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Hydrodynamic fish modeling for potential-expansion evaluations of exotic species (largemouth bass) on waterway tunnel of Andong-Imha Reservoir

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Abstract

Background: The objectives of this study were to establish a swimming capability model for largemouth bass using the FishXing (version 3) program, and to determine the swimming speed and feasibility of fish passage through a waterway tunnel. This modeling aimed to replicate the waterway tunnel connecting the Andong and Imha Reservoirs in South Korea, where there is a concern that largemouth bass may be able to pass through this structure. As largemouth bass are considered an invasive species, this spread could have repercussions for the local environment.

Results: Flow regime of water through the waterway tunnel was calculated via the simulation of waterway tunnel operation, and the capability of largemouth bass to pass through the waterway tunnel was then estimated. The swimming speed and distance of the largemouth bass had a positive linear function with total length and negative linear function with the flow rate of the waterway tunnel. The passing rate of small-size largemouth bass (10–30 cm) was 0% at a flow of 10 m^3/s due to rapid exhaustion from prolonged upstream swimming through the long (1.952 km) waterway tunnel.

Conclusions: The results of FishXing showed that the potential passing rate of large size largemouth bass (>40 cm) through the waterway tunnel was greater than 10%; however, the passage of largemouth bass was not possible because of the mesh size (3.4 × 6.0 cm) of the pre-screening structures at the entrance of the waterway tunnel. Overall, this study suggests that the spread of largemouth bass population in the Imha Reservoir through the waterway tunnel is most likely impossible.

Keywords: Invasive species, Largemouth bass (*Micropterus salmoides*), Waterway tunnel, Fish swimming capability, Inflow rate

Background

Largemouth bass (*Micropterus salmoides*) were introduced into South Korea in 1973 from Louisiana, USA, with the intent of providing a sustainable food source. However, their population has rapidly increased in the ecosystems of rivers and reservoirs across the country and consequently has exerted great influence on freshwater food webs (Lee et al. 2008; Kim et al. 2013). Largemouth bass prey upon native fishes, amphibians, crustaceans, and other organisms, and this high predation pressure, coupled with the absence of any known natural enemies, has enabled largemouth bass to occupy the position of top predator in freshwater environments. Furthermore, largemouth bass inhabit large reservoirs and rivers in high densities because they can spawn up to 100,000 eggs and the males protect their eggs and young (Wheeler and Allen 2003; Almeida et al. 2012). Because of the threat to food webs posed by the feeding habits of largemouth bass, their rapidly growing population, and the lack of natural enemies, in 1998 the Ministry of Environment designated largemouth bass as an invasive alien species that disrupts local ecosystems.

Cases of ecological disturbances due to high predation pressure and rapid population growth of largemouth bass have been reported in many countries across the world. In Guatemala, the majority of indigenous fish species were reported to have disappeared from Atitlan

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Reservoir after the introduction of largemouth bass (Zaret and Paine 1973); in South Africa, three indigenous species were reported to have been extirpated by largemouth bass (Hickley et al. 1994); and Cuba also witnessed a considerable decrease in the number of individuals of indigenous fish species after the introduction of largemouth bass, which increased the number of malaria mosquitoes and consequently raised malaria infection rates among residents (Lasenby and Kerr 2000). Furthermore, such ecological disturbances caused by largemouth bass have been reported at a global level, including Canada, Japan, and Europe (Lasenby and Kerr 2000; Yasunori and Tadashi 2003; Wasserman et al. 2011; Almeida et al. 2012). In fact, largemouth bass were originally endemic only to the eastern half of the United States, and their spread to other regions within the country has also resulted in ecological disturbances (Findlay et al. 2000; Brown et al. 2009). The detrimental spread of largemouth bass directly affects freshwater food webs, thereby reducing species richness and biodiversity, and their potential for damaging the integrity of aquatic ecosystems has led to widespread discussion (and disagreement) with regard to the best methods to manage this ecological challenge.

In general, categories of fish swimming are classified into three types: sustained swimming, prolonged swimming, and burst swimming (Beamish 1978). Sustained swimming is defined as having the capability of swimming over 200 min without muscle fatigue, an adequate energy supply for metabolism, and the ability to excrete metabolic wastes before they accumulate. Prolonged swimming refers to swimming for a time ranging between 20 s and 200 min with metabolic waste accumulating in the muscles. In this type of swimming, muscle fibers turn pink (fast oxidative glycolytic when aerobic) or white (fast glycolytic when anaerobic) due to low energy supply. In particular, white muscle fibers have a high-energy efficiency but rapidly fatigue after all energy is consumed (Webb 1975). Burst swimming involves swimming for a short length of time (≤20 s) when maximum speed is required. After burst swimming under excessive energy consumption, a large amount of intracellular waste accumulates (Colavecchia et al. 1998). Most fish species perform burst swimming when entering or exiting a waterway tunnel by stiffening the caudal fin and giving strong horizontal thrusts to achieve the greatest propulsive force (Nursall 1962). Burst swimming requires a long recovery time, which varies depending on the fish species, ranging from several hours to several days, and can even be fatal to some fish (Black et al. 1962). For example, when trout are forced to swim intensively for 6 min, 40% die, and almost 100% die after additional forced swimming of 4–6 h (Wood et al. 1983). Largemouth bass have a carangiform body that minimizes friction with water, enabling them to swim rapidly. They can swim most efficiently in water temperatures of 10–25 °C, which corresponds to the water temperature of summer season in South Korea, and their swimming capability is rapidly reduced at temperatures ≥30 or ≤10 °C (Beamish 1978, Hammer 1995; Brown et al. 2009).

In South Korea, over two thirds of the annual precipitation occurs during the summer monsoon period and because of these concentrated rainfalls, a large portion of national water resources flows into the ocean without being efficiently processed through stable water resource management (Ahn and Kim 2010; Yum 2010). To ensure secure water resource management and address fundamental water problems such as floods and droughts, growing attention has been paid to the integrated management of neighboring dams (Lee 2005; Kang et al. 2007). As part of such nationwide projects, the Andong-Imha Integrated Project was implemented in the Andong and Imha Reservoirs. The purpose of the Andong-Imha Integrated Project was to connect the Andong and Imha Reservoirs with a waterway tunnel to secure additional water resources by reducing spillway discharge during flood events and improve downstream water quality. However, this waterway tunnel could also be used as a passage by largemouth bass, an invasive species threatening native species and disrupting local ecosystems, thereby accelerating their spread. According to the study *Monitoring of Invasive Alien Species Designated by the Wildlife Protection Act* by the National Institute of Environmental Research (Ministry of Environment, Korea 2013), the Andong Reservoir has a large population of largemouth bass and the Imha Reservoir has not been invaded by this species. If these two reservoirs are connected, there is a concern that largemouth bass could be introduced into the Imha Reservoir, which would result in a disturbance of its aquatic ecosystems.

This study was conducted to establish a swimming capacity model of largemouth bass using the computer program FishXing (Love et al. 1999; Furniss et al. 2006), which was developed to assess the potential for fish passage through an artificial structure depending on water flow rate and velocity, and to calculate the swimming speed of largemouth bass based on body length and inflow rate into the waterway tunnel. Additionally, swimming distance was calculated using these swimming speeds to determine the feasibility of largemouth bass passing through the waterway tunnel in order to derive the optimal waterway tunnel management strategy. The rate of water flow at the inlet that would inhibit their entrance into the waterway tunnel was also determined, with the overall goal of finding ways to inhibit the spread of largemouth bass and conserve local ecosystems.

Methods

Overview of the survey sites and waterway tunnel

The Andong Reservoir study site is located upstream at the northernmost extent of the Nakdong River, approximately 340 km from its estuary. The Nakdong River

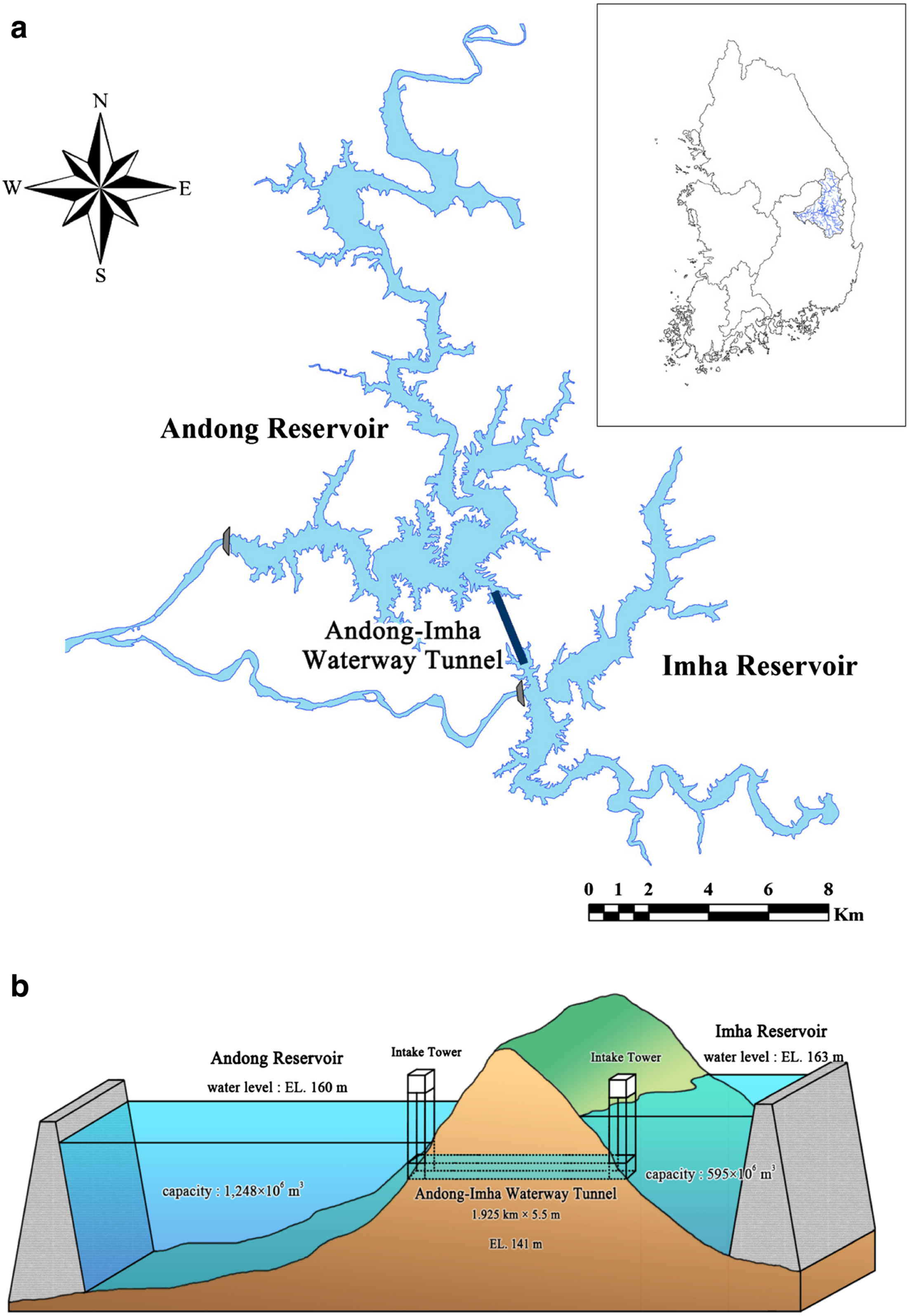

Fig. 1 Locations of the Andong and Imha Reservoirs (**a**) and general characteristics and detailed schematic of the waterway tunnel (**b**)

Table 1 Empirical model (regression) for the swimming speed of largemouth bass (B_{SS}, m/s) using water temperature and body length (T_L, cm) (Beamish, 1970)

Habitat water temperature (°C)	Largemouth bass swimming speed (B_{SS}, m/s)	Period of study sites
10	$\text{Log } B_{SS} = 0.9342 + 0.0303\ T_L$	April/December
15	$\text{Log } B_{SS} = 1.2068 + 0.0210\ T_L$	May/November
20	$\text{Log } B_{SS} = 1.4465 + 0.0137\ T_L$	June–July/October
25	$\text{Log } B_{SS} = 1.5023 + 0.0117\ T_L$	August–September
30	$\text{Log } B_{SS} = 1.5008 + 0.0120\ T_L$	Expected water temperature
35	$\text{Log } B_{SS} = 1.3968 + 0.0139\ T_L$	

plays a vital role as a source of household and industrial water for major industrial cities located in the southern part of the East Sea, including Busan, Pohang, and Ulsan. The Andong Reservoir occupies 6.6% of the total Nakdong drainage area and has maximum and mean water depths of 60 and 19.4 m, respectively, a total drainage area of 1584 km^2, full-water surface area of 51.5 km^2, and reservoir capacity of 1,248,000,000 m^3. The Imha Reservoir is a multipurpose artificial reservoir constructed next to the Andong Reservoir to facilitate efficient development of water resources, reduce flood-induced damages in downstream areas, improve water quality, and provide an alternative source of water for the industries in the mid- and downstream areas of the Nakdong River. The reservoir occupies 5.7% of the total Nakdong drainage area and has a total drainage area of 1361 km^2, full-water surface area of 26.4 km^2, and reservoir capacity of 595,000,000 m^3 (Fig. 1).

While the two reservoirs have drainage areas of similar size, the water storage capacity of the Imha Reservoir is less than half that of the Andong Reservoir. In other words, the low ratio of water storage capacity to drainage area of the Imha Reservoir makes it vulnerable to water release through spillways due to rapidly rising water levels whenever its drainage area is inundated. The Andong-Imha waterway tunnel was installed to connect the two reservoirs in order to ensure stable procurement of water resources and their efficient management by preventing spillway losses (Fig. 1). The waterway tunnel is a round tunnel with a total length of 1.925 km, inner diameter of 5.5 m, and invert elevation (EL) of 141 m. The structure procures additional water resources by inducing the water released from the Imha Reservoir to flow into the Andong Reservoir. Also, pre-screening structure (mesh size 3.4 × 6.0 cm) at the entrance of the waterway tunnel was installed to block waste and local fish over 40 cm into the waterway tunnel.

Calculation of the water flow through the waterway tunnel

Water flow from one reservoir to the other through the Andong-Imha waterway tunnel depends on the water level of the two reservoirs, with water flowing from the higher to the lower water level. The quantity of water flowing through a waterway tunnel widely varies depending on the physical and hydrological characteristics of the waterway tunnel, including length, head loss, difference of water head, and flow rate. For calculating the inflow rate, surface water levels of both reservoirs are taken into consideration, because water level determines whether the water flowing within the waterway tunnel has the characteristics of pipe flow or open channel flow. If the reservoir water level is higher than the invert elevation of the waterway tunnel (i.e., in the case of pipe flow), then the Darcy–Weisbach formula can be applied as follows:

Table 2 Inflow rate (m^3/s) into the waterway tunnel depending on water head difference and inner diameter of the waterway tunnel

Water head difference (m)	Inner diameter of the waterway tunnel									
	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	10 m
1.0	15.1	23.4	29.9	35.3	39.8	43.7	47.0	50.0	52.5	54.8
2.0	21.4	33.1	42.3	49.9	56.3	61.7	66.5	70.6	74.3	77.6
3.0	26.2	40.6	51.8	61.1	68.9	75.6	81.4	86.5	91.0	95.0
4.0	30.2	46.9	59.9	70.5	79.6	87.3	94.0	99.9	105.1	109.7
5.0	33.8	52.4	66.9	78.9	89.0	97.6	105.1	111.7	117.5	122.6
6.0	37.0	57.4	73.3	86.4	97.4	106.9	115.2	122.4	128.7	134.3
7.0	40.0	62.0	79.2	93.3	105.2	115.5	124.4	132.2	139.0	145.1
8.0	42.7	66.3	84.6	99.8	112.5	123.5	133.0	141.3	148.6	155.1
9.0	45.3	70.3	89.8	105.8	119.3	131.0	141.0	149.9	157.6	164.5
10.0	47.8	74.1	94.6	111.5	125.8	138.0	148.7	158.0	166.2	173.4
15.0	58.5	90.8	115.9	136.6	154.1	169.1	182.1	193.5	203.5	212.4
20.0	67.6	104.8	133.8	157.7	177.9	195.2	210.2	223.4	235.0	245.3

Table 3 Number of days and quantity of water flow through the waterway tunnel estimated via simulation

	Number of days of water flow			Quantity of water flow ($\times 10^6$ m^3)		
	Total	Flood period	Dry period	Total	Flood period	Dry period
Flow through the waterway tunnel	9349 (85.3%)	2351	6998	8214 (100.0%)	4152	4062
Transferring from I_R to A_R	7818 (71.3%)	2016	5802	7552 (91.9%)	3859	3693
Transferring from A_R to I_R	1531 (14.0%)	335	1196	661 (8.1%)	293	368
Non-flow through the waterway tunnel	1609 (14.7%)	–	–	–	–	–

Inner diameter of the waterway tunnel: 5.5 m; invert elevation: EL 141 m
A_R Andong Reservoir, I_R Imha Reservoir

$$H_f = f \times \frac{L}{D} \times \frac{V^2}{2g} \tag{1}$$

where H_f is head loss (m); f is friction factor; L is length of pipe work (m); D is inner diameter of pipe work (m); V is average velocity of water flow within the waterway tunnel (m/s); and g is acceleration due to gravity (m/s^2).

In the case of open channel flow in which the reservoir water level is lower than the invert elevation, the Manning formula was applied as follows:

$$V = \frac{1}{n} {R_h}^{2/3} S^{1/2} \tag{2}$$

$$Q = A \times V = (\theta - \sin\theta)\frac{D^2}{8} \times \frac{1}{n} {R_h}^{2/3} S^{1/2} \tag{3}$$

where V is average velocity of water flow within the waterway tunnel (m/s); R_h is hydraulic radius (m); S is energy slope (m/m); Q is inflow rate (m^3/s); A is cross-sectional area of pipe work (m^2); and n is Manning's roughness coefficient.

Hydrodynamic modeling of the swimming capability of largemouth bass

The FishXing program is a hydrodynamic model for dam engineers, hydrologists, and fish biologists that evaluates the design of waterway tunnels for fish passage. The FishXing program demonstrates the complexities of waterway tunnel hydraulics and fish swimming performance for a certain fish species and is frequently used to identify waterway tunnels that impede fish passage, which can lead to the removal of dams or fish passage barriers. Fish swimming capabilities against waterway tunnel hydraulics across a range of expected stream discharges are estimated, in addition to comparing flow regime, velocities, and leap conditions according to the specific swimming abilities of a fish species.

Fish swimming capability is determined by many variables, including body length, weight, time to exhaustion, water temperature, and water flow rate. The following fish swimming speed formula used in the FishXing program was developed by Hunter and Mayor (1986):

$$V = \mathrm{a} L^b t^{-c} \tag{4}$$

where V (m/s) is swim speed of fish relative to the water; L (cm) is body length of the fish; t (min) is time to exhaustion of the fish; and a, b, and c are regression constants.

Fish swimming capability analysis and modeling involve the calculation of the migration potential of fish through an artificial structure based on the flow regime of water and the range of swimmable water. If an artificial structure cannot be traversed, factors contributing to the failure to pass are analyzed. In addition, the swimming distance, swimming type, and time it takes for fish to pass through the artificial structure are calculated. Based on these results, we compared fish swimming capability based on the size of individuals and flow rate and analyzed the comparison results.

Variables and characteristics of hydrodynamic model

Variables used for the calculation of the swimming capability of largemouth bass can be grouped into 3 categories: (1) fish-related data such as body length, weight, swimming speed, and time to exhaustion; (2) waterway tunnel-related data such as dimensions, materials, and slope; and (3) hydraulic-hydrological data such as minimum and maximum flow rate and water depths of the waterway tunnel inlet and outlet.

The swimming capability of individuals by size can be analyzed using fish-related data such as body length, weight, sustained and burst swimming speeds, and optimal habitat water temperature. We entered the waterway data necessary (length, diameter, material, shape, and gradient of the waterway) for fish to migrate upstream or move from pool to pool, in order to analyze the factors influencing the upstream migration of fish.

Table 4 Number and percentage of days by inflow rate into the waterway tunnel estimated via simulation

	Inflow rate (m^3/s)							Flow	Non-flow	Maximum inflow rate (m^3/s)
	>100	>80	>60	>40	>20	>10	≤10			
Number of days of water flow	37	83	98	280	717	853	7281	9349	1609	135.0
Ratio (%)	0.3	0.8	0.9	2.6	6.5	7.8	66.4	85.3	14.7	

Finally, by analyzing the hydraulic-hydrological data, such as minimum and maximum flow rate and water depths in the inlet and outlet, we determined the effects of varying flow velocity and rate on the migration of fish.

In order to calculate the swimming capability and maximum swimming speed of largemouth bass, we first calculated the swimming speed by size of individuals using the empirical model (regression) proposed by Beamish (1970) (Table 1). Swimming distance and maximum possible speed were then calculated using the FishXing program based on the pre-calculated swimming speed.

Results and discussion

Inflow rate of waterway tunnel via simulation

The inflow rate depended on the inner diameter of the waterway tunnel and the difference in water head between the two reservoirs (Table 2). The water inflow rate into tunnel tended to increase proportionally as the waterway tunnel inner diameter and water level difference between two reservoirs. The peak inflow rate into the Andong-Imha waterway tunnel (ø 5.5 m) was shown to be 135.0 m^3/s at the water head difference of 10.92 m.

The results of the simulation run of waterway tunnel operation are as follows. The number of days that water flowed from the Imha Reservoir to the Andong Reservoir and in the reverse direction were 7818 (71.3%) and 1531 days (14.0%), respectively (Table 3), and water flow during the flood period (June 21 to September 20) and dry period were 21.5 and 63.9%, respectively. In terms of the quantity of water that passed through the waterway tunnel, water flow from the Imha Reservoir to the Andong Reservoir and in the opposite direction accounted for 91.9 and 8.1%, and the total water flow during the flood and dry periods accounted for 50.5 and 49.5%, which was not a significant difference. Comparing the number of water flow days by inflow rate, water flowed at an inflow rate of ≥100 m^3/s on 37 days (0.3%), with the highest inflow rate being 135.0 m^3/s. The inflow rate ranged from 10 to 20 m^3/s on 853 days (7.8%), and the inflow rate of ≤10 m^3/s accounted for the majority of time (7281 days, 66.4%) (Table 4).

Swimming speed of largemouth bass

Table 5 Swimming speed of largemouth bass (m/s) by total length (cm) and water temperature (°C)

Fish growth stage	Total length	Water temperature (°C)					
		10 °C	15 °C	20 °C	25 °C	30 °C	35 °C
Juvenile to young stage	10 cm	0.17	0.26	0.38	0.42	0.42	0.34
	15 cm	0.24	0.33	0.45	0.48	0.48	0.40
	20 cm	0.31	0.42	0.53	0.54	0.55	0.47
Adult stage of medium size	30 cm	0.44	0.69	0.72	0.71	0.73	0.65
	35 cm	0.56	0.87	0.84	0.82	0.83	0.76
	40 cm	0.68	1.11	0.99	0.93	0.96	0.90
Adult stage of large size	50 cm	0.84	1.81	1.35	1.22	1.26	1.24
	55 cm	0.96	2.30	1.58	1.40	1.45	1.45
	60 cm	1.03	2.93	1.86	1.60	1.66	1.70

The swimming speed increased as individuals grew in size. At a water temperature of 25 °C, which is the optimal habitat water temperature for largemouth bass, the swimming speed ranged between 0.42 (individuals with 10 cm body length) and 1.60 m/s (60 cm), demonstrating remarkable size-dependent differences (Table 5). According to a study conducted by Hocutt (1973), at water temperatures of 15–30 °C, juveniles of 5–10 cm body length swam at 0.3–0.5 m/s and adult fish of 20–25 cm body length swam at 0.5–0.6 m/s, concordant with the results of the present study. Additionally, Bell (1991) reported that the prolonged swimming speed corresponded to 50–70% of the burst swimming speed. When this percentage was applied to the results of the present study, the burst swimming speed of 10-cm juveniles was 0.8 m/s, and that of 20–25-cm

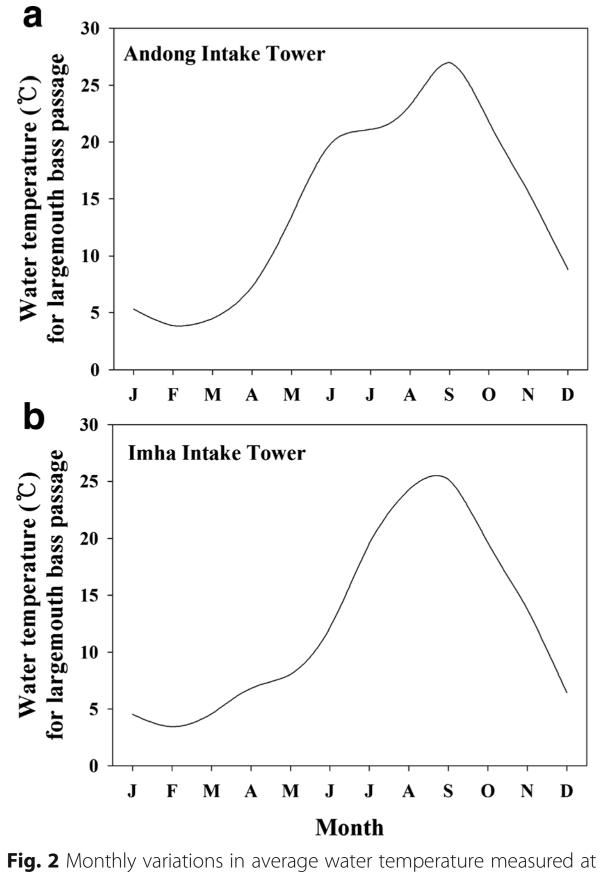

Fig. 2 Monthly variations in average water temperature measured at the water intake tower of the Andong Reservoir (**a**) and Imha Reservoir (**b**) above the invert elevation of the waterway tunnel (EL 141 m)

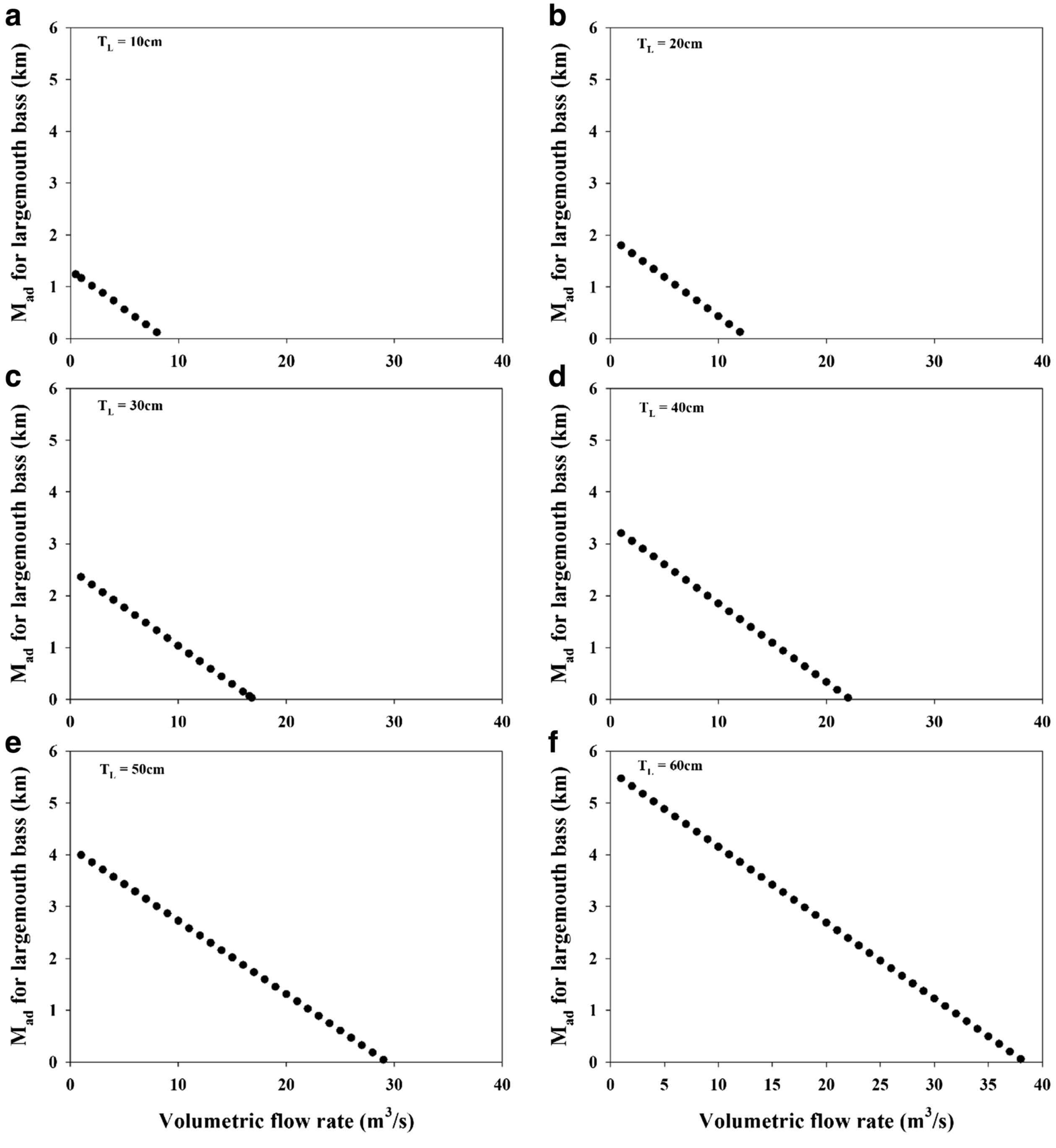

Fig. 3 Maximum attainable distance (M_{ad}) for largemouth bass by size of individuals (total length (cm), T_L) and inflow rate

individuals was 1.1–1.3 m/s, which was consistent with the results of Bell (1991).

In addition to the size of individuals and the inflow rate into the waterway tunnel, the distribution pattern of water temperature was also a key factor influencing fish swimming capability. At the Andong and Imha Reservoirs study sites, the drinking water source had a high content of dissolved oxygen (DO) and low carbon dioxide concentration and salinity and was thus considered to have no to negligible toxic components (An et al. 2006; Park and Chung 2014). Therefore, of all factors presented by Beamish (1978) and physical constraint factors, including water temperature distribution, solar radiation, nutrient composition, DO concentration, carbon dioxide concentration, and salinity, water temperature was considered to exert the greatest influence on fish swimming performance.

Largemouth bass showed widely varying swimming performance at different water temperatures. For example, 10-cm juveniles swam at 0.17 m/s at 10 °C and 0.42 m/s at 25 °C. The swimming capability and maximum swimming speed of largemouth bass were found to increase linearly in the temperature range of 10–30 °C and decrease in the range of 30–40 °C (Beamish 1970). Large individuals more markedly demonstrated the temperature-dependent difference, with some individuals showing the highest swimming speed at temperatures lower than 25 °C (Table 5).

The average water depth measured at the water intake tower of the Andong Reservoir was 7.7 m above the invert elevation of the Andong-Imha waterway tunnel (EL 141 m), and the average, lowest, and highest water temperatures were measured at 13.8, 3.7, and 28.3 °C, respectively. Equivalent values for the Imha Reservoir were 9.6, 3.0, and 29.11 °C (Fig. 2). The results presented in Table 5 revealed that fish swimming speed rapidly declined by over 30% at water temperatures of 10 °C or less and consequently, the potential swim distance also decreased.

Swim distance of largemouth bass into the waterway tunnel

The distance covered by largemouth bass for 60 min was calculated based on the swimming speed of largemouth bass at the lowest inflow rate of 1 m^3/s. The results showed that the 10-cm largemouth bass swam 1.17 km upstream, which linearly increased to 1.80, 2.36, 3.21, 3.99, and 5.47 km, as the size of individuals grew to 20, 30, 40, 50, and 60 cm, respectively.

According to the results of swim distance based on the inflow rate into the waterway tunnel, the 10-cm largemouth bass that swam 1.17 km at an inflow rate of 1 m^3/s tended to cover short distances as the inflow rate increased and could not pass through the waterway tunnel at inflow rates of 9 m^3/s or more. The same result was found for the 20-cm largemouth bass that swam 1.8 km at inflow rates of 13 m^3/s or more. The length of the Andong-Imha waterway tunnel is 1.925 km, which was too long for the 10- to 20-cm largemouth bass to traverse, even at the lowest inflow rate of 1 m^3/s. Smaller individuals reached a state of exhaustion more rapidly than larger individuals, making it impossible to pass the waterway tunnel. The minimum size of individuals capable of swimming through the waterway tunnel was 25 cm (Fig. 3).

At inflow rates of ≤3 m^3/s, the 30-cm largemouth bass were capable of swimming 2 km or more (i.e., passing the waterway tunnel), with a time requirement of 49–57 min. However, they could not pass the waterway tunnel at inflow rates of 4 m^3/s or more. At inflow rates of 17 m^3/s or higher, migration via the waterway tunnel was determined to be nearly impossible.

According to the results regarding the time requirement for the passage of the waterway tunnel, the 40-cm largemouth bass took 37 min to traverse the waterway tunnel at an inflow rate of 1 m^3/s, the 50-cm largemouth bass took 28 min, and the 60-cm largemouth bass took 21 min, which demonstrated that the larger the individuals, the less time it took them to cross the waterway tunnel. The time requirement for passage increased as the inflow rate increased. The 40-cm largemouth bass took 37–60 min at an inflow rate of 9 m^3/s or less, the 50-cm largemouth bass took 28–56 min at 15 m^3/s or less, and the 60-cm largemouth bass took 21–56 min at 24 m^3/s or less (Fig. 4).

Modeling analysis of the swimming capability of largemouth bass

According to the results of FishXing, the success potential for 10-cm largemouth bass migrating via the waterway tunnel was analyzed to be 0%, and the lowest and highest inflow rates allowing them to enter and swim along the waterway tunnel were estimated at 1 and 9 m^3/s, respectively (Fig. 5). The success potential for the 20-cm largemouth bass was also analyzed to be 0%, with the highest inflow rate allowing them to enter and swim along the waterway tunnel being 13 m^3/s. Largemouth bass with 30-cm body length could migrate via the waterway tunnel at the inflow rate of 3 m^3/s or less, with a success rate of 7%. The success rates for the 40-, 50-, and 60-cm largemouth bass were 10.9% at 8 m^3/s or less, 15% at 15 m^3/s or less, and 20% at 24 m^3/s or less, respectively. At higher inflow rates (25–38 m^3/s), larger largemouth bass were found to be capable of entering the waterway tunnel and swimming, but migration from the Andong Reservoir to the Imha Reservoir and vice versa was found to be impossible. Analysis also

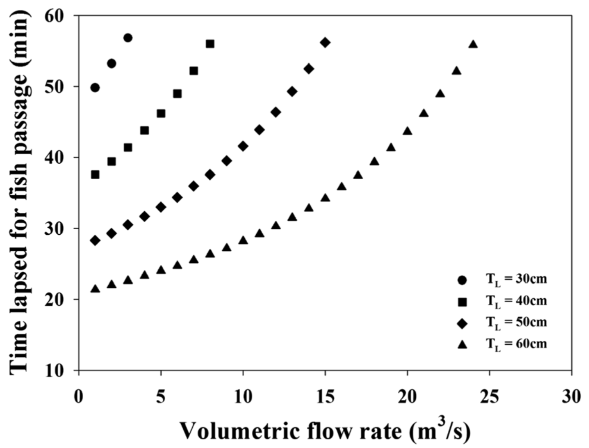

Fig. 4 Time lapsed for waterway tunnel passage by inflow rate and size of individuals (total length (cm), T_L)

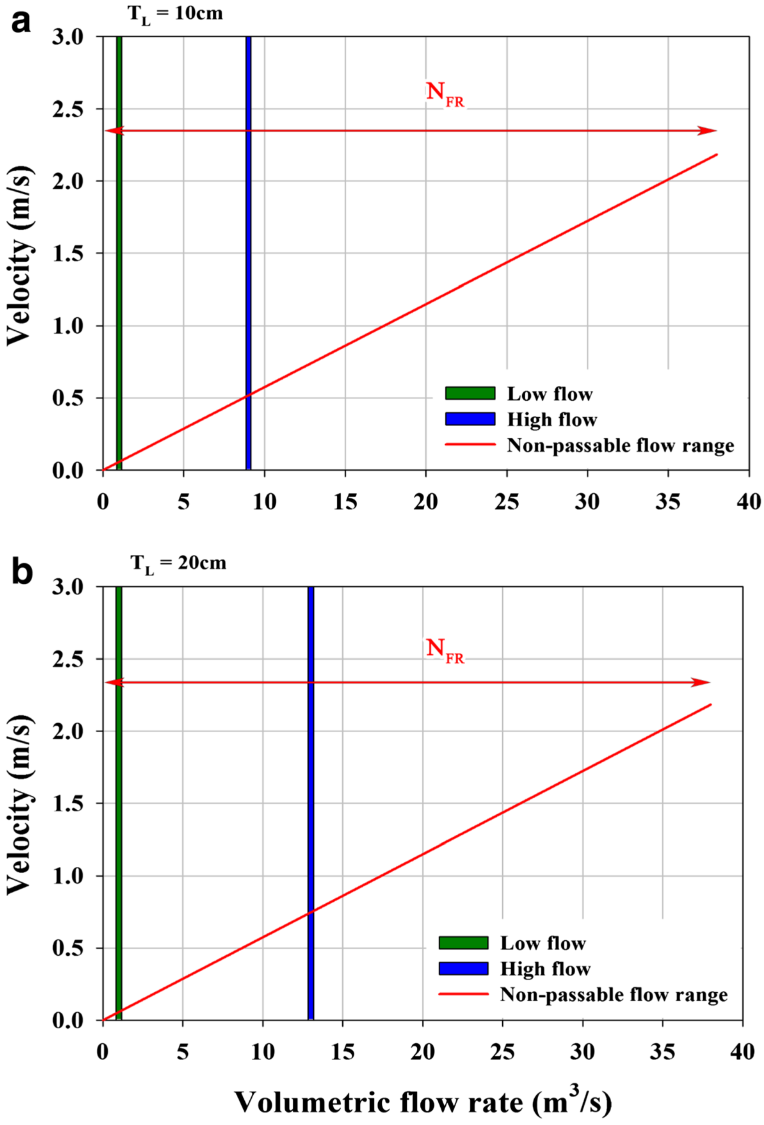

Fig. 5 Passable (P_{FR}) or non-passable (N_{FR}) flow range of the calculated inflow rates for juvenile/young largemouth bass based on size of individuals (total length (cm), T_L)

showed that at inflow rates of 38 m^3/s or higher, the use of the waterway tunnel by largemouth bass was next to impossible (Fig. 6).

Conclusions

Swimming speed and distance increased as the size of largemouth bass increased, and largemouth bass of the same body length swam slower and covered less distance as the inflow rate of the waterway tunnel increased. The frequency of transferring the waterway tunnel was highest (66.4%) at an inflow rate of 10 m^3/s or less. For smaller individuals (10–30 cm), the migration rate was 0% at 10 m^3/s. The success rate of migration was 10.9% at 9 m^3/s or less for the 40-cm largemouth bass, 15% at 15 m^3/s or less for the 50-cm largemouth bass, and 20% at 24 m^3/s or less for the 60-cm largemouth bass. However, these migration rates were estimated at an assumed water temperature of 25 °C, the optimal habitat condition for largemouth bass. At water temperatures of 10 °C or lower, their swimming speed rapidly decreased by more than 30%, and the migration rate and swimming distance in the waterway tunnel were also assumed to decrease (Mitchell 1989; Bell 1991).

During the dry period in which water levels do not fluctuate significantly in the Andong and Imha Reservoirs, larger largemouth bass (≥30 cm) are expected to have higher migration rates than those during the flood period because of low water head differences between the two reservoirs and consequently, low inflow rates. However,

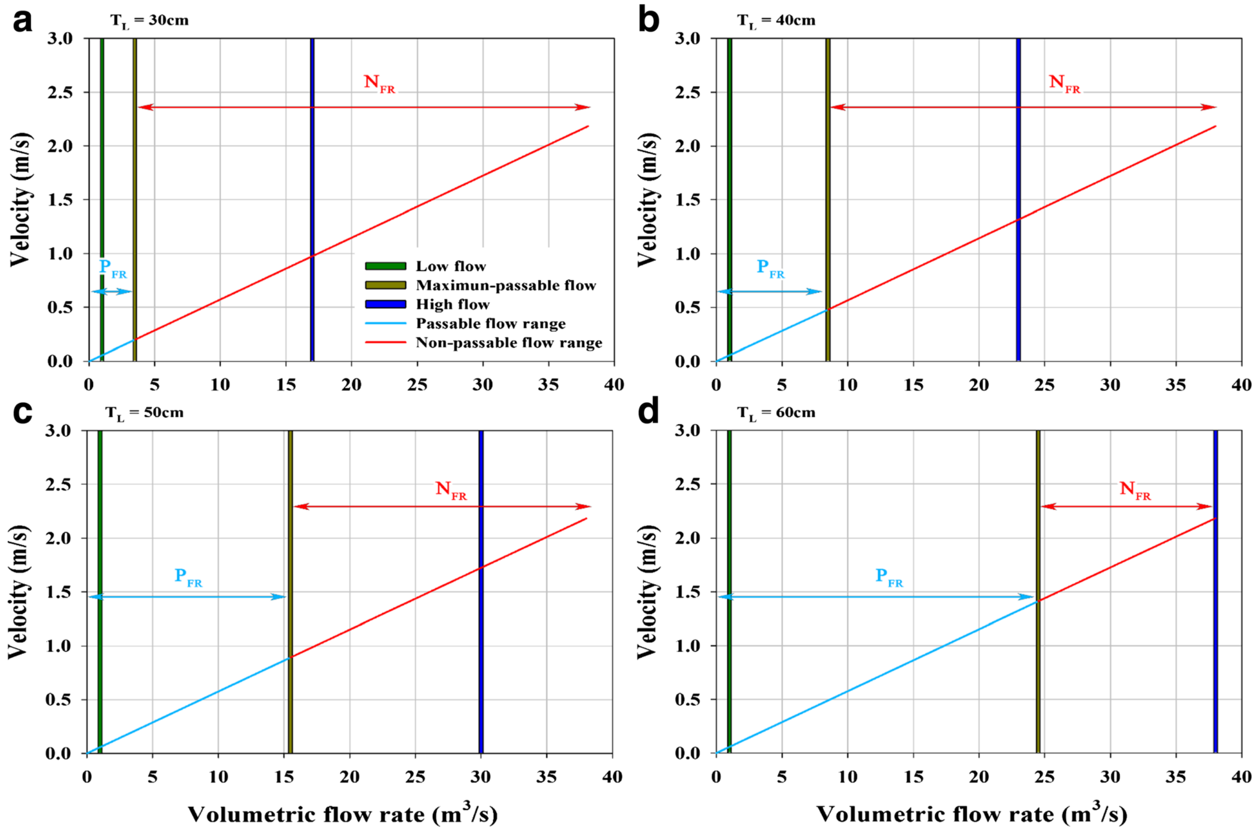

Fig. 6 Calculated inflow rates at which adult bass of medium (30–40 cm) and large size (≥50 cm) are capable or incapable of passing the waterway tunnel. P_{FR} and N_{FR} indicate passable and non-passable flow ranges, respectively. T_L is total length (cm) of largemouth bass

during the flood period with concentrated precipitation, increased inflow rates (≥40 m^3/s) due to the rapid water level rise of the Imha Reservoir and subsequent increase in water head difference (≥1 m) would impede the migration of largemouth bass via the waterway tunnel. In particular, smaller individuals (10–30 cm) are assumed to be unable to pass through the long waterway tunnel because they quickly reach a state of exhaustion during prolonged upstream swimming against rapidly flowing water (Farlinger and Beamish 1977). In summary, the potential for the spread of largemouth bass to the Imha Reservoir via the waterway tunnel is not remarkable enough to raise any concern.

Abbreviations

EL: Elevation; M_{ad}: Maximum attainable distance; N_{FR}: Non-passable flow range; P_{FR}: Passable flow range; T_L: Total length

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Authors' contributions

Prof. KGA got a research project for the topic, and Dr. JWC analyzed the data with Prof. KGA and Dr. JWC and KGA wrote the manuscript and then edited together. Both authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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References

Ahn, J. B., & Kim, H. J. (2010). Characteristics of monsoon climate in the Korean peninsula. *Journal Climate Research, 5*, 91–99 (in Korean).

Almeida, D., Almodóvar, A., Nicola, G. G., Elvira, B., & Grossman, G. D. (2012). Trophic plasticity of invasive juvenile largemouth bass *Micropterus salmoides* in Iberian streams. *Fisheries Research, 113*, 153–158.

An, K. G., Park, S. J., Choi, S. M., & Park, J. S. (2006). Comparative analysis of long-term water quality data monitored in Andong and Imha reservoirs. *Korean Journal of Limnology, 39*, 21–31 (in Korean).

Beamish, F. W. H. (1970). Oxygen consumption of largemouth bass, *Micropterus salmoides*, in relation to swimming speed and temperature. *Canadian Journal of Zoology, 48*, 1221–1228.

Beamish, F. W. H. (1978). Swimming capacity. In W. H. Hoar & D. J. Randall (Eds.), *Fish physiology* (pp. 101–187). New York: Academic.

Bell MC. 1991. Fisheries handbook of engineering requirements and biological criteria. Fish Passage Development and Evaluation Program, U.S. Army Corps of Engineers

Black, E. C., Connor, A. R., Lam, K., & Chiu, W. (1962). Changes in glycogen, pyruvate and lactate in rainbow trout (*Salmo gairdneri*) and following muscular activity. *Journal of the Fisheries Research Board of Canada, 19*, 409–436.

Brown, T. G., Runciman, B., Pollard, S., & Grant, A. D. A. (2009). Biological synopsis of largemouth bass (*Micropterus salmoides*). *Canadian Manuscript Report of Fisheries and Aquatic Sciences, 2884*.

Colavecchia, M., Katopodis, C., Goosney, R., Scruton, D. A., & Mckinley, R. S. (1998). Measurement of burst swimming performance in wild Atlantic salmon (*Salmo salar* L.) using digital telemetry. *Regulated River, 14*, 41–51.

Farlinger, S., & Beamish, F. W. H. (1977). Effects of time and velocity increments on the critical swimming speed of largemouth bass (*Micropterus salmoides*). *Transactions of the American Fisheries Society, 106*, 436–439.

Findlay, C. S., Bert, D. G., Zheng, L. (2000). Effect of introduced piscivores on native minnow communities in Adirondack lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, 57, 570–580.

Furniss, M., Love, M., Firor, S., Moynan, K., Llanos, A., Guntle, J., & Gubernick, R. (2006). *FishXing version 3.0*. Corvallis: US Forest Service.

Hammer, C. (1995). Fatigue and exercise tests with fish. *Comparative Biochemistry and Physiology Part A:, 112*, 1–20.

Hickley, P., North, R., Muchiri, S. M., & Harper, D. M. (1994). The diet of largemouth bass (*Micropterus salmoides*) in Lake Naivasha, Kenya. *Journal of Fish Biology, 44*, 607–619.

Hocutt, C. H. (1973). Swimming performance of three warmwater fishes exposed to a rapid temperature change. *Chesapeake Science, 14*, 11–16.

Hunter LA, Mayor L. 1986. Analysis of fish swimming performance data. Volume I. North-south consultants for the Department of Fisheries and Oceans, Government of Canada, and Alberta Department of Transportation

Kang, M. G., Lee, G. M., & Cha, H. S. (2007). Evaluation of effects of real joint-operation of multi-purpose dams. *Journal of Korea Water Resources Association, 40*, 101–112 (in Korean).

Kim, H. M., Kil, J. H., Lee, E. H., & An, K. G. (2013). Distribution characteristics of largemouth bass (*Micropterus salmoides*) as an exotic species, in some medium-to-large size Korean reservoirs and physico-chemical water quality in the habitats. *Korean Journal of Ecology and Environment, 46*, 541–550 (in Korean).

Lasenby, T. A., & Kerr, S. J. (2000). *Bass stocking and transfers: an annotated bibliography and literature review*. Peterborough: Fish and Wildlife Branch, Ontario Ministry of Natural resources.

Lee, J. U. (2005). Development of optimal operation rule for multipurpose reservoirs systems. *Journal of Korea Water Resources Association, 37*, 487–497 (in Korean).

Lee, W. O., Yang, H., Yoon, S. W., & Park, J. Y. (2008). Study on the feeding habits of *Micropterus salmoides* in Lake Okjeong and Lake Yongdam. *Korean Journal of Ichthyology, 21*, 200–207 (in Korean).

Love, M. S., Firor, S., Furniss, M., Gubernick, R., Dunklin, T., & Quarles, R. (1999). *FishXing version 2.2. USDA forest service*. San Dimas: San Dimas Technology and Development Center.

Ministry of Environment, Korea. (2013). *Monitoring of invasive alien species designated by the wildlife protection act (VII)*. Incheon: National Institute of Environmental Research (NIER) (in Korean).

Mitchell, C. P. (1989). Swimming performances of some native freshwater fishes. *New Zealand Journal of Marine and Freshwater, 23*, 181–187.

Nursall, J. R. (1962). Swimming and the origin of paired appendages. *American Zoologist, 2*, 127–141.

Park, H. S., & Chung, S. W. (2014). Water transportation and stratification modification in the Andong-Imha linked reservoirs system. *Journal of Korean Society on Water Environment, 30*, 31–43 (in Korean).

Wasserman, R. J., Strydom, N. A., & Weyl, O. L. F. (2011). Diet of largemouth bass, *Micropterus salmoides* (Centrarchidae), an invasive alien in the lower reaches of an Eastern Cape river, South Africa. *African Zoology, 46*, 378–386.

Webb, P. W. (1975). Hydrodynamics and energetics of fish propulsion. *Journal of the Fisheries Research Board of Canada, 190*, 1–158.

Wheeler, A. P., & Allen, M. S. (2003). Habitat and diet partitioning between shoal bass and largemouth bass in the Chipola River, Florida. *Transactions of the American Fisheries Society, 132*, 438–449.

Wood, C. M., Turner, J. D., & Graham, M. S. (1983). Why do fish die after severe exercise? *Journal of Fish Biology, 22*, 189–201.

Yasunori, M., & Tadashi, M. (2003). Community-level impacts induced by introduced largemouth bass and bluegill in farm ponds in Japan. *Biological Conservation, 109*, 111–121.

Yum, K. (2010). The roles and effects of the four rivers restoration project to cope with climate change. *Journal of the Korean Society of Civil Engineers, 58*, 10–15 (in Korean).

Zaret, T. M., & Paine, R. T. (1973). Species introduction in a tropical lake. *Science, 182*, 449–455.