). In subsequent swim trials, water pumped from the chute was filtered as it entered the tunnel through a 200 L drum containing polyester fiber floss and foam “sponge” pads, reducing turbidity substantially (< 20 NTU). Once the water was in the tank, it was regularly aerated between trials with compressed oxygen to maintain normoxia (> 5 mg/L).

Table 3. Test conditions in the ERDC Mobile Swim Tunnel, 24-26 September 2013.

	24 Sep 2013	25 Sep 2013	26 Sep 2013
Water Temperature (C)	27.0–29.4	26.9–31.4	27.3–30.3
Specific Conductance (S/cm)	0.574–0.580	0.588–0.592	0.595–0.597
pH	7.00–7.40	7.10–7.86	7.64–7.94
Dissolved Oxygen (mg/L)	3.60–7.40	5.90–11.93	5.67–7.88
Turbidity (NTU)	41.2–66.4	12.1–18.8	8.70–11.1

Figure 3. Variation in water clarity. Turbidity was > 40 NTUs during first swim trials (upper) but can be reduced to < 20 NTUs with on-site filtration, and < 2 NTUs with the use of on-site tap water comparable in water quality (conductivity, pH, etc.) to river water (lower).

Carp were collected on site using monofilament gillnets. One to four nets were set and monitored continuously. When a "hit" was observed (i.e., sudden submergence of float line or jug), the net was "run" (i.e., lifted vertically from the water along its length). Non-targeted fish were removed and released. Targeted fish (Bighead Carp, Silver Carp) were placed in an on-board, aerated live-well. The live-well is a double hatched aluminum tank (1.8 m L, 0.5 m W, 0.5 m H) filled with river water to a depth of approximately 36.5 cm, for a total water volume of 330 L.

Catch time for the test fish was recorded and the fish immediately transported to shore for testing. Transport and holding time in the live well was 3–43 min, $\leq$10 min for 75% of all fishes caught and tested. On shore, the fish were removed from the live-well, placed in a wet soft mesh hammock (soft nylon netting for seines), carried to the swim tunnel (< 0.5 min duration), placed immediately in the tank, and time recorded. The lid of the tank was locked down, sealed using C-clamps, covered with opaque material (dark fabric or plastic), and the acclimation start time was recorded. If the fish behaved normally during the first few minutes of acclimation, the nets were removed from water. Any fishes caught were released, but a single fish was occasionally retained as a back-up subject for testing should the test fish in the tunnel fail to perform. These carp were initially confined in live nets tethered in shaded water but the fish became stressed and subsequently were not tested. Back-up fish were subsequently tethered around the peduncle using #48 tarred seine twine (a coated braided line made of nylon) and tied to a dock piling or tree root so that they could move about freely in shaded water. Based on their behavior, which was similar to un-tethered freshly-caught fish, this appeared to reduce stress. Those fish were released after 1–2 hours, or following the completion of the final swim trial of the day.

Testing procedure and analyses: There was no prioritization made for species or size; fish were tested in the order in which they were collected. The majority of fish (N = 10) were tested with no tank inserts so that they had a maximum volume of water in which to move. On the third day of the trial, some fish (N=4) were tested in the tube-insert.

Carp were acclimated for 30–45 minutes; 10–15 minutes each in progressively faster water (50, 100, and 150 rpm in tank without inserts; 0, 25, and 50 rpm with tube insert). After acclimation, fish were subjected to test velocity by increasing the motor speed by 100 rpm in intervals of 2–5 seconds. If a fish failed to orient headfirst into the flowing water (i.e., positive rheotaxis) or was impinged during acclimation or initial exposure to test velocity, it was provided a brief rest period (2–4 min) at a lower water velocity and testing resumed. If after three attempts the fish failed to orient, it was considered a non-performer and removed from tank. If it did orient into the flow throughout acclimation and after exposure to test speed, a stopwatch was used to time endurance. Endurance (aka time to fatigue) was measured as the period from initial exposure (i.e., to test velocity) to prolonged impingement (i.e., > 10 sec) on the rear grid.

Data were analyzed using Microsoft EXCEL. Summary statistics were calculated for all size based variables. These variables included Fulton's Condition Factor, a ponderal index which indicates the robustness of an individual subject (Carlander 1969). It is calculated as:

$$K_F = (100)(\text{Weight}/\text{Length}^3)$$

Weight is expressed as g and length as cm. Values approximate one with higher numbers indicating individuals of greater robustness for their size. Relationship between motor speed (independent or predictor variable) and fish endurance (dependent or response variable) was explored using scatter plots and regression analyses. Five regression approaches were used; exponential, linear, logarithmic, polynomial, and power. Best model (highest R^2) was chosen as the representative for the data.

RESULTS: Fourteen fish were tested during the study. Of those, thirteen were Silver Carp (> 560 mm TL, > 1.7 kg, and $K_F > 0.9100$) (Table 4) and one was a Bighead Carp (920 mm TL, 8.3 kg, and $K_F = 1.068$). One Silver Carp had a deformed mouth and skull suggesting recovery from a traumatic injury (Figure 4). Length and weight of that specimen was low (715 mm TL and 3.87 kg), indicative of a younger specimen, but condition was comparatively high ($K_F = 1.059$).

Performance (positive rheotaxis) was non-existent (0%) in the rectilinear flow of the smaller tube insert but high (90%) in the turbulent flow of the larger unmodified tank. Of the four Silver Carp (< 650 mm TL) tested in rectilinear flow, three inverted and became catatonic during the first 2–7.5 minute acclimation process (0 cm/s). One Silver Carp (835 mm TL) was initially rheotactic but inverted and began ventilating heavily after 10 minutes during the initial lowest acclimation velocity (25 cm/s). That fish was re-tested in the turbulent flow of the tank without an insert and performed well (0.35 minutes at 450 rpm). The subject recovered immediately following the test. Of the ten Silver Carp (nine naïve and one experienced) that were tested in the turbulent flow, nine were positively rheotactic throughout acclimation and when exposed to the test velocity. The single Bighead Carp was also positively rheotactic.

The endurance of Silver Carp in turbulent flow was negatively correlated with motor speed (Figure 5). Prolonged swimming (0.63-4.63 min) predominated at 400 and 450 rpm, equivalent to average water velocities of 109 and 123 cm/s respectively. Burst swimming (0.05-0.47 min) predominated at 500 and 550 rpm, or 137 and 151 cm/s respectively. Silver Carp used in the regression were, on average, 803 (15.9) mm TL, suggesting that the maximum predicted burst speeds, based on mean water velocity, were equivalent to 1.9 body lengths per second (BLS)(151 cm/s/80.3 cm/body length). Replication at any individual speed was limited, but variability was higher at 550 rpm than at 450 rpm. Endurance of the jawless Silver Carp at 450 rpm was the lowest of the four fish tested (0.63 min) but just slightly lower than the least of the three morphologically normal individuals (0.69–4.18 minutes). Endurance of the single Bighead Carp at 400 rpm was comparable to, but slightly lower than that of a Silver Carp (2.62 vs 4.63 minutes).

Table 4. Size of Silver Carp (N=12) tested in mobile swim tunnel, 24–26 September 2013. One Silver Carp was not measured.

Variable	Minimum	Mean (SD)	Maximum
Total Length (mm)	560	761.8 (87.7)	868
Weight (kg)	1.7	4.84 (1.60)	7.9
Condition (K_F)	0.9199	1.0468 (0.0772)	1.2065

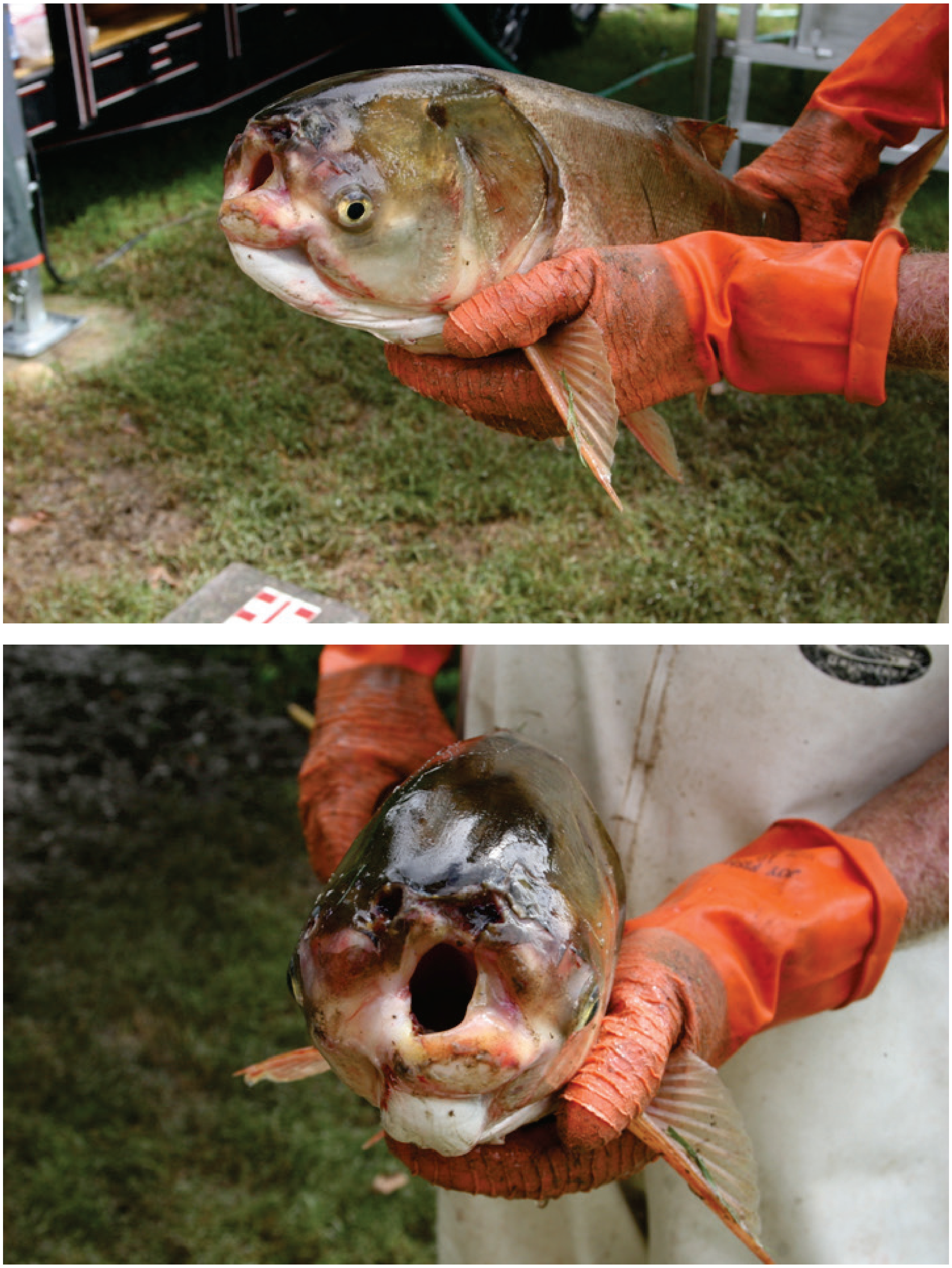

Figure 4. Morphologically anomalous Silver Carp. Upper jaw (maxillary and premaxillary) and portions of lower jaw (dentary) are absent; skull and nasal cavities are deformed.

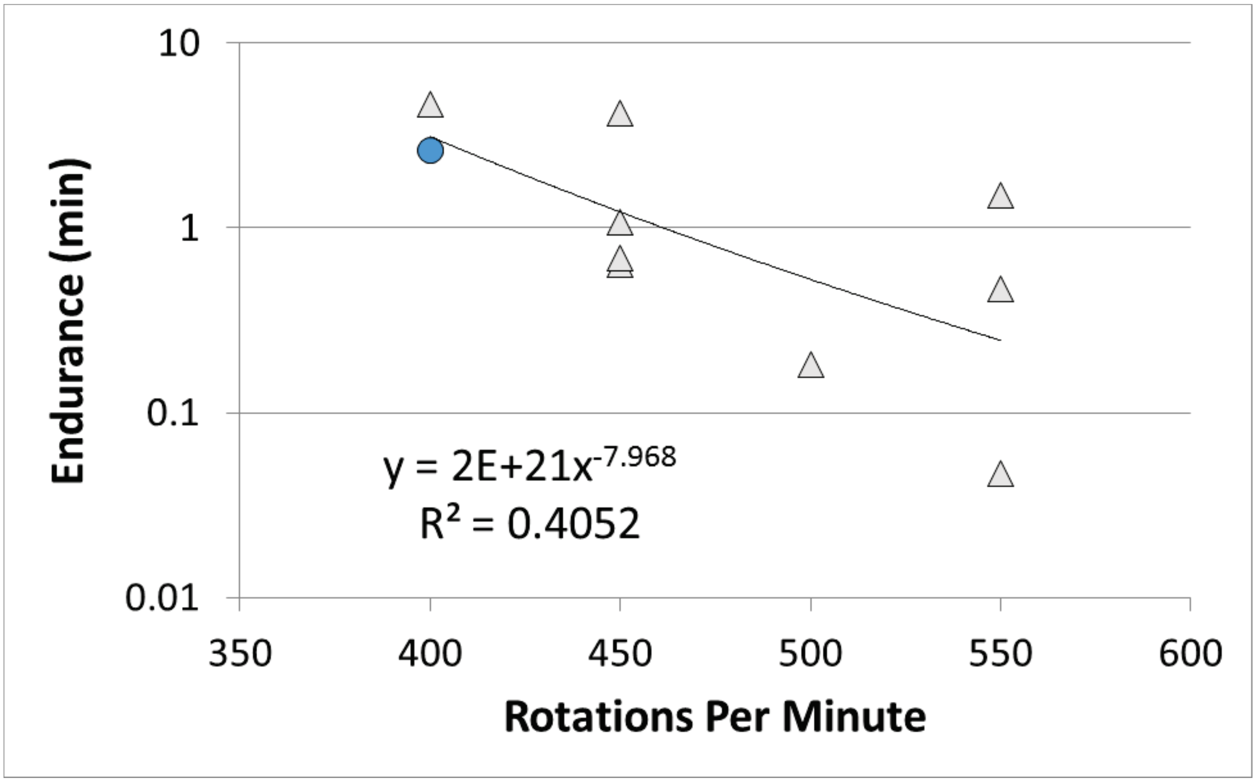

Figure 5. Relationship between motor shaft speed and swimming endurance of adult Asian carp. Bighead Carp, indicated by the blue circle, was not included in the regression analysis. Silver Carp, indicated by gray triangles, demonstrate declining endurance with increasing motor speed and water velocity. Mean and maximum water velocities corresponding to shaft speed are reported in Table 1.

Carp of both species were simple free-swimmers and recovered quickly from the test effects. Although the position in the tank varied among individuals, 80–100% of locomotion at the test velocity was free-swimming in the water column. Half of the fish tested tail-braced against the rear grid, but this occurred for only 5–10% of the time. Ten of the eleven fish tested in turbulent flow, recovered quickly from the test, extricating themselves from the grid on which they were impinged, re-orienting, and then resumed normal swimming activity. This usually took place in less than 1 minute.

DISCUSSION:

Utility of mobile swim tunnel. The portability of the mobile swim tunnel enabled fish to be tested in ambient conditions (e.g., light, water quality) and natural conditioning (e.g., diet, interactions with conspecifics) with minor logistic constraints. Travel time was low (in this case < 1 hour). The tunnel was easily towed and parked on flat ground. Set-up required only two people working approximately 45 minutes. Pumping and filtering river water were minor bottlenecks, but these issues could be avoided by strategically locating the tunnel near public or private boat access with available running water. The tank was filled with small water pumps submerged in the native water of the test fish. With the protocol described here, up to eight fish can be tested in a single day (depending on motor speeds tested) with trial times inversely related to test speed. This assumes that running water and electricity are available. When water must be pumped and electrical generators maintained, the number of fish tested will probably be reduced due to greater time requirements for filling the tunnel and maintaining power.

Because adult carp could be transported singly and expeditiously, handling stress was minimal and performance was high. In the un-modified tank, all but one fish exhibited characteristic locomotion and none died or became moribund during testing. In contrast, the majority of fish tested in the confines of the tube insert failed to perform. Reasons for these responses are uncertain. The water was well-mixed and therefore, oxygen depletion unlikely. The assumption can be made that the structural constraints on the lateral and vertical movements of the fish exceeded normal adaptive behaviors of the species. Wild-caught Asian carp it seems, are not pre-programmed to swim in a straight line or confined spaces.

Swimming performance of adult Asian carp. Although sample size was small, results remained consistent among individuals within the study and to those within other swim studies. Endurance decreased with increasing water velocity (Figure 5). This is consistent with most fish swimming studies including those of juvenile Asian carp (Hoover et al. 2012).

Because of its anomaly, the jawless Silver Carp (Figure 4) had a different hydrodynamic profile and challenges to normal ventilation. However, it was sufficiently resilient to exhibit endurance only slightly lower than one morphologically normal conspecific tested at that same speed (0.63 min vs 0.69 min) (Figure 5). The near-par performance of this fish is not without precedent. Jawless specimens of large cypriniform fishes, presumably the result of traumatic head injuries, have been recorded from the lower Mississippi River Basin for more than a century (Leidy 1875; Fuller 1951; George et al. 1996; Hoover and Killgore 2001). Species that are filter feeders like Silver Carp (e.g, buffalo suckers, *Ictiobus* spp.) exhibit only slightly lower condition and similar behavior to unimpaired conspecifics. Because morphological anomalies are not uncommon in Asian carp (JJH pers. obs.), and because morphological variation in Silver Carp can vary substantially, possibly due to hybridization (Lamer et al. 2010), it is important to evaluate morphological effects on swimming performance.

Swim speeds documented here are low when compared with those of other taxa (Videler and Wardle 1991). Maximum burst speeds for fish generally approach 10 BLS but the carp we tested were burst-swimming < 2 BLS. Bighead and Silver Carp may indeed be slow swimmers. Telemetry data for four carp suggest that predominant speeds were < 0.75 BLS (Konagaya and Cai 1987; 1989). If so, hydraulic containment or control of Asian carp seems feasible since comparatively moderate speeds (<< 200 cm/s) caused fatigue in this study (Figure 5).

Burst speeds are traditionally defined as those swim speeds maintained for < 30 sec. The upper range of these speeds, however, may be underestimated in this type of study. An endurance model based on carp tested over a wider range of water velocities could be more "hyperbolic" and less "linear" if endurance exhibits lower rates of decline at higher velocity increments (equivalent to burst speeds) than at lower velocity increments (equivalent to prolonged speeds). Such models have been documented for river fishes like Sockeye Salmon (Brett 1964) and Pallid Sturgeon (Adams et al. 1999). Also swim tunnels limit certain types of high-speed swimming. Burst-and-gliding, used by some pelagic fishes, is virtually impossible for a large fish confined in a swim tunnel. The length of a swim tunnel is insufficient to accommodate a fast start and endurance of more than a few seconds. Statistical and spatial limitations on estimates of burst speeds both underscore the necessity for testing carp over a wide range of water velocities (and environmental conditions) and for the need of developing alternative techniques for estimating burst speeds (outside the traditional swim tunnel methodology). In unrestricted spaces, maximum speeds were rarely employed but for a single Bighead Carp were estimated at approximately 750 cm/s or 6 BLS and for a single Silver Carp were estimated at approximately 450 cm/s or 10 BLS (Konagaya and Cai 1987).

Confounding variables. Data from this study provide only a snapshot of swimming capabilities for a few selected adult Asian carp. Fish were relatively uniform and their coefficients of variation in size and robustness were < 12% (Table 4). Swimming performance is influenced by a complex suite of factors. These may be intrinsic, such as fish size, reproductive condition, and prior exposure to flow (e.g., Adams and Parsons 1998; Boysen and Hoover 2009). They may also be extrinsic, such as water temperature and water quality (e.g., Fuiman et al. 1997; Lee et al. 2003). The fish tested here were similar in size and robustness, but were tested in water quality that varied from one day to the next, and over the course of any single day (Table 3). Variation in swimming performance was to some extent constrained by size but may have been influenced by other factors. To develop representative models of swimming performance, tests with larger numbers of fish representing individuals of different ages, histories, form, and physiological condition are necessary. It is recommended that the water quality should be standardized to whatever extent is practical.

RECOMMENDATIONS:

1. <u>Role of Morphology on Swimming Performance</u> – Prior studies conducted with adult (Konagaya and Cai 1987; 1989) and juvenile Asian carp (Hoover et al. 2012) demonstrate pronounced differences in swim speeds between species and among size classes. Results of this study (Figure 5), demonstrate that Bighead Carp and an anomalous Silver Carp had comparable endurance and behavior to phenotypically normal Silver Carp. Given recent reports of hybridization and introgression of North American bigheaded carps (Lamer et al. 2010) and frequent catches of fish with missing or anomalous fins (JJH, pers. obs.), there is a need to identify morphological features associated with swimming performance so that managers can assess risk presented by specific populations with specific morphologies.

2. <u>Influence of Confounding Environmental and Demographic Variables</u> - Turbidity, pH, and dissolved oxygen varied appreciably during the tests (Table 3), although no impacts on swimming performance were obvious. Gender and reproductive condition were not assessed, but size was relatively uniform. Future studies should minimize variation in the former and maximize variation in the latter within sampling episodes and repeat tests seasonally when environmental condition are likely to vary long-term. This will lead to a better understanding of the respective roles of extrinsic and intrinsic variables on swimming performance. Comprehensive examinations of the fish is also recommended to determine gender, reproductive stage, and age.

3. <u>Role of Physiological Recovery</u> – Most of the fish tested recovered rapidly. When evaluating efficacy of hydraulic barriers on the exclusion of Asian carp, managers must assume that displaced fish will recover in close proximity to the barrier and will in all likelihood continue to challenge it. Exhaustion (from collective effects of repeated swimming challenges) will, to some extent, be overcome by training effects (from repeated exposure to the same mosaic of

hydraulic conditions). Managers should consider varying flows of short-term duration to maximize likelihood of fatigue and minimize effects of conditioning (i.e., learning, training).

4. Fine-Grain Evaluations of Swimming Behavior – This study assumes that that there is a single velocity representative of the tank at a given rpm. It ignores small scale variation in water velocity and direction characteristic of turbulent flow that results when water from a 46 cm circular pipe discharges into a 91 cm rectangular tank (Figure 2). Fine-grain hydraulic mapping of the test chamber coupled with short-term spatial distributions of the fish would provide better functional responses from the fish to variation in flow.

5. Alternative approaches to Burst Speed Determinations - Quantification of burst speeds is critical for the successful containment of carp. Burst speeds documented here (approximately 2 and 6 BLS) are conspicuously lower than maximum burst speeds for fish of comparable size and form which approximate 10 BLS (Videler and Wardle 1991). Alternative techniques should be explored for quantifying the burst speeds of carp. These techniques could include videography of fish in the field and in laboratory macrocosms.

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