

Fisheries

American Fisheries Society • www.fisheries.org

AFS

VOL 39 NO 3

MAR 2014



In this Issue:

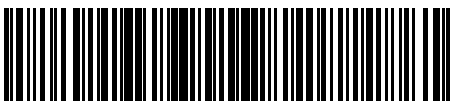
Understanding Barotrauma

Overpopulation and Fish

AFS Chapter Roles

Ecosystem Modeling

Social Media: Take the Plunge!



03632415 (2014) 39 (3)

Fisheries

VOL 39 NO 3 MARCH 2014



135 An angler in Kerala, India. Photo credit: Antony Grossy.

Contents

COLUMNS

President's Commentary

99 How Many People Are Enough (Too Many)?

Those of us who think ecologically see the effects of population growth multiplied by per capita resource consumption manifested in increased listings of threatened and endangered species, climate change, climate chaos, and degraded ecosystem services (including water quality and availability, fisheries, and coral reef condition).

Bob Hughes

Letter from the Executive Director

101 The Foundational Role of Chapters

The AFS as a corporate body—Chapters, Sections, Divisions—needs to show how the additive value of the Society to a prospective member's professional and conservation goals is worth the investment of his or her funds.

Doug Austen

Policy

102 Ecosystem Modeling to Support Fishery Management

Managing fisheries with improved success will rely on models that offer contextual, heuristic, tactical, and strategic advice, depending on their design and our needs.

Thomas E. Bigford

Digital Revolution

103 Tablet Computers in Fisheries

These computers work well in all conditions and are built to last.

Jeff Kopaska

The Communication Stream

104 What to Do With Your New Twitter Account (or Facebook, or ...)

You have your Twitter account. Okay. Now what?

Jeremiah Osborne-Gowey

SPECIAL

105 Water Quality Section Introduction and History

Water quality is integral to fisheries scientists' work, whether monitoring an aquaculture pond, measuring fine sediment in streams, or restoring a natural waterway.

Gregg A. Lomnický, Robert H. Gray, and John W. Meldrim

AFS NEWS

107 Don't forget to vote; AFS wants to help you; April is Award Nominations Month; New *Fisheries* Guide for Authors is out (with a new Mission Statement); AFS seeks Co-Chief Science Editor for *Fisheries* magazine; Bigford retires from NOAA (psst... AFS grabs him!).

FEATURES

108 Understanding Barotrauma in Fish Passing Hydro Structures: A Global Strategy for Sustainable Development of Water Resources

Understanding the causes of barotrauma in fish can be critical for sustainable development of water resources.

Richard S. Brown, Alison H. Colotelo, Brett D. Pflugrath, Craig A. Boys, Lee J. Baumgartner, Z. Daniel Deng, Luiz G. M. Silva, Colin J. Brauner, Martin Mallen-Cooper, Oudom Phonekhang, Garry Thorncraft, and Douangkham Singhanouvong

123 Response to Dettmers et al. (2012): Great Lakes Fisheries Managers Are Pursuing Appropriate Goals

Randall M. Claramunt and David F. Clapp

126 Considerations When Determining Appropriate Management Goals: A Reply to Claramunt and Clapp

John M. Dettmers, Christopher I. Goddard, and Kelley D. Smith

IN MEMORIAM

128 Robert J. Behnke, George Gordon Fleener, Curt Kerns, Daniel Lluch Belda, Jacqueline F. Savino, and David W. Willis

AFS CALL TO ACTION

133 Killed in the Line of Work

Robert A. Klumb and Maegan E. Spindler

FRESHWATER, FISH, AND THE FUTURE

135 Global Inland Fisheries Conference: Theme 1—Biological Assessment

AFS ANNUAL MEETING 2014

137 Meeting Update: Exploring Québec City

JOURNAL HIGHLIGHTS

139 North American Journal of Aquaculture, Volume 76, Number 1, January 2014

CALENDAR

142 Fisheries Events

NEW AFS MEMBERS 143

Cover: An everted intestine in Serrudo. Photo credit: Carlos Bernardo M. Alves, Bio-Ambiental Consultancy.

Understanding Barotrauma in Fish Passing Hydro Structures: A Global Strategy for Sustainable Development of Water Resources

Richard S. Brown

Pacific Northwest National Laboratory, Ecology Group, 902 Battelle Boulevard, P.O. Box 999, MSIN K7-70, Richland, WA 99352. E-mail: Rich.Brown@pnnl.gov

Alison H. Colotelo and Brett D. Pflugrath

Pacific Northwest National Laboratory, Ecology Group, Richland, WA

Craig A. Boys

New South Wales Department of Primary Industries, Port Stephens Fisheries Institute, Taylors Beach, New South Wales, Australia

Lee J. Baumgartner

New South Wales Department of Primary Industries, Narrandera Fisheries Centre, Narrandera, New South Wales, Australia

Z. Daniel Deng

Pacific Northwest National Laboratory, Hydrology Group, Richland, WA

Luiz G. M. Silva

PPGTDS, DTECH/CAP, Federal University of São João Del-Rei, Ouro Branco/MG, Brazil

Colin J. Brauner

University of British Columbia, Department of Zoology, Vancouver, BC, Canada

Martin Mallen-Cooper

Fishway Consulting Services, St. Ives Chase, New South Wales, Australia

Oudom Phonekhampeng and Garry Thorncraft

National University of Laos, Vientiane, Laos

Douangkham Singhanouvong

Living Aquatic Resources Research Center, Vientiane, Laos

ABSTRACT: *Freshwater fishes are one of the most imperiled groups of vertebrates, and population declines are alarming in terms of biodiversity and to communities that rely on fisheries for their livelihood and nutrition. One activity associated with declines in freshwater fish populations is water resource development, including dams, weirs, and hydropower facilities. Fish passing through irrigation and hydro infrastructures during downstream migration experience a rapid decrease in pressure, which can lead to injuries (barotrauma) that contribute to mortality. There is renewed initiative to expand hydropower and irrigation infrastructure to improve water security and increase low-carbon energy generation. The impact of barotrauma on fish must be understood and mitigated to ensure that development is sustainable for fisheries. This will involve taking steps to expand the knowledge of barotrauma-related injury from its current focus, mainly on seaward-migrating juvenile salmonids*

Sobre el barotrauma en peces durante su tránsito por hidro-estructuras: una estrategia global para el desarrollo sustentable de los recursos hídricos

RESUMEN: *los peces de agua dulce constituyen uno de los grupos más amenazados entre los vertebrados y las disminuciones poblacionales se consideran como alarmantes en términos de biodiversidad y suceden en perjuicio de las comunidades humanas cuyo bienestar y nutrición dependen de las pesquerías basadas en estos recursos. Una actividad que se asocia a la declinación de las poblaciones de peces de agua dulce es la construcción de infraestructura para el desarrollo de recursos hídricos, como presas, weirs e instalaciones hidroenergéticas. Los peces que transitan a través de la infraestructura hidráulica y de irrigación durante su migración hacia el mar, experimentan disminuciones de presión que producen lesiones (barotrauma), las cuales pueden contribuir a la mortalidad. Existe una nueva iniciativa para expandir la infraestructura para la hidroenergía e irrigación y aumentar así la seguridad de agua y la generación de energía de bajo costo en términos de producción de carbono. El efecto del barotrauma en los peces debe ser estudiado y mitigado para asegurar que el progreso sea sustentable para las pesquerías. Esto implicará expandir el conocimiento acerca de las lesiones relacionadas al barotrauma con respecto a como se encuentra ahora; sobre todo el conocimiento de la migración hacia el mar que realizan los juveniles de especies de salmón en el Pacífico noroeste, con el fin de incorporar una mayor diversidad de estadios de vida y especies de diferentes partes del mundo. En este artículo se resume la investigación concerniente al barotrauma en los peces durante su tránsito por hidro-estructuras y se plantea un marco investigativo para promover un enfoque estandarizado y global. El enfoque que se ofrece provee relaciones precisas para el desarrollo adaptativo de tecnologías amigables para los peces, diseñadas con la finalidad de mitigar las amenazas que enfrentan las pesquerías de agua dulce ante la rápida expansión de la infraestructura hídrica.*

of the Pacific Northwest, to incorporate a greater diversity of fish species and life stages from many parts of the world. This article summarizes research that has examined barotrauma during fish passage and articulates a research framework to promote a standardized, global approach. The suggested approach provides clearly defined links to adaptive development of fish friendly technologies, aimed at mitigating the threats faced by global freshwater fisheries from the rapid expansion of water infrastructure.

INTRODUCTION

Freshwater fish are the second most endangered vertebrate group (Saunders et al. 2002), and many species currently face extinction (Ricciardi et al. 1999). Species declines are not abating, and in many parts of the world such declines have significant social and economic implications. Many of the world's developing nations rely heavily on freshwater fish for their livelihood, as both a source of income and food. For example, the Lower Mekong River basin (i.e., Cambodia, Laos, Thailand, Vietnam) supports the world's largest inland fishery, worth between US\$4.3 and \$7.8 billion annually (Hortle 2009). Fish and other aquatic organisms are essential for the livelihood, nutrition, and food security of citizens of the Lower Mekong River basin, accounting for 47%–80% of total animal protein consumed (Hortle 2007).

Many activities have had a role in freshwater fish declines throughout the world, including development of water infrastructure (Dudgeon et al. 2006). Water infrastructure, including dams, weirs, and hydropower facilities, can change natural flow regimes, degrade habitat and water quality, and interrupt or otherwise negatively impact important upstream and downstream fish migrations (Kingsford 2000; Agostinho et al. 2008). Though water infrastructure can create a complete barrier to fish movements, structures can also selectively injure or kill fish as they pass (Williams et al. 2001; Godinho and Kynard 2009). In such cases, barotrauma (trauma due to changes in barometric pressure) is of particular concern where hydropower facilities and irrigation structures create adverse hydraulic conditions that can injure and kill passing fish (Cada 1990; Baumgartner et al. 2006; Brown et al. 2012a).

Globally, the infrastructure associated with hydropower and other water resource development are extensive and expanding rapidly, especially in areas such as China, Brazil, and Africa (Geoscience Australia and ABARE 2010). Brazil is one example where hydropower generation is projected to increase 38% by 2020 (Ministério de Minas e Energia/Empresa de Pesquisa Energética [MME/EPE] 2011) through large hydropower projects, such as the Belo Monte Dam on the Xingu River of the Amazon Basin (the third largest [11,233 MW] hydropower production facility in the world; MME/EPE 2011; Castro et al. 2012) and the Santo Antônio (3,150 MW power potential) and Jirau (3,300 MW power potential) dams on the Madeira River. Worldwide, opportunities are being explored to install small-scale (typically less than 10 MW) hydroelectric facilities at water infrastructures built for other purposes, such as existing irrigation weirs (Bartle 2002; Paish 2002; Baumgartner et al. 2012).

The expansion of hydropower generation is in response to increasing demand for power in developing regions and a global desire for increased use of renewable energy in response to climate change. However, to maintain fish diversity and curb social and economic impacts in light of this development, research is needed to guide the design and management of hydropower facilities and other water infrastructure. In particular,

minimizing barotrauma associated with passage through water infrastructure is a complex issue and of particular concern. In this article we review the science related to barotrauma with the objective of highlighting what is known and the knowledge gaps that exist in adaptively managing the threats faced by freshwater fisheries from the rapid expansion of water infrastructure. Though information covered may provide insight for barotrauma induced by angling, commercial fishery bycatch operations, or scientific sampling involving quickly bringing fish to the surface of a water body, the main focus of this article is furthering the understanding of barotrauma among fish passing downstream through dams, weirs, and hydropower facilities. In addition, this article does not provide an exhaustive review of all such water infrastructure passage related barotrauma (for further background information see Cada 1990) but focuses on the state of the science, provides insight for interpreting past research, and provides modeling and research frameworks for future endeavors in barotrauma research.

BAROTRAUMA DURING WATER INFRASTRUCTURE PASSAGE

It has long been acknowledged that fish can be killed or injured when passing through hydroturbines at hydroelectric facilities (Cramer and Oligher 1964). Similarly, it has been shown that fish can be harmed during passage through bypass systems or spillways at hydroelectric facilities (Muir et al. 2001). But the impact is not confined to structures specifically designed for the generation of hydropower, and considerable injury and mortality rates have also been reported for fish passing weirs primarily built to capture and divert river flows for irrigation (Baumgartner et al. 2006). This aside, research carried out to understand the mechanisms for injury during water infrastructure passage has been predominately focused around hydroelectric turbine passage (Coutant and Whitney 2000).

When fish pass through hydrostructures, such as hydroturbines, shear forces, blade strike, and pressure changes can lead to injury and death (Deng et al. 2005, 2007a, 2010; Cada et al. 2006; Brown et al. 2009, 2012b). Although one of the most apparent sources of injuries to fish may be strike from turbine blades, the likelihood of strike is low for small fish (Franke et al. 1997). Not all fish passing through hydroturbines are exposed to damaging levels of shear force or blade strike (Deng et al. 2007b), because this depends on the route taken by fish through the system and blade strike can vary to a large degree with fish size (Franke et al. 1997). All fish, however, are exposed to pressure changes, and the magnitude of change depends largely on turbine design, the path of the fish through the turbine, the operation of the turbine, the total operating head, the submergence of the turbine, and the rate of flow through the turbine (Carlson et al. 2008; Deng et al. 2010; Brown et al. 2012b).

As fish pass between turbine blades, they are typically exposed to a sudden (occurring in <1 s) decompression before returning to near surface pressure as they enter the downstream channel (Deng et al. 2007b, 2010). In hydroturbines, this can commonly involve decreases in pressure to levels between

surface pressure (101 kPa) and half of surface pressure of approximately 50 kPa (Carlson et al. 2008). Fish passing through other types of hydrostructures are also exposed to rapid pressure changes (see Carlson et al. [2005] for an example of pressure fluctuations at a pump storage facility). Although little research has been done to quantify pressure changes outside of the hydroturbine realm, initial hydraulic investigations of irrigation weirs, where water is discharged under a gate (referred to as “undershot weirs”), show that passing fish would experience rapid decompression (in <1 s) to slightly below surface pressure as they are taken from depth in the upstream pool and discharged into surface waters downstream of a structure (C. A. Boys [New South Wales Department of Primary Industries] and Z. D. Deng [Pacific Northwest National Laboratory], personal communication).

The rapid decompression associated with infrastructure passage can lead to barotrauma arising from one of two major pathways. The first is governed by Boyle’s law, where damage occurs due to the expansion of a preexisting gas phase within the body of the fish, such as contained in the swim bladder (Keniry et al. 1996; Brown et al. 2012e; Pflugrath et al. 2012). Boyle’s law ($P_1 V_1 = P_2 V_2$ [where P_1 and V_1 are the initial pressure and gas volume and P_2 and V_2 are the resultant pressure and gas volume]) states that within a closed system (at constant temperature), the volume of a gas is inversely proportional to the pressure acting on the volume (Van Heuvelen 1982). For a fish passing through infrastructure, if the surrounding pressure is decreased by half, the volume of the preexisting gas in the body doubles. Injuries arising from this pathway typically include ruptured swim bladders and exophthalmia (Figure 1), everted stomach or intestine (Figures 2A and 2B), internal rupture of vasculature (hemorrhaging), and gas bubbles (emboli) in the vasculature, organs, gills, and fins (Tsvetkov et al. 1972; Rummer and Bennett 2005; Gravel and Cooke 2008; Brown et al. 2009, 2012b).

The second pathway is governed by Henry’s law, where gas may come out of solution due to decompression-induced reduction in solubility, resulting in bubble formation (Brown et al. 2012e). Henry’s law states that the amount of gas that can be dissolved in a fluid, such as blood plasma, is directly proportional to the partial pressure to which it is equilibrated. Thus, when the surrounding pressure is reduced, the dissolved gas may come out of solution, resulting in gas bubble formation, the basis for the bends in scuba divers who return to the surface too quickly. As fish pass through areas of low pressure, such as through hydroturbines, and experience decompression, their blood and other bodily fluids may become temporarily supersaturated and gas bubbles may form in the blood, organs, gills, or fins (emboli). As the gas bubbles grow, they can also lead to internal rupture of vasculature (hemorrhaging; Brown et al. 2012b; Colotelo et al. 2012).

Henry’s and Boyle’s laws may not be equally important in governing injury to fish during water infrastructure passage. Brown et al. (2012e) determined that, among juvenile Chinook Salmon (*Oncorhynchus tshawytscha*), injury and mortalities ob-

served due to rapid decompression (simulating turbine passage) were largely caused by swim bladder expansion and rupture (as governed by Boyle’s law), and the likelihood of mortality due to gases coming out of solution in the blood and tissue (as governed by Henry’s law) was relatively low. They found that if juvenile Chinook Salmon were slowly decompressed to very low pressures (13.8 kPa; with 101 kPa representing surface pressure) over 2.9–3.6 min (median = 3.3 min), the fish could expel gas from their swim bladder via the pneumatic duct (a connection between the swim bladder and esophagus; Figure 3), preventing its rupture and subsequent barotraumas (e.g., emboli in the fins, gills, and blood vessels; exophthalmia; hemorrhaging). If fish were maintained at these low pressures, it took several



Figure 1. Exophthalmia (eyes popped outward) observed in (A) the Brazilian species *Corvina* captured downstream of a hydropower facility and (B) in juvenile Steelhead exposed to rapid decompression from depth (510.1 kPa, the equivalent to 40.7 m) to near surface pressure (117.2 kPa; Brown et al. 2012e). Photo credit: Carlos Bernardo M. Alves, Bio-Ambiental Consultancy.



Figure 2. Images of an (A) everted stomach in the Brazilian species *Mandi-amarelo* and (B) an everted intestine in *Serrudo*. Photo credit: Carlos Bernardo M. Alves, Bio-Ambiental Consultancy.

minutes (mean = 3.0; range 2.2–7.0) before emboli and mortality were observed, presumably associated with Henry's law. In comparison, however, if juvenile Chinook Salmon were rapidly decompressed, the swim bladder often ruptured, expelling gas into the tissue and vasculature leading to hemorrhaging, emboli, and exophthalmia.

Though it appears that barotraumas governed by Henry's law are slow to develop relative to those linked to Boyle's law in juvenile Chinook Salmon, there are species-specific differences in damages that occur when fish are exposed to decompression. For instance, where Brown et al. (2012e) saw mortality due to Henry's law in juvenile Chinook Salmon exposed to 2.2–7.0 min of low pressure (13.8 kPa), Colotelo et al. (2012) found that juvenile Brook (*Lamprologus richardsonii*) and Pacific Lamprey (*Entosphenus tridentatus*) were uninjured when exposed to these same low pressures for over 17 min. Thus, the likelihood of emboli formation (and associated injuries such as hemorrhaging) may vary substantially among species. Though only a few species have been examined to date, it appears unlikely that gas coming out of suspension and forming emboli is the major cause of injury and mortality among fish passing hydrostructures because they are seldom if ever exposed to pressures below surface pressure for more than even a single second.

However, it should be kept in mind that supersaturation of gas is a large problem associated with dams. High levels of total dissolved gas (TDG) are associated with water routed over spillways. Water falling over spillways and into deep plunge basins of dams can cause gas to be entrained into the water (Ebel 1969). Prolonged exposure to elevated TDG can cause gas bubble disease (GBD) in fish. The difference between GBD and bubbles forming in the blood associated with barotrauma is that GBD involves gas moving from the surrounding supersaturated water into the tissues of the fish, leading to the formation of emboli (Beyer et al. 1976). Alternatively, when fish are decompressed during passage of a hydrostructure, the temporary supersaturation of the blood can cause bubbles to come out of suspension in the blood and tissues (Beyer et al. 1976). Thus, the source of the supersaturated gas is from within the fish instead of from the surrounding supersaturated water. Although a review of GBD is not within the scope of this article, it is possible that elevated TDG could lead to an increase of barotrauma. If fish with emboli present in their body due to GBD are decompressed during passage of hydrostructures, a higher amount of barotrauma may occur due to the expansion of those bubbles than may occur when the river water does not have elevated levels of TDG.

This leads to another factor that should be kept in mind when interpreting the barotrauma literature. Some researchers have had issues with confusing barotrauma with GBD when conducting decompression studies on fish. If the water the fish are held in while under pressure in test chambers is aerated or otherwise saturated with gas (similar to experiments by Bishai [1960] and D'Aoust and Smith [1974]), fish could experience GBD when decompressed, essentially the same condition as the bends in humans. This would lead to an extended period where the blood and tissues of the fish would be supersaturated instead of the very short period of supersaturation that fish would be exposed to during hydrostructure passage.

IMPLICATION OF SWIM BLADDER MORPHOLOGY

Barotrauma damage is frequently attributed to swim bladder expansion and rupture and, as such, the diversity in swim bladder form and function among fish may have significant implications for the relative susceptibility to injury. There are two broad groups, physoclists and physostomes. Physostomes, which are evolutionarily more basal fishes (e.g., lungfishes, sturgeons, and euteleosts), have a swim bladder that is connected to the esophagus via a pneumatic duct (often referred to as an open swim bladder). These fish gulp air at the surface and force it into their swim bladder. The second group is called physoclists, which are evolutionarily more derived fishes (neoteleosts), which have a swim bladder that is not connected to the esophagus (often referred to as a closed swim bladder; Figures 3 and 4) and the presence of a gas gland and countercurrent vasculature (called "retia") is used to regulate swim bladder volume and thus buoyancy (Pelster and Randall 1998). Physoclists may be much more likely to be injured during passage of hydrostructures than physostomes because they cannot quickly

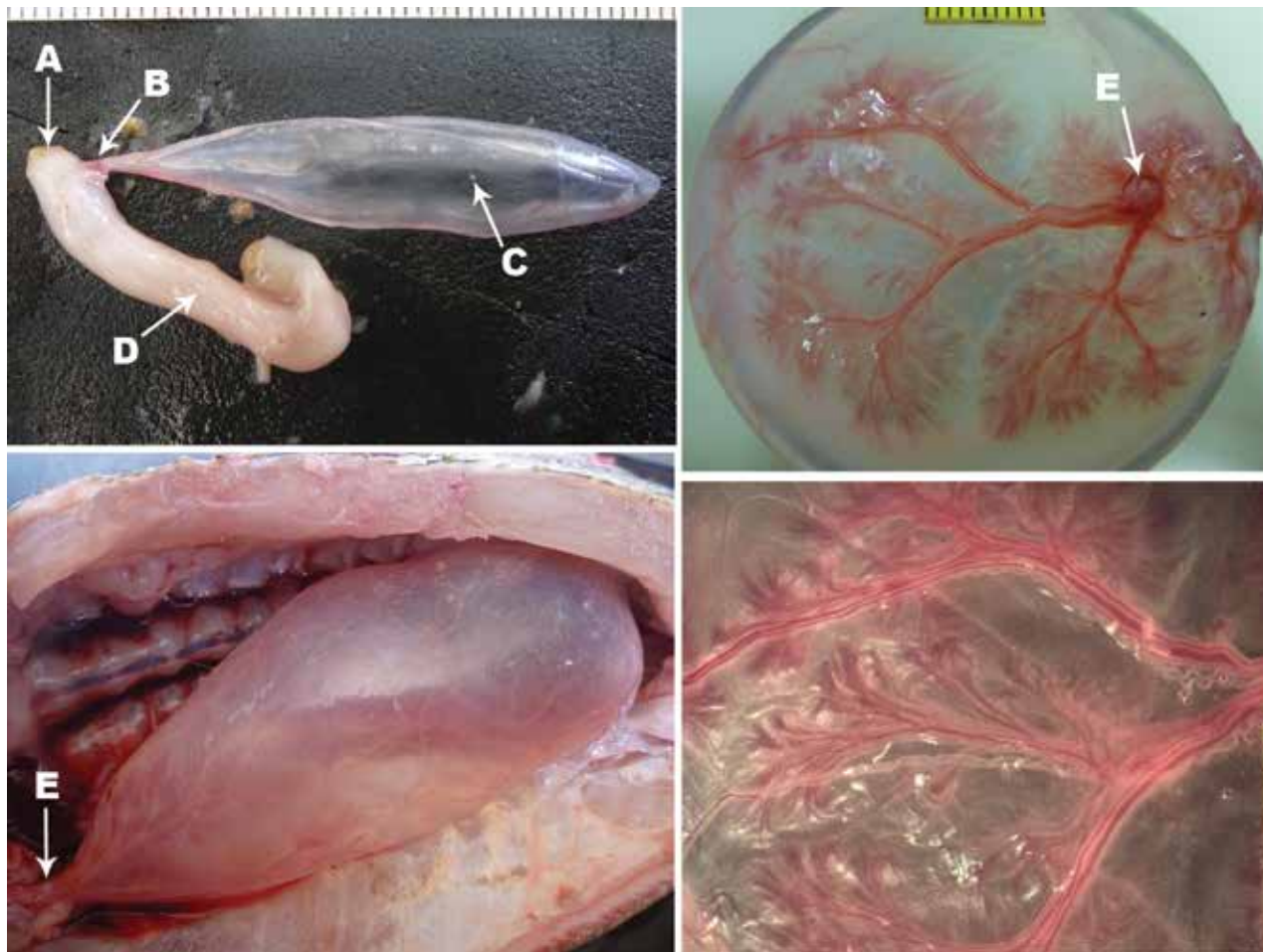


Figure 3. (A) Esophagus, (B) pneumatic duct, (C) physostomous swim bladder, and (D) stomach of a juvenile Chinook Salmon are shown in the upper left panel. The other three panels are photos of a physoclistous Smallmouth Bass swim bladder. The inflated swim bladder is shown in the lower left panel with the incoming vasculature source shown (E). The upper and lower right panels show a deflated swim bladder and the vascular rete (E also shows the incoming source of the vasculature). Photo credit: Ricardo W. Walker.

release gas as the swim bladder expands during rapid decompression (Brown et al. 2012e). To add to the complexity, most fish that are physoclistous as adults are physostomous as larvae, which enables initial swim bladder inflation by gulping air (e.g., Bailey and Doroshov 1995; Rieger and Summerfelt 1998; Trotter et al. 2003). Thus, the vulnerability to barotrauma may vary greatly within a species depending on its life stage (Tsvetkov et al. 1972). Another noteworthy variation in swim bladder morphology is found in the most diverse family of freshwater fishes, the cyprinids, which form a major component of the migratory fauna of Asian rivers. They have a physostomous swim bladder, but it has two chambers with an anterior projection closer to the Weberian apparatus to enhance hearing (Alexander 1962; Figure 5). The chambers are connected by an additional duct under autonomic muscular control (Dumbarton et al. 2010). Thus, during rapid decompression, excess gas would need to be voided through both chambers and two ducts simultaneously in order to prevent barotrauma due to swim bladder damage.

In order to predict the extent of inter- and intraspecific barotraumas that may be induced by hydrostructures within a given river system, it is crucial to understand how pressure changes affect fish with different types of swim bladders at different life stages. Physostomes are able to quickly expel gas via the

pneumatic duct, using the *gass-puckreflex* (gas spitting reflex; Franz 1937), which is under autonomic control. The rate of this reflex is likely critical in reducing injury due to rapid decompression but appears to vary between—and even within—species (Harvey et al. 1968; Shrimpton et al. 1990). Shrimpton et al. (1990) determined that smaller Rainbow Trout had a higher gas pressure release threshold than larger fish (when examining fish in a range from less than 10 to ~250 g). Additionally, there have been observations of siluriform Catfish with everted stomachs (Figures 2A and 2B) downstream of hydroelectric facilities, which indicates that gas was not released fast enough from their physostomous swim bladder to avoid barotrauma during rapid decompression.

Unlike physostomes, physoclists can only regulate buoyancy through a relatively slow process of gas diffusion into and out of the swim bladder (see Figure 3). The physoclistous swim bladder is filled predominantly by oxygen that is released from a pH-sensitive hemoglobin as it is acidified within the retia of the swim bladder (Pelster and Randall 1998). The rate of swim bladder filling and the partial pressures that can be ultimately generated varies widely among physoclists, with some species able to attain neutral buoyancy at much deeper depths than others (Fänge 1983). Some species, like Tench (*Tinca tinca*), can

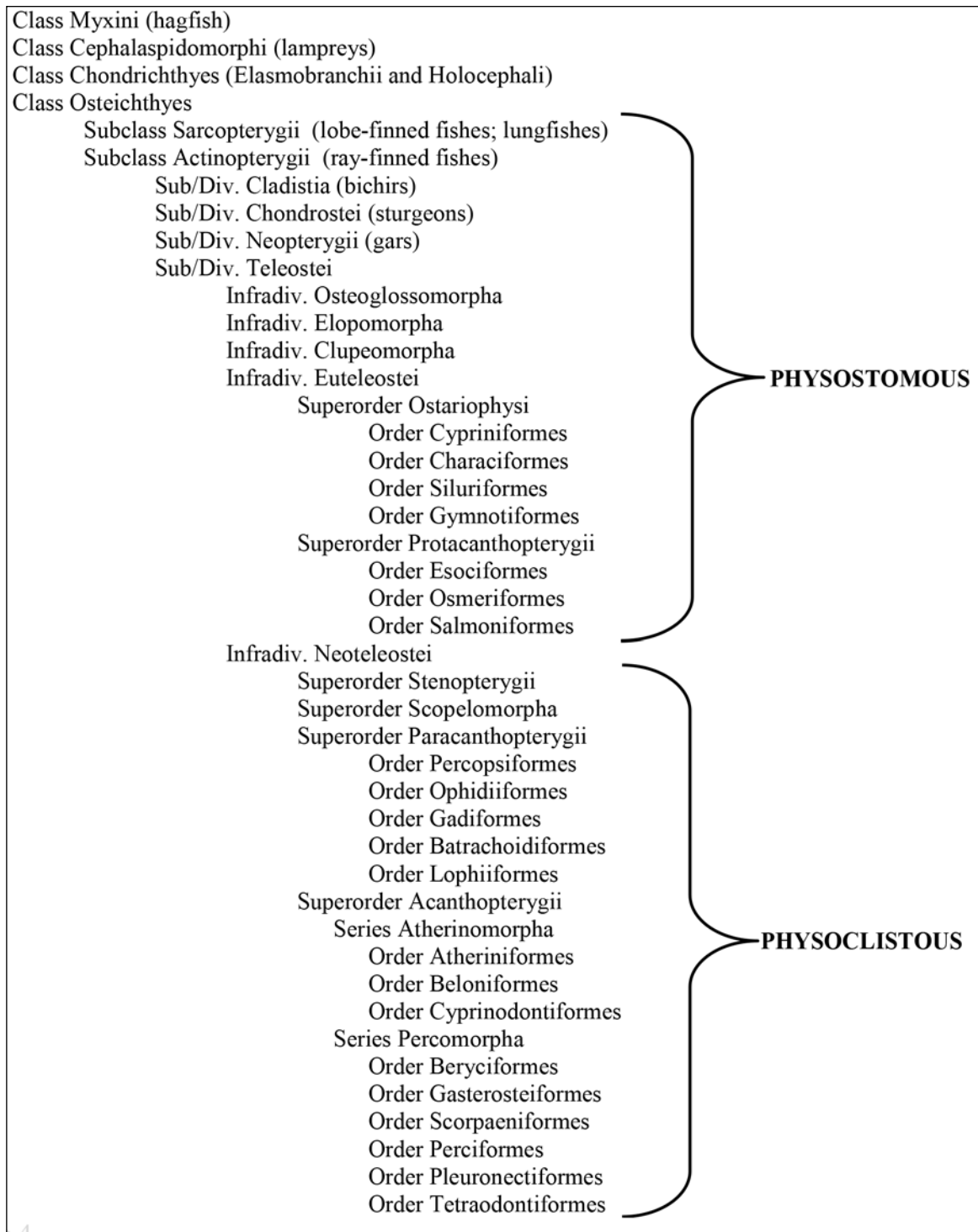


Figure 4. The type of swim bladder present in different taxa of fish. Fish with an opening between the swim bladder and the esophagus (physostomes) and without this opening (physoclists) are shown, as well as fish without a swim bladder (the upper most three classes).

take weeks to fill their swim bladder (Jacobs 1934), whereas Bluefish (*Pomotomus saltatrix*) may be able to do so relatively rapidly (less than 4 h after puncture; Wittenberg et al. 1964) but still require hours to days. Presumably, these rates of swim bladder filling are indicative of rates of emptying, which are much too slow to prevent barotrauma due to the rapid (occurring in a fraction of a second) pressure changes that occur during water infrastructure passage. Thus, physoclistous species are likely

very susceptible to barotraumas and likely much more sensitive than physostomous species; however, this remains to be investigated.

In addition to physoclists and physostomes, there is a third group of freshwater fishes that do not have a swim bladder and are therefore likely to have low susceptibility to barotrauma arising from Boyle's law. Juvenile Brook and Pacific Lamprey



Figure 5. Two-chambered swim bladder of the *Hypsibarbus lagleri*, a species endemic to the Mekong basin of South East Asia.

are two such species and were uninjured when rapidly decompressed in simulations of hydroturbine passage including exposure to pressures much lower (13.8 kPa) than commonly seen during turbine passage (Colotelo et al. 2012). Additionally, both species were held at this low pressure for an extended period of time (>17 min) without either immediate or delayed (>120 h) mortality (Colotelo et al. 2012). Together, these results suggest limited susceptibility to barotrauma via either the Boyle's or Henry's law pathways. In comparison to the Pacific Lamprey, when juvenile Chinook Salmon were rapidly decompressed to these same low pressures, more than 95% suffered mortal injuries (Brown et al. 2012b). Migratory fish species that reside in freshwater at least part of their lives and do not have swim bladders are not common but include Bull Shark (*Carcharhinus leucas*), freshwater Sawfish (*Pristis microdon*; a threatened species), and lampreys.

Other researchers have noted that fish without swim bladders had low susceptibility to barotrauma. For example, Bishai (1961) found larval Plaice (*Pleuronectes platessa* L.; 3.5–5.0 cm long) held at 202 kPa for 2–8 days were uninjured when decompressed over 5–10 min back to surface pressure (101 kPa). Similarly, Tsvetkov et al. (1972) found no damage to larval Atlantic Salmon (*Salmo salar*; 2–2.5 cm long; without a developed swim bladder) after being held at 101–606 kPa for 40 h or more and brought to surface pressure in less than 3 s. However, neither of these experiments involved reducing fish to pressures below surface pressure where barotrauma due to Henry's law (gas coming out of suspension in their blood and tissues) would have been anticipated.

IMPLICATION OF LIFE HISTORY AND BEHAVIOR

In addition to the physiological traits of fish, barotrauma research on freshwater species needs to be based on a template of ecology and behavior (Table 1). Understanding what life stages will be exposed to water infrastructure passage is critical to understanding the susceptibility of wild populations to barotrauma. The majority of research related to hydroturbine passage has been focused on seaward-migrating juvenile salmo-

nids. Most salmonid species are semelparous (having a single reproductive episode before death) and, as such, the only life stage that may be affected by downstream passage is juveniles. There are, however, iteroparous (having multiple reproductive cycles over a lifetime) species that may pass through turbines as they migrate back to the ocean after spawning (e.g., Steelhead Trout [*Oncorhynchus mykiss*], Brown Trout [*Salmo trutta*], Atlantic Salmon, and Dolly Varden [*Salvelinus malma malma*]). Iteroparous species are also common in other bioregions such as South America, Asia, and Australia, where both adult and juvenile life stages may have to migrate downstream through hydropower and irrigation structures. In large floodplain rivers such as in South East Asia, South America, and Australia, egg and larval drift is a common life history trait (Baran et al. 2001; Humphries et al. 2002; Koehn and Harrington 2005; Godinho and Kynard 2009), and this mode of migration will increase the likelihood of encountering water infrastructure. Within North America, there are also many species (such as Paddlefish [*Polyodon spathula*], Walleye [*Sander vitreus*], and sturgeon [*Scaphirhynchus* spp.]) where eggs, larvae, or small juveniles can drift for long distances (Purkett 1961; Corbett and Powles 1986; Braaten et al. 2008). Early life stages are fragile and may be more susceptible to barotrauma than larger individuals because their bodies (swim bladder and other internal organs) are less robust (Tsvetkov et al. 1972), and the expansion of gas in the swim bladder may be more likely to cause damage relative to their body size. Understanding the ecology and timing of larval drift, as well as the time of first inflation of the swim bladder, will be critical in understanding their susceptibility to barotrauma. Additionally, more information is needed about physiological changes in larval physoclistous fish. They commonly have larvae with an open swim bladder but lose the connection between their swim bladder and esophagus as they develop. Identifying when this occurs may aid in understanding their increased susceptibility to barotrauma, important information for managing systems where these types of fish are present.

Larval drifting fish may also be susceptible to barotrauma due to expansion of metabolically produced gas. Brown et al. (2013a) noted barotrauma in the form of erratic swimming, death, and herniation-like abnormalities on the abdomen of larval White Sturgeon (*Acipenser transmontanus*) at the point when they first started feeding (8 days after hatching) but did not have an inflated swim bladder. They also noted gas in the intestines about 7 months after hatching that could also lead to barotrauma upon decompression.

Susceptibility to barotrauma is also likely to be influenced by the position fish occupy in the water column. Neutral buoyancy in fish is achieved by maintaining swim bladder volume constant, which is accomplished at deeper depths by having a higher gas pressure according to Boyle's law (see above). The depth and water pressure a fish has occupied prior to infrastructure passage (commonly referred to as "acclimation pressure") likely dictates the amount of gas a fish must have in its swim bladder to maintain neutral buoyancy because gases are compressible. If fish are benthic oriented, such as catfish, which are abundant riverine species in Asia and North and South America,

Table 1. Various traits that can influence the susceptibility of fish to barotrauma, along with example species.

Physiological, behavioral, or life history trait affecting susceptibility to barotrauma	Presence or absence	Susceptibility to barotrauma	Example species or project	References
The amount of free (undissolved) gas in the body				
Presence of a swim bladder	Yes	High	Chinook Salmon	Colotelo et al. (2012)
	No	Low	Pacific Lamprey	
Type of swim bladder	Open (physostomous)	Low	Chinook Salmon	Abernethy et al. (2001)
	Closed (physoclistous)	High	Bluegill	
Ability to expel gas out of the swim bladder through pneumatic duct	Better	Low	Large Rainbow Trout	Shrimpton et al. (1990)
	Poorer	High	Small Rainbow Trout	
Ability to fill the swim bladder with vasculature (rete)	Better	High	Bluegill	Harvey (1963); Fange (1983)
	Poorer	Low	Chinook Salmon	
Acclimation depth ability	Better	High	Burbot, Rainbow Trout	Fange (1983)
	Poorer	Low	Chinook Salmon	
Pressure exposure				
Acclimation depth	Deeper	High	Burbot	Stephenson et al. (2010); Fange (1983)
	Shallower	Low	Chinook Salmon	
Exposure pressure	Higher	Low	Irrigation weirs/spillways	Brown et al. (2012b)
	Lower	High	High-head dams	
Ratio of pressure change (acclimation pressure/exposure pressure)	Higher	High	Hydroturbine	Brown et al. (2012a)
	Lower	Low	Bypass system	
Rate of ratio pressure change	Higher	High	Hydroturbine	Brown et al. (2012e)
	Lower	Low	Angling	
Life history				
Migrational patterns	More migratory	High	Murray Cod, Salmonids	
	More sedentary	Low	Trout Perch (<i>Percopsis omiscomaycus</i>)	
Larval or juvenile drift stage	Yes	High	Sturgeon, Murray Cod	Brown et al. (2013); Baumgartner et al. (2009)
	No	Low	Salmonids	
Structural integrity				
	High	Low	Adult fish	Baumgartner et al. (2009); Tsvetkov et al. (1972)
	Low	High	Larval or juvenile fish or eggs	

their initial acclimation pressure may be high and the lowest pressure (often referred to as “nadir”) experienced during hydroturbine passage will likely have a greater impact on swim bladder expansion. The ratio of pressure change (acclimation pressure/hydroturbine nadir pressure) experienced by the fish during passage is therefore likely a major factor dictating the level of injury a fish may experience. In contrast, fish that typically occupy shallower depths (including those species with buoyant drifting larval stages) require less gas to achieve the same swim bladder volume needed for neutral buoyancy and therefore may be less susceptible to barotrauma due to rapid decompression. However, research is needed to determine whether benthic-oriented fish are neutrally or negatively buoyant, because this will have implications for the impact of the pressure change on barotrauma.

IMPLICATION OF THE RATIO OF PRESSURE CHANGE ON SWIM BLADDER INJURY

Fish injury following rapid pressure change is predominantly associated with expansion of preexisting gases, which often leads to rupture of the swim bladder (Brown et al. 2012e). Thus, prediction of barotraumas in fish passing through hydrostructures requires a firm understanding of the degree to which gas expands within fish when they are decompressed. Based upon Boyle’s law (see above), one of the primary determinants

of swim bladder volume change (and therefore likelihood of injury) will be the ratio of pressure change experienced by the fish during passage. This ratio may be as simple as dividing the pressure associated with the depth to which fish are acclimated and neutrally buoyant prior to passage with the nadir (lowest pressure) experienced during infrastructure passage. The following analogy acts to illustrate the importance of the ratio of pressure change rather than absolute pressure change to swim bladder volume and thus the potential for barotrauma. If a fish is brought to the surface (101 kPa) from an acclimation depth of 10 m (202 kPa) at which it is neutrally buoyant, it will experience a pressure change ratio of 2 (202 kPa/101 kPa), which implies that swim bladder volume would double (in the absence of body wall constraints). In this scenario, the absolute pressure change is 101 kPa (202 – 101 kPa; see Figure 6 for an example). The same doubling of swim bladder volume would also occur in a fish acclimated to surface water (101 kPa) that passes through a hydroturbine with a nadir pressure of 50.5 kPa because the ratio of pressure change is 2, even though the absolute pressure change is only 50.5 kPa, half the value of the example above. Understanding the significance of Boyle’s law and its potential impacts on fish can inform the hydraulic design of hydroturbines and other water control structures to control the nadir pressure and minimize the ratio of pressure change. This approach is currently being used by the U.S. Army Corps of Engineers to design new turbines to replace aging turbines at Columbia and Snake River dams (Brown et al. 2012a; Trumbo

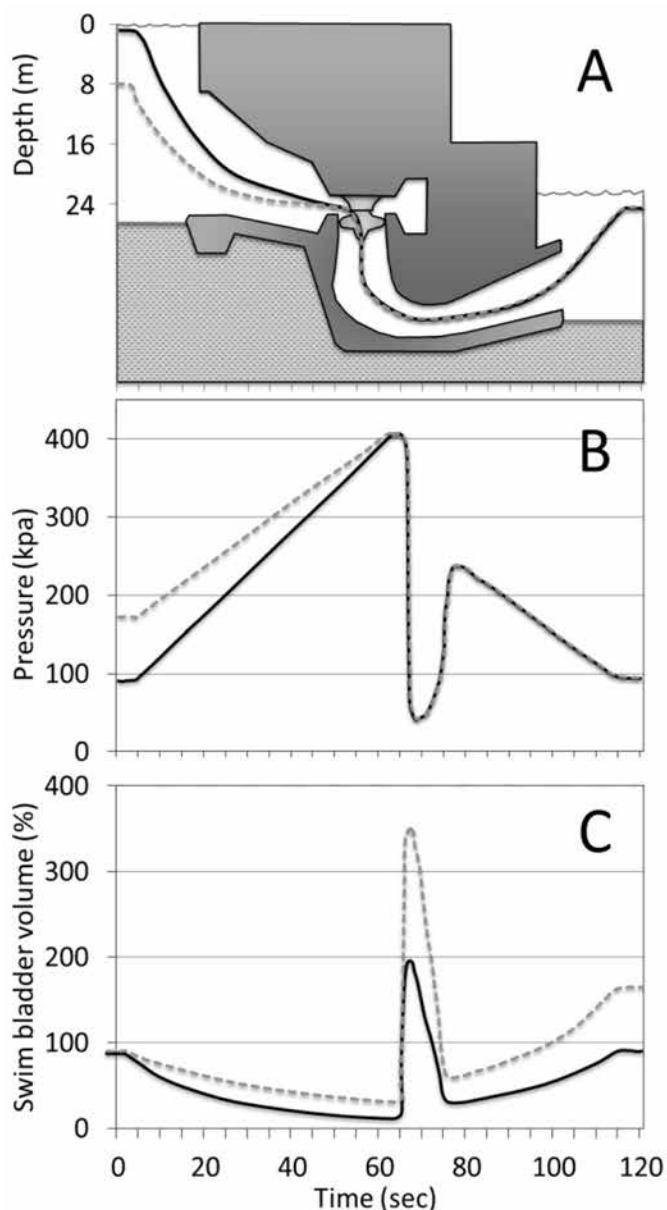


Figure 6. (A) Path through a hydroturbine, (B) an example of a pressure scenario that could be experienced, and (C) the swim bladder volume change (%) for fish neutrally buoyant at two different depths. The solid line represents a fish acclimated to near surface pressure, and the dotted line represents a fish acclimated to a depth of approximately 8 m (181.7 kPa).

et al. 2013). They recently contracted with industry to design and supply two new turbine runners for installation into Ice Harbor Lock and Dam.

DETERMINING ACCLIMATION PRESSURES AND CAPACITY FOR SWIM BLADDER INFLATION

Due to the importance of the ratio of pressure change in predicting the likelihood of barotrauma, it is necessary to determine the acclimation depth of fish as they approach hydrostructures and then determine the extent of the low pressures the fish will be exposed to during passage. Consideration must also be given to the swim bladder volume immediately prior to nadir exposure because some fish may expel gas from the

bladder when exposed to pressure reductions associated with hydrostructure passage (Brown et al. 2012e) but before the nadir pressure exposure. Some different approaches can be used when trying to determine the acclimation depths of approaching fish, based upon the physiology of that particular species.

As a first approach, the depth from which fish are approaching structures should be known. Fish could be captured or monitored just upstream of dams or weirs under the assumption that this is the depth occupied during downstream migration. Identifying these migration depths could be facilitated by stratified sampling at different depths in the water column. Fish could then be captured and placed into a simple field hyperbaric chamber, where the pressure could be controlled and modified to determine the pressure or depth where the fish is neutrally buoyant. A neutrally buoyant fish appears level in the water column, instead of head down (positively buoyant) or head up (negatively buoyant; see Pflugrath et al. 2012). Another approach would be to move fish up and down in a water column (thus varying pressure) to determine at which depth they are neutrally buoyant. It may be necessary, depending on behavior, for some fish species to be sedated in order to determine buoyancy (Brown et al. 2005). Though these types of approaches have been used in laboratory research (Brown et al. 2005), field research into this area is needed.

The above methods may be fairly straightforward in fish with physoclistous swim bladders but more complicated in physostomes where gases can be expelled through a pneumatic duct. The latter may be minimized by sedating fish in a way to minimize stress such as slowly adding anesthetic to the water (similar to Brown et al. 2005); however, specific methods need to be developed.

Determining the maximum depth at which a fish species or life stage can attain neutral buoyancy is also very important information. This information can be used to predict susceptibility to barotraumas because it will influence the maximal ratio of pressure change that a fish may experience when passing through a specific hydroturbine or weir structure. Pflugrath et al. (2012) determined the maximum depth at which juvenile Chinook Salmon could maintain neutral buoyancy by attaching weights to the outside of the fish. As more mass was added, fish would gulp air at the water surface and fill their swim bladder until they were again neutrally buoyant. As more mass was added, the point at which fish could no longer attain neutral buoyancy was determined. Calculations of swim bladder volume and Boyle's law were then used to estimate the depth at which the determined maximum swim bladder volume resulted in neutral buoyancy (Pflugrath et al. 2012). This method is only useful for physostomous fish that only fill their swim bladder through gulping air at the water surface and forcing it through the pneumatic duct (such as Chinook and Sockeye Salmon; Harvey 1963; unlike fish like American Eels [*Anguilla rostrata*], which have an open swim bladder and an active rete).

Determining the maximum depth of neutral buoyancy in physoclistous fish or physostomous fish with a functioning rete

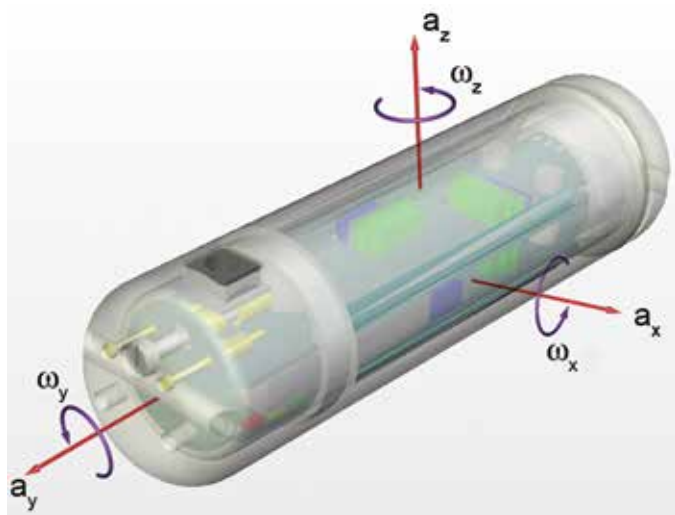


Figure 7. The multisensor fish surrogate showing the location of the measurement axes for the three rate gyros (that measure angular velocity, ω), three linear accelerometers (that measure the acceleration, a), and pressure transducers (Deng et al. 2007b).

could be conducted by slowly increasing the pressure in a hyperbaric chamber until neutral buoyancy can no longer be attained. The rate of swim bladder inflation in these fish is slow and variable among species and life stages (Fänge 1983). This will have to be taken into account in experimental designs to assess maximum acclimation depths because some species may need to be held under pressure for long periods to determine the bounds of their buoyancy regulatory abilities. In addition, if pressures are increased too quickly, fish may not be able to attain neutral buoyancy at depths as great as those treated with slower increases in pressure. For physostomous fish, it may be necessary to remove all gas bubbles from the chamber to ensure that the swim bladder is inflated solely through the rete and not by gulping compressed gas bubbles inside the chamber, which could otherwise overestimate acclimation depths.

DETERMINING EXPOSURE PRESSURES DURING FISH PASSAGE

The nadir pressure is critical in determining the ratio of pressure change and is an essential parameter in predicting barotraumas as fish pass through hydro or irrigation structures. This pressure can be estimated using computational fluid dynamics models or can be determined in situ using a multiple sensor fish surrogate (Deng et al. 2007b). The latest generation 6-degree-of-freedom version of this device is an autonomous sensor package, consisting of three rate gyros, three acceleration sensors, a pressure sensor, and a temperature sensor (Deng et al. 2007b; Figure 7). It was developed at Pacific Northwest National Laboratory for the U.S. Department of Energy and U.S. Army Corps of Engineers to characterize the physical conditions and physical stressors to which fish are exposed as they pass through complex hydraulic environments. This device is currently 24.5 mm in diameter and 90 mm in length, weighs 42 g, and is nearly neutrally buoyant in freshwater. Although this makes it similar to the size and density of a migrating yearling

Salmon smolt, this does not preclude its usefulness in systems where juvenile salmonids are not present. The multiple sensor fish surrogate provides actual measurements of pressure, the three components of linear acceleration (up-down, forward-back, and side-to-side), and the three components of rotational velocities (pitch, roll, and yaw) and internal temperature at a sampling frequency of 2,000 Hz, extending from its release location to the end of the particular passage.

For barotrauma research, the most important parameter to measure from a multiple sensor fish surrogate is pressure, which can be used to determine pressure profiles, estimate the depth of the fish during passage, and determine passage rates through different regions of a hydropower or weir structure. For example, the pressure profile of a typical turbine passage is characterized by an increase in pressure as fish pass downward toward and through the turbine intake, a rapid decompression (typically significantly below surface pressure in a fraction of a second) as the fish pass the turbine blade and a slow return to surface pressure through the draft tube (examples are provided in Brown et al. [2009] and Stephenson et al. [2010]). For passage through an undershot irrigation weir (where bypass water flows underneath the weir), the pressure profile reveals a slow increase in pressure upstream of the gate and a rapid decompression (<1 s) to slightly below surface pressure under the gate and a return to surface pressure in the tailwater.

The rate of decompression mentioned above is an important consideration when determining barotrauma susceptibility, because it can affect a physostomous species' ability to expel gas from the swim bladder. Brown et al. (2012e) found that when decompression occurred slowly (0.6–1.0 kPa/s), Chinook Salmon expelled gas more frequently and thus avoided barotrauma when compared to those decompressed at rapid rates (758.4 to 3,874.9 kPa/s; Brown et al. 2012b). Thus, clearly the rate of decompression associated with structure passage is crucial in predicting impacts; however, this information is often lacking and is needed.

Multiple sensor fish surrogates have been widely used to evaluate hydroturbine, spillway, and other fish bypass systems as well as pump storage and irrigation weir facilities. For example, it was deployed at different elevations and operation conditions to evaluate the biological performance of the advanced hydropower turbine (AHT) at Wanapum Dam (Washington State) to support its relicensing application. The AHT was designed to improve operational efficiency and increase power generation while improving the survival for fish passing through the turbines. The multiple sensor fish surrogate measurements confirmed that the AHT provided a better pressure and rate of pressure change environment for fish passage and improved the passage of juvenile salmon at Wanapum Dam (Deng et al. 2010). The multiple sensor fish surrogate is undergoing design changes such as the size, aspects of function, deployment and recovery, availability, and cost to extend its range of use and provide information for the development of fish-friendly hydrosystems internationally.

MODELING THE PROBABILITY OF MORTALITY OR INJURY

Once the range of natural acclimation pressures and the exposure pressures to be expected during passage through the hydraulic structures are determined, laboratory experiments can be conducted to relate the rate and magnitude of decompression to the expected mortality and injury of fish during infrastructure passage (Brown et al. 2009, 2012b, 2012e). These experiments involve exposing fish to pressure profiles that simulate passage through a hydroturbine or irrigation infrastructure under a range of ratios of pressure change. Such a laboratory approach for the simulation of infrastructure passage is being used to great effect to guide engineers when replacing turbines at dams in the Pacific Northwest of the United States (Brown et al. 2012a). However, a relationship between ratio pressure change and mortality and injury has only been determined for one species and life stage—juvenile Chinook Salmon (Brown et al. 2012b, 2012c)—and is likely to be species and life stage specific.

The type of equipment needed to simulate the different types of infrastructure passage can vary. Simulation of rapid decompression associated with hydroturbine passage requires sophisticated pressure chambers such as those described by Stephenson et al. (2010). These chambers are able to replicate the large ratio of pressure changes commonly observed during hydroturbine passage, which include nadirs well below atmospheric to pressures approaching 0 kPa. However, systems that only need to simulate smaller ratio pressure changes with nadirs of surface pressure (as may be characteristic of irrigation structures) or fairly slow pressure changes may be comparably simpler and inexpensive to construct. Simple systems could also be used in the laboratory to increase and decrease pressures to examine the capacity of fish to regulate their buoyancy.

The ultimate goal of this type of laboratory work should be to model the relationship between the ratio of pressure change fish are exposed to and the probability of injury or mortality. For all of the reasons previously mentioned, the ranges of ratio pressure change to be tested should be informed through careful consideration of the acclimation pressures prior to passage and the range of nadir pressures a fish is likely to be exposed to when it encounters various infrastructures throughout its life history. Once a relationship between mortality and pressure change is established with suitable statistical rigor, it is theoretically possible to predict the mortality of that species and life stage to any passage scenario, and it is only necessary to know the acclimation depth of the fish prior to passage and the nadir pressure expected at the hydropower or irrigation structure.

It is rarely practical to hold fish for extended periods following experimentation, and these holding conditions could vary widely and not represent field conditions. For these reasons, it may be possible to infer delayed mortality from the injuries immediately evident following rapid decompression during laboratory studies. McKinstry et al. (2007) combined the likelihood that fish had certain injuries present following simulated turbine passage with the likelihood of mortality to establish a

mortal injury metric. Brown et al. (2012b, 2012c) subsequently determined that the likelihood a fish will be mortally injured relates to pressure exposure using the following equation:

$$\text{Probability of mortal injury} = \frac{e^{-5.56+3.85*LRP}}{1 + e^{-5.56+3.85*LRP}}$$

where LRP is the natural log of the ratio of pressure change (acclimation/nadir pressures) to which the fish are exposed.

Techniques similar to those used by McKinstry et al. (2007) and Brown et al. (2012b) could be used to derive mortality metrics for other species. Brown et al. (2012e) determined that the ability of physostomes to expel gas from their swim bladder increases the variability in mortality when they are exposed to pressure changes. However, because physoclists cannot expel gas when rapidly decompressed, the anticipated level of variation is expected to be lower. Consequently, though Brown et al. (2012b) tested over 5,000 juvenile Chinook Salmon to determine the relationship between pressure change and fish damage, smaller sample sizes will likely suffice for physoclistous fish. However, to guide the international development of a broad range of sustainable hydro and irrigation structures, it is important to characterize the effect of pressure changes on a diverse range of physostomous and physoclistous species at different life history stages.

Laboratory experiments to determine the relationship between pressure changes and fish damage must take into consideration the depth to which fish are acclimated prior to water infrastructure contact, as well as the limits of fish buoyancy compensation. Researchers, managers, and turbine designers should be very careful when interpreting existing literature related to barotrauma in fish. Even 40 years ago, researchers like Tsvetkov et al. (1972) were concerned about the underestimation of fish injury associated with pressure changes due to methodological problems and inaccuracies. Examples provided by Tsvetkov et al. (1972) include tests where fish were not allowed to properly acclimate before being exposed to pressure reductions, such as placing physoclistous fish under high pressure and allowing them inadequate time to acclimate (just a few minutes, which is not adequate time for the swim bladder to be filled by the retia). They also highlighted studies of physostomous species where fish were acclimated to high pressures without access to air, thus not allowing fish to acclimate and fill their swim bladder.

These types of problems are not uncommon and also exist with a series of early experiments conducted by Abernethy et al. (2001, 2002, 2003). In these studies, juvenile Rainbow Trout and Chinook Salmon were placed into pressure chambers and held at surface pressure (101 kPa) or the pressures present at 19 m (191 kPa) of depth for 16–22 h. Fish were then exposed to rapid pressure reduction to pressures approximately in the range of 2–10 kPa (although the actual lowest pressures fish were exposed to during all tests were not noted). However, because the

fish held at 191 kPa were not provided with an air surface, they could not fill their swim bladder and become neutrally buoyant. Thus, results indicated that fish approaching turbines at 19 m would have the damage similar to that of fish approaching at surface pressure. However, these unrealistic results were part of a chain of research that developed into the understanding of the importance of acclimation in barotrauma experiments (Stephenson et al. 2010).

Caution should also be taken when interpreting some field-based research and scale-model investigations of turbines. For many studies of turbine passage survival, balloons and radio transmitters are attached to fish to aid in their retrieval (see Mathur et al. [1996] for an example). Before release from the surface of a dam, the balloons are injected with a liquid, leading to a chemical reaction that creates gas. This allows fish to pass through the turbine while the balloons are deflated and then be recaptured in the tailwater of a dam after the balloons have inflated. Though these studies have provided a large amount of valuable data on the effects of turbine passage, the information they provide related to barotrauma is likely a best-case scenario because fish are typically injected into turbine entrances from surface pressure. In addition, some studies done on scaled models of turbines (Cook et al. 2003; Electric Power Research Institute and U.S. Department of Energy 2011), which hold promise for reducing strike and shear injuries to fish, were conducted by releasing fish into the scale turbine at surface pressure. Thus, these studies also likely provide a best-case scenario for barotrauma-related injuries.

FIELD VALIDATION OF MODELED MORTALITY RELATIONSHIPS

Any modeled data will benefit from ground-truthing to ensure that the predictions generated in the laboratory adequately reflect the complexities experienced in real-world systems. The mortality models described above are no exception. When possible, estimates made in the laboratory can be verified on existing or pilot hydroturbine or weir structures. The development of new designs is progressing at a rapid rate, particularly in the small-scale hydropower market (Baumgartner et al. 2012). Therefore, there are great opportunities for researchers to work with developers to validate the predictions made in the laboratory when assessing the suitability of pilot projects. In some parts of southeastern Australia, state fisheries management agencies are already requiring developers to initiate field validation of new small-scale hydro designs as a preferred intermediate step between laboratory studies and possible large-scale adoption of any technology (Baumgartner et al. 2012). Field validations may involve running live fish through facilities in parallel with multiple sensor fish surrogates, with the measured mortality rates and ratio of pressure changes compared with laboratory modeling. In the end, this will improve the confidence that developers and fisheries management agencies have in laboratory generated predictions.

Another factor that is critical for increasing the confidence in field results is to design experiments so that injury and mor-

tality estimates are not biased. One important consideration is to ensure that all fish are acclimated to appropriate depths (corresponding to natural migration behavior) prior to being exposed to infrastructure passage. This has often not been the case in field examinations, as pointed out by Stephenson et al. (2010).

Another consideration involves the use of telemetry tags to estimate the route of passage and survival of fish. The mass of the tag relative to the mass of the fish (referred to as “tag burden”) has been shown to influence growth, behavior, swimming performance, and survival for tagged fish when compared to untagged conspecifics (Zale et al. 2005; Brown et al. 2010), and is of particular importance for fish exposed to rapid changes in pressure. Carlson et al. (2012) demonstrated that for juvenile Chinook Salmon exposed to rapid decompression associated with simulated turbine passage, the probability of injury and mortality increased as tag burden increased. Fish carrying a negatively buoyant telemetry tag increase the amount of gas forced into the swim bladder to offset the additional mass and achieve neutral buoyancy, making them more susceptible to barotrauma (Gallepp and Magnuson 1972; Perry et al. 2001). In addition, having a telemetry transmitter inside the body cavity may limit the amount that a swim bladder can expand before it ruptures or causes compression-related injuries. Therefore, field estimates of mortality that are based upon tagged fish have the potential to overestimate the severity of barotrauma injury. To overcome this, we recommend using the smallest tag possible to minimize tag burden or a neutrally buoyant, externally attached tag (tag burden of 0%; Deng et al. 2012; Janak et al. 2012; Brown et al. 2012d, 2013b), when examining survival of fish exposed to rapid decompression associated with infrastructure passage.

AN ADAPTIVE APPROACH TO SUSTAINABLE DEVELOPMENT

Recently there have been renewed global efforts in the expansion of hydropower projects. The retrofitting of new hydro projects to existing structures has also been encouraged by the U.S. Department of Energy to increase the output of American hydropower capability (Hadjerioua et al. 2012). In some parts of the world, established irrigation networks are being explored for their potential to support new economies relating to power generation (Botto et al. 2010). In many other regions, new dams are being planned. As part of Brazil’s decennial plan (MME/EPE 2011), 48 hydropower dams are proposed for construction by 2020. Most of these would be in the Amazon and Tocantins-Araguaia hydrographic regions. These dams are likely to threaten fish diversity of the Amazon (20% of the world’s freshwater fishes, representing about 1,400 species) by regulating flows and disrupting important fish migrations (Rosa and Lima 2008). It is a similar story for the world’s largest inland fishery in the Lower Mekong River, where it is predicted that construction of 11 mainstem dams will lead to a major decline in fish populations, significantly compromising food security (Halls and Kshatriya 2009). If these dire scenarios are to be avoided, it will be necessary to ensure safe fish passage at new and existing structures, with management decisions underpinned by rigorous science.

Based on the information provided in this review, we recommend a logical staged approach to conducting the barotrauma research that will be necessary for refining infrastructure design throughout the world (Figure 8). The first stage involves conducting the field or desktop investigations necessary to determine which species and life history stages are of interest. The majority of barotrauma research to date has focused on the susceptibility of juvenile Chinook Salmon, largely driven by the legislative need to protect this threatened species during its critical seaward-migration in the U.S. Pacific Northwest, where a large number of hydropower facilities could negatively influence their survival. In other large river systems of the world, including the Mekong River in Southeast Asia, the Amazon in South America, and the Murray-Darling River in Australia, a diverse range of species and life history stages undertake downstream migrations (Barthem et al. 1991; Araujo-Lima and Oliveira 1998; Humphries and King 2004; Lintermans and Phillips 2004; Baran and Myschowoda 2008) and are therefore at risk of injury and mortality at existing and proposed hydro-

power and irrigation operations. For fisheries scientists wishing to embark on barotrauma-related research in these regions, the decision regarding which species and size classes to prioritize for study is daunting. Such decisions could be aided by considering the many factors associated with the susceptibility to barotrauma (see Table 1), including both ecological and biological considerations. By assigning weighted scores corresponding to the factors for each species in an assemblage of fish, multivariate classification approaches could be used to identify key groupings of fish based upon similarity in barotrauma vulnerability (see Table 1). Choosing some fish and life history stages from the higher vulnerability groupings may provide a good starting point for experimentation.

Once the species of study have been selected, a combination of field and lab testing and modeling can both determine the depth of neutral buoyancy as fish approach structures during migration (or acclimation depth) and the expected range of exposure pressures during infrastructure passage (Figure 8). This will provide a range of ratio pressure changes that fish can be subjected to in experimental pressure chambers and, from this, injury or mortality relationships can be modeled. Care must be taken during this experimentation to ensure that fish are properly acclimated (acclimated to the range of pressures that reflect depths where fish are neutrally buoyant as they approach structures). Fish acclimated to surface pressures are likely to provide results that are not necessarily representative of fish in the natural environment because acclimation depth is a very important parameter (Tsvetkov et al. 1972; Stephenson et al. 2010).

The models generated by laboratory experiments can then be used to refine infrastructure design, with models and designs further validated during pilot field trials. This field validation and testing is seen as a critical link in the adaptive management loop that will ensure that fisheries scientists and engineers keep the research and development applied and ultimately targeted on the goal of promoting sustainable water resource development.

Minimizing fisheries losses at water infrastructure is a global problem, and major investment will be needed to promote innovative technology if the current fisheries losses throughout the world are to be abated. A global problem requires a global solution, and we therefore encourage international cooperation in future research efforts. There are many similarities in fish species among different regions of the world and, thus, international collaboration will greatly reduce redundancy. For example, catfish species are common throughout North and South America, Asia, and Europe, and sturgeons (a type of fish with drifting larval stages) are common in North America, Asia, and Europe.

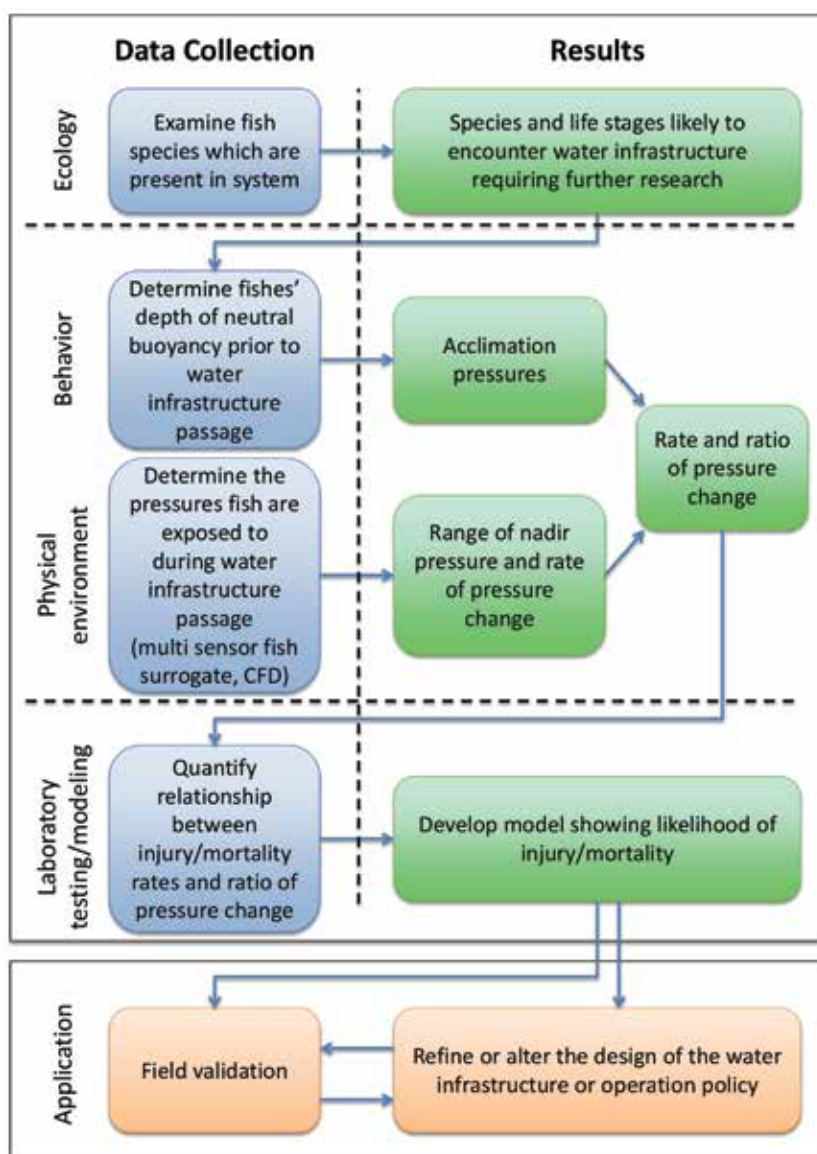


Figure 8. Recommended barotrauma research framework showing logical flow of activities and linkages with industry under an adaptive management model.

Similarly, larval drift will be a key consideration in many parts of Australia, Asia, and South America and also occurs among North American species. We are at a time where technology allows us to initiate downstream passage research among many species at a global scale using standardized approaches. Such a global approach could provide a more rapid advancement of science and engineering while minimizing duplication of effort.

ACKNOWLEDGMENTS

We thank Ricardo Walker, Katrina Cook, Rachelle Johnson, Latricia Rozeboom, and Joanne Duncan of PNNL for assistance. We thank Brad Trumbo and Martin Ahmann of the Walla Walla District, U.S. Army Corps of Engineers, for comments on the article. We also thank Kent Hortle for comments on an earlier draft of this article.

FUNDING

We thank the U.S. Department of Energy for providing funding for interns who assisted with this article through their Science Undergraduate Laboratory Internship program.

REFERENCES

- Abernethy, C. S., B. G. Amidan, and G. F. Čada. 2001. Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish. Report of the Pacific Northwest National Laboratory, PNNL-1347, Richland, Washington.
- . 2002. Simulated passage through a modified Kaplan turbine pressure regime: a supplement to “laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish.” Report of the Pacific Northwest National Laboratory, PNNL-13470-A, Richland, Washington.
- . 2003. Fish passage through a simulated horizontal bulb turbine pressure regime: a supplement to “laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish.” Report of the Pacific Northwest National Laboratory, PNNL-13470-B, Richland, Washington.
- Agostinho, A., F. Pelicice, and L. Gomes. 2008. Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. *Brazilian Journal of Biology* 68:1119–1132.
- Alexander, R. M. 1962. The structure of the Weberian apparatus in the cyprini. *Proceedings of the Zoological Society of London* 139:451–473.
- Araujo-Lima, C., and E. Oliveira. 1998. Transport of larval fish in the Amazon. *Journal of Fish Biology* 53:297–306.
- Bailey, H. C., and S. I. Doroshov. 1995. The duration of the interval associated with successful inflation of the swimbladder in larval striped bass (*Morone saxatilis*). *Aquaculture* 131:135–143.
- Baran, E., and C. Myschowoda. 2008. Dams and fisheries in the Mekong basin. *Aquatic Ecosystem Health and Management* 12:227–234.
- Baran, E., N. Van Zalinge, and P. B. Ngor. 2001. Floods, floodplains and fish production in the Mekong basin: present and past trends. Pages 920–932 in A. Ahyaudin, et al., editors. *Proceedings of the Second Asian Wetlands Symposium, 27–30 August 2001, Penang, Malaysia*. Penerbit Universiti Sains Malaysia, Pulau Pinang, Malaysia.
- Barthem, R. B., M. C. L. de Brito Ribeiro, and M. Petrere. 1991. Life strategies of some long-distance migratory catfish in relation to hydroelectric dams in the Amazon Basin. *Biological Conservation* 55:339–345.
- Bartle, A. 2002. Hydropower potential and development activities. *Energy Policy* 30(14):1231–1239.
- Baumgartner, L. J., C. Boys, and R. Barton. 2012. Mini hydro development workshop: developing sustainable solutions for native fish. *Ecological Management and Restoration* 13(3):1–2.
- Baumgartner, L. J., N. Reynoldson, and D. M. Gilligan. 2006. Mortality of larval Murray Cod (*Maccullochella peelii peelii*) and Golden Perch (*Macquaria ambigua*) associated with passage through two types of low-head weirs. *Marine and Freshwater Research* 57:187–191.
- Beyer, D. L., B. G. D’Aoust, and L. S. Smith. 1976. Decompression-induced bubble formation in salmonids: comparison to gas bubble disease. *Undersea Biomedical Research* 3(4):321–338.
- Bishai, H. M. 1961. The effect of pressure on the survival and distribution of larval and young fish. *Journal du Conseil International pour l’Exploration de la Mer* 26(3):292–311.
- Botto, A., P. Claps, D. Ganora, and F. Laioa, F. 2010. Regional-scale assessment of energy potential from hydrokinetic turbines used in irrigation channels. *Proceedings of the SEEP2010 Conference, June 29–July 2, Bari, Italy*.
- Braaten, P. J., D. B. Fuller, L. D. Holte, R. D. Lott, W. Viste, T. F. Brandt, and R. G. Lagare. 2008. Drift dynamics of larval Pallid Sturgeon and Shovelnose Sturgeon in a natural side channel of the Upper Missouri River, Montana. *North American Journal of Fisheries Management* 28(3):808–826.
- Brown, R. S., M. L. Ahmann, B. A. Trumbo, and J. Foust. 2012a. Fish protection: cooperative research advances fish friendly turbine design. *Hydro Review* 31(8):48–53.
- Brown, R. S., T. J. Carlson, A. J. Gingerich, J. R. Stephenson, B. D. Pflugrath, A. E. Welch, M. J. Langeslay, M. L. Ahmann, R. L. Johnson, J. R. Skalski, A. G. Seaburg, and R. L. Townsend. 2012b. Quantifying mortal injury of juvenile Chinook Salmon exposed to simulated hydro-turbine passage. *Transactions of the American Fisheries Society* 141(2):570.
- . 2012c. Erratum: Quantifying mortal injury of juvenile Chinook Salmon exposed to simulated hydro-turbine passage. *Transactions of the American Fisheries Society* 141(1):147–157.
- Brown, R. S., T. J. Carlson, A. E. Welch, J. R. Stephenson, C. S. Abernethy, B. D. Ebberts, M. J. Langeslay, M. L. Ahmann, D. H. Feil, J. R. Skalski, and R. L. Townsend. 2009. Assessment of barotrauma from rapid decompression of depth-acclimated juvenile Chinook Salmon bearing radiotelemetry transmitters. *Transactions of the American Fisheries Society* 138(6):1285–1301.
- Brown, R. S., K. V. Cook, B. D. Pflugrath, L. L. Rozeboom, R. C. Johnson, J. McLellan, T. J. Linley, Y. Gao, L. J. Baumgartner, F. E. Dowell, E. A. Miller, T. A. White. 2013a. Vulnerability of larval and juvenile White Sturgeon to barotrauma: can they handle the pressure? *Conservation Physiology* 1:1–9.
- Brown, R. S., Z. D. Deng, K. V. Cook, B. D. Pflugrath, X. Li, T. Fu, J. J. Martinez, H. Li, B. A. Trumbo, M. L. Ahmann, and A. G. Seaburg. 2013b. A field evaluation of an external and neutrally buoyant acoustic transmitter for juvenile Salmon: implications for estimating hydro-turbine passage survival. *PLoS ONE* 8(10):e77744.
- Brown, R. S., D. R. Geist, and K. A. Deters. 2005. Laboratory evaluation of surgically implanted acoustic transmitters on the swimming performance, buoyancy compensation, survival, and growth of juvenile Sockeye and fall Chinook Salmon. Pacific Northwest National Laboratory, PNWD-3515, Richland, Washington.
- Brown, R. S., R. A. Harnish, K. M. Carter, J. W. Boyd, K. A. Deters, and M. B. Eppard. 2010. An evaluation of the maximum tag burden for implantation of acoustic transmitters in juvenile Chinook Salmon. *North American Journal of Fisheries Management* 30:499–505.
- Brown, R. S., B. D. Pflugrath, T. J. Carlson, and Z. D. Deng. 2012d. The effect of an externally attached neutrally buoyant transmitter on mortal injury during simulated hydro-turbine passage. *Journal of Renewable and Sustainable Energy* 4(013107):1–7.
- Brown, R. S., B. D. Pflugrath, A. H. Colotelo, C. J. Brauner, T. J. Carlson, and Z. D. Deng. 2012e. Pathways of barotrauma in juvenile salmonids exposed to simulated hydro-turbines passage: Boyle’s law vs. Henry’s law. *Fisheries Research* 121–122:43–50.
- Cada, G. F. 1990. A review of studies relating to the effects of propeller-type turbine passage on fish early life stages. *North American Journal of Fisheries Management* 10:418–426.
- Cada, G., J. Loar, L. Garrison, R. Fisher, and D. Neitzel. 2006. Efforts to reduce mortality to hydroelectric turbine-passed fish: locating and quantifying damaging shear stresses. *Environmental Management* 37(6):898–906.
- Carlson, T. J., R. S. Brown, J. R. Stephenson, B. D. Pflugrath, A. H. Colotelo, A. J. Gingerich, P. L. Benjamin, M. J. Langeslay, M. L. Ahmann, R. L. Johnson, J. R. Skalski, A. G. Seaburg, and R. L. Townsend. 2012. The influence of tag presence on the mortality of juvenile Chinook Salmon exposed to simulated hydro-turbine passage: implications for survival estimates and management of hydroelectric facilities. *North American Journal of Fisheries Management* 32(2):249–261.
- Carlson, T. J., J. P. Duncan, and Z. Deng. 2008. Data overview for sensor fish samples acquired at Ice Harbor, John Day, and Bonneville II dams in 2005, 2006, and 2007. Pacific Northwest National Laboratory, Report PNNL-17398, Richland, Washington.
- Carlson, T. J., J. P. Duncan, and R. L. Johnson. 2005. Characterization of pump flow at the Grand Coulee Dam pumping station for fish passage, 2004. Pacific Northwest National Laboratory, Report PNNL-14998, Richland, Washington.
- Castro, N. J., G. A. Dantas, and A. S. Leite. 2012. The real question about Belo Monte: have or not have it? *Economical Value Journal*: January: Book A: 8p. Available: <http://www.nuca.ie.ufij.br/gesel/>. (February 2014).
- Colotelo, A. H., B. D. Pflugrath, R. S. Brown, C. J. Brauner, R. P. Mueller, T. J. Carlson, Z. D. Deng, M. L. Ahmann, and B. A. Trumbo. 2012. The effect of rapid and sustained decompression on barotrauma in juvenile Brook Lamprey and Pacific Lamprey: implications for passage at hydroelectric facilities. *Fisheries Research* 129–130:17–20.
- Cook, T. C., G. E. Hecker, S. Amaral, P. Stacy, F. Lin, and E. Taft. 2003. Pilot scale tests Alden/Concepts NREC turbine. Alden Research Laboratory, Holden, MA, No. DOE/ID/13733.
- Corbett, B. W., and P. M. Powles. 1986. Spawning and larva drift of sympatric walleyes and white suckers in an Ontario stream. *Transactions of the American Fisheries Society* 115(1):41–46.
- Coutant, C. C., and R. R. Whitney. 2000. Fish behavior in relation to passage through hydropower turbines: a review. *Transactions of the American Fisheries Society* 129:351–380.
- Cramer, F. K., and R. C. Oligher. 1964. Passing fish through hydraulic turbines. *Transactions of the American Fisheries Society* 93:243–259.
- D’Aoust, B. G., and L. S. Smith. 1974. Bends in fish. *Comparative Biochemistry and Physiology* 49A:311–321.
- Deng, Z., T. J. Carlson, J. P. Duncan, and M. C. Richmond. 2007a. Six-degree-of-freedom sensor fish design and instrumentation. *Sensors* 7:3399–3415.
- Deng, Z., T. J. Carlson, J. P. Duncan, M. C. Richmond, and D. D. Dauble. 2010. Use of

- an autonomous sensor to evaluate the biological performance of the advanced turbine at Wanapum Dam. *Journal of Renewable and Sustainable Energy* 2(053104):1–11.
- Deng, Z., T. J. Carlson, G. R. Ploskey, M. C. Richmond, and D. D. Dauble. 2007b. Evaluation of blade-strike models for estimating the biological performance of Kaplan turbines. *Ecological Modelling* 208(2–4):165–176.
- Deng, Z., G. R. Guensch, C. A. McKinstry, R. P. Mueller, D. D. Dauble, and M. C. Richmond. 2005. Evaluation of fish-injury mechanisms during exposure to turbulent shear flow. *Canadian Journal of Fisheries and Aquatic Sciences* 62(7):1513–1522.
- Deng, Z. D., J. J. Martinez, A. H. Colotelo, T. K. Abel, A. P. LeBarge, R. S. Brown, B. D. Pflugrath, R. P. Mueller, T. J. Carlson, A. G. Seaburg, R. L. Johnson, M. L. Ahmann. 2012. Development of external and neutrally buoyant acoustic transmitters for juvenile salmon turbine passage evaluation. *Fisheries Research* 113:94–105.
- Dudgeon, D., A. H. Arthington, M. O. Gessner, Z. I. Kawabata, D. J. Knowler, C. Lévêque, R. J. Naiman, A. H. Prieur-Richard, D. Soto, and M. L. J. Stiassny. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* 81:163–182.
- Dumbarton, T. C., M. Stoyek, R. P. Croll, and F. M. Smith. 2010. Adrenergic control of swimbladder deflation in the Zebrafish (*Danio rerio*). *Journal of Experimental Biology* 213:2536–2546.
- Ebel, W. J. 1969. Supersaturations of nitrogen in the Columbia River and its effect on Salmon and Steelhead Trout. *Fishery Bulletin* 68(1):1–11.
- Electric Power Research Institute and U.S. Department of Energy. 2011. “Fish friendly” hydropower turbine development and deployment: Alden turbine preliminary engineering and model testing. Electric Power Research Institute, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.
- Fange, R. 1983. Gas exchange in fish swim bladder. *Reviews in Physiological and Biochemical Pharmacology* 97:112–148.
- Franke, G. F., D. R. Webb, R. K. Fisher, Jr., D. Mathur, P. N. Hopping, P. A. March, M. R. Headrick, I. T. Laczó, Y. Ventikos, and F. Sotiropoulos. 1997. Development of environmentally advanced hydropower turbine system design concepts. Report to Idaho National Engineering Laboratory, Idaho Operations Office, Idaho Falls, Idaho.
- Franz, G. 1937. The gas secretion reflex [gasspucken] in fish and the function of the Weberian apparatus. *Journal of Comparative Physiology* 25:193–238.
- Gallepp, G. W., and J. J. Magnuson. 1972. Effects of negative buoyancy on the behavior of the bluegill, *Lepomis macrochirus* Rafinesque. *Transactions of the American Fisheries Society* 101:507–512.
- Geoscience Australia and ABARE (Australian Bureau of Agricultural and Resource Economics). 2010. Hydro energy. Pages 225–238 in Department of Resources Energy and Tourism, Geoscience Australia and Australian Bureau of Agricultural and Resource Economics, editors. Australian Energy Resource Assessment. Commonwealth Government of Australia, Canberra, ACT.
- Godinho, A., and B. Kynard. 2009. Migratory fishes of Brazil: life history and fish passage needs. *River Research and Applications* 25:702–712.
- Gravel, M., and S. J. Cooke. 2008. Severity of barotrauma influences the physiological status, postrelease behavior, and fate of tournament-caught smallmouth bass. *North American Journal of Fisheries Management* 28:607–617.
- Hadjerioua, B., Y. Wei, and S. C. Kao. 2012. An assessment of energy potential at non-powered dams in the United States. Prepared for the U.S. Department of Energy, Wind and Water Power Program, Budget Activity Number ED 19 07 04 2. Report of Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Halls, A. S., and M. Kshatriya. 2009. Modelling the cumulative barrier and passage effects of mainstream hydropower dams on migratory fish populations in the Lower Mekong basin. Mekong River Commission, MRC Technical Paper No. 25, Vientiane, Laos.
- Harvey, H. H. 1963. Pressure in the early life history of Sockeye Salmon. Doctoral dissertation. University of British Columbia, Vancouver.
- Harvey, H. H., W. S. Hoar, and C. R. Bothorn. 1968. Sounding response of the Kokanee and Sockeye Salmon. *Journal of the Fisheries Research Board of Canada* 25(6):1115–1131.
- Hortle, K. G. 2007. Consumption and the yield of fish and other aquatic animals from the Lower Mekong basin. Mekong River Commission, MRC Technical Paper No. 16, Vientiane, Laos.
- . 2009. Fisheries of the Mekong River basin. 87pp. in C. Campbell, editor. The Mekong. biophysical environment of an international river basin. Elsevier, New York.
- Humphries, P. and A. J. King. 2004. Drifting fish larvae in Murray-Darling Basin rivers: Compositions, spatial and temporal patterns and distance drifted. Pages 51–58 in M. Lintermans and B. Phillips, editors. Downstream movement of fish in the Murray-Darling basin. Statements, recommendations and supporting papers from a workshop held in Canberra, 3–4 June 2003. Murray-Darling Basin Commission, Canberra, Australia.
- Humphries, P., L. G. Serafini, and A. J. King. 2002. River regulation and fish larvae: variation through space and time. *Freshwater Biology* 47:1307–1331.
- Jacobs, W. 1934. Studies on the physiology of the swimbladder of fish. III. Air swallowing and gas secretion in physostomes. *Journal of Comparative Physiology* 20:674–698.
- Janak, J. M., R. S. Brown, A. H. Colotelo, B. D. Pflugrath, J. R. Stephenson, Z. D. Deng, and T. J. Carlson. 2012. The effects of neutrally buoyant, externally attached transmitters on swimming performance and predator avoidance of juvenile Chinook salmon. *Transactions of the American Fisheries Society* 141(5):1424–1432.
- Keniry, M. J., W. A. Brofka, W. H. Horns, and J. E. Marsden. 1996. Effects of decompression and puncturing the gas bladder on survival of tagged Yellow Perch. *North American Journal of Fisheries Management* 16:201–206.
- Kingsford, R. T. 2000. Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* 25:109–127.
- Koehn, J. D., and D. J. Harrington. 2005. Collection and distribution of the early life stages of the Murray cod (*Maccullochella peelii peelii*) in a regulated river. *Australian Journal of Zoology* 53:137–144.
- Lintermans, M., and B. Phillips, editors. 2004. Downstream movement of fish in the Murray-Darling basin—workshop held in Canberra, 3–4 June 2003: statement, recommendations and supporting papers. Murray-Darling Basin Commission, Canberra, Australia.
- Mathur, D., P. G. Heisey, E. T. Euston, J. R. Skalski, and S. Hays. 1996. Turbine passage survival estimation for chinook salmon smolts (*Oncorhynchus tshawytscha*) at a large dam on the Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 53:542–549.
- McKinstry, C. A., T. J. Carlson, and R. S. Brown. 2007. Derivation of a mortal injury metric for studies of rapid decompression of depth-acclimated physostomous fish. Pacific Northwest National Laboratory, Richland, Washington.
- MME/EPE (Ministério de Minas e Energia/Empresa de Pesquisa Energética). 2011. Decennial Plan for energy expansion 2020. Report: Ministry of Mines and Energy/Energy Research Company, Brasília, Brazil, 343pp.
- Muir, W. D., S. G. Smith, J. G. Williams, and B. P. Sandford. 2001. Survival of juvenile salmonids passing through bypass systems, turbines, and spillways with and without flow deflectors at Snake River dams. *North American Journal of Fisheries Management* 21(1):135–146.
- Paish, O. 2002. Small hydro power: technology and current status. *Renewable and Sustainable Energy Reviews* 6:537–556.
- Pelster, B., and D. Randall. 1998. The physiology of the root effect. Pages 113–149 in S. F. Perry II and B. L. Tuffis, editors. Fish physiology “fish respiration.” Academic Press, San Diego, California.
- Perry, R. W., N. S. Adams, and D. W. Rondorf. 2001. Buoyancy compensation of juvenile Chinook salmon implanted with two different size dummy transmitters. *Transactions of the American Fisheries Society* 130:46–52.
- Pflugrath, B. D., R. S. Brown, and T. J. Carlson. 2012. Maximum neutral buoyancy depth of juvenile Chinook Salmon: implications for survival during hydroturbine passage. *Transactions of the American Fisheries Society* 141:2:520–525.
- Purkett, C. A. 1961. Reproductions and early development of the paddlefish. *Transactions of the American Fisheries Society* 90(2):125–129.
- Ricciardi, A., R. J. Neves, and J. B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. *Conservation Biology* 13:1–3.
- Rieger, P. W., and R. C. Summerfelt. 1998. Microvideography of gas bladder inflation in larval Walleye. *Journal of Fish Biology* 53:93–99.
- Rosa, R. S., and F. C. T. Lima. 2008. The Brazilian endangered fish species. Pages 9–275 in Machado, A. B. M., G. M. Drummond, and A. P. Paglia, editors. Red list of endangered species of the Brazilian fauna. 1st Edition, Brasília-DF: MMA (Ministry of the Environment), Belo Horizonte, MG: Biodiversitas Foundation.
- Rummer, J. L., and W. A. Bennett. 2005. Physiological effects of swim bladder overexpansion and catastrophic decompression on Red Snapper. *Transactions of the American Fisheries Society* 134:1457–1470.
- Saunders, D. L., J. J. Meeuwig, and C. J. Vincent. 2002. Freshwater protected areas: strategies for conservation. *Conservation Biology* 16:30–41.
- Shrimpton, J. M., D. J. Randall, and L. E. Fidler. 1990. Factors affecting swim bladder volume in Rainbow Trout (*Oncorhynchus mykiss*) held in gas supersaturated water. *Canadian Journal of Zoology* 68:962–968.
- Stephenson, J. R., A. G. Gingerich, R. S. Brown, B. D. Pflugrath, Z. Deng, T. J. Carlson, M. J. Langeslay, M. L. Ahmann, R. L. Johnson, and A. G. Seaburg. 2010. Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory. *Fisheries Research* 106:271–278.
- Trotter, A. J., S. C. Battaglene, and P. M. Pankhurst. 2003. Effects of photoperiod and light intensity on initial swim bladder inflation, growth and post-inflation viability in cultured striped trumpeter (*Latris lineata*) larvae. *Aquaculture* 224:141–158.
- Tsvetkov, V. I., D. S. Pavlov, and V. K. Nezdolij. 1972. Changes of hydrostatic pressure lethal to young of some freshwater fish. *Journal of Ichthyology* 12:307–318.
- Van Heuvelen, A. 1982. Physics; a general introduction. Little, Brown and Co., Boston, Massachusetts.
- Williams, J. G., S. G. Smith, and W. D. Muir. 2001. Survival estimates for downstream migrant yearling juvenile salmonids through the Snake and Columbia rivers hydropower system, 1966–1980 and 1993–1999. *North American Journal of Fisheries Management* 21:310–317.
- Wittenberg, J. B., M. J. Schwend, and B. A. Wittenberg. 1964. The secretion of oxygen into the swim-bladder of fish. *Journal of General Physiology* 48:337–355.
- Zale, A. V., C. Brooke, and W. C. Fraser. 2005. Effects of surgically implanted transmitter weights on growth and swimming stamina of small adult Westslope Cutthroat Trout. *Transactions of the American Fisheries Society* 134:653–660. 