

Estimation of the Risks of Collision or Strike to Freshwater Aquatic Organisms Resulting from Operation of Instream Hydrokinetic Turbines

May 2011

Prepared by

Peter E. Schweizer
Glenn F. Cada
Mark S. Bevelhimer

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via the U.S. Department of Energy (DOE) Information Bridge.

Web site <http://www.osti.gov/bridge>

Reports produced before January 1, 1996, may be purchased by members of the public from the following source.

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Web site <http://www.ntis.gov/support/ordernowabout.htm>

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange (ETDE) representatives, and International Nuclear Information System (INIS) representatives from the following source.

Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Web site <http://www.osti.gov/contact.html>

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Environmental Sciences Division

**ESTIMATION OF THE RISKS OF COLLISION OR STRIKE
TO FRESHWATER AQUATIC ORGANISMS RESULTING
FROM OPERATION OF INSTREAM HYDROKINETIC TURBINES**

P. E. Schweizer
G. F. Cada
M. S. Bevelhimer

Date Published: May 2011

FY 2010 Annual Progress Report

Prepared for the
Wind and Water Power Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
Washington, D.C.

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

| | Page |
|--|-------------|
| LIST OF FIGURES | v |
| LIST OF TABLES | vii |
| ACKNOWLEDGEMENTS | IX |
| 1. INTRODUCTION | 1 |
| 2. EFFECTS OF ROTOR BLADE STRIKE ON AQUATIC ANIMALS | 3 |
| 3. PROPOSED FRESHWATER HK DEVELOPMENT SITES AND TURBINE DESIGNS..... | 9 |
| 4. POTENTIALLY AFFECTED FRESHWATER ORGANISMS | 13 |
| 4.1 AQUATIC HABITATS | 13 |
| 4.2 FISH | 15 |
| 4.3 LARVAL FISH AND DRIFT ASSEMBLAGES | 15 |
| 5. STRIKE RISK MODEL | 17 |
| 5.1 IDENTIFIED KNOWLEDGE GAPS | 27 |
| 6. DISCUSSION | 29 |
| 6.1 FUTURE EFFORTS | 30 |
| 6.1.1 EPRI/Alden Studies of Fish Interactions with Scale Model MHK Rotor | 31 |
| 6.1.2 ORNL Studies of Blade Strike in Passively Drifting Juvenile Fish | 32 |
| 7. REFERENCES | 35 |
| APPENDIX A. FISH SPECIES IN THE MISSISSIPPI RIVER BASIN THAT MAY BE AFFECTED BY HYDROKINETIC TURBINE STRIKE | A-1 |

LIST OF FIGURES

| Figure | | Page |
|--------|--|------|
| 1 | General types of current energy converters | 4 |
| 2 | Artist's impression of the Seagen marine current turbine in Strangford Lough, UK | 5 |
| 3 | Predicted zone of potentially damaging strike associated with an unducted horizontal axis turbine..... | 6 |
| 4 | Ducted horizontal axis hydrokinetic turbine, installed on the Mississippi River near Hastings, Minnesota..... | 6 |
| 5 | Ducted horizontal axis Free Flow Power SmarTurbine™ generator for in-stream deployment at locations in the Mississippi and the Atchafalaya rivers | 6 |
| 6 | Preliminary permits issued by the Federal Energy Regulatory Commission for tidal, wave, and riverine hydrokinetic projects | 10 |
| 7 | Preliminary permits under consideration (pending) by the Federal Energy Regulatory Commission for tidal, wave, and riverine hydrokinetic projects | 12 |
| 8 | Simplified cross section of a river, with different aquatic habitats that contrast in water depth and flow velocity | 13 |
| 9 | Increase in probability of blade encounter with increasing number of turbine blades | 19 |
| 10 | Probability of blade strike as a function of total length of a fish passing through the rotor-swept area | 20 |
| 11 | Hypothetical probabilities of blade encounter for a fish of 15 cm length, passively entrained in the water column during single passage through the rotor-swept area of a hydrokinetic turbine..... | 21 |
| 12 | Decline in risk of blade encounter to fish with increase in river flow velocity | 22 |
| 13 | Increased ground speed relative to flow velocity during passage through the rotor-swept area of a HK device reduces the probability of blade encounter for fish..... | 23 |
| 14 | Distribution of plankton, macroinvertebrates and fish larvae across habitats in a large river, with > 60 percent of drift assemblage concentrated in the uppermost 1.8 meters of a hypothetical river with 5.4 meter depth | 24 |
| 15 | Densities of fish larvae (number/100 m ³) in various portions of a cross section of lower Navigation Pool 5 in the Upper Mississippi River during low density (a) and high density (b) periods..... | 24 |
| 16 | Conceptual overlay of a hydrokinetic array transect on a river cross section showing river habitat for different fish taxa | 25 |
| 17 | Simplified riverbed geometry for calculation of river cross section area, looking downstream..... | 25 |
| 18 | Example of a cross-section velocity profile for the Tanana River near Nenana, Alaska | 29 |
| 19 | Proposed fish screen assembly to reduce risk of blade strike, by UEK® System (Underwater Electric Kite) for the Yukon River Hydrokinetic Project..... | 30 |

LIST OF TABLES

| Table | | Page |
|--------------|--|-------------|
| 1 | Preliminary permits issued or pending for hydrokinetic projects as of July 01, 2010..... | 11 |
| 2 | Distribution of freshwater organisms along a cross section of a large river..... | 14 |
| 3 | Mean horizontal and vertical distribution of fish larvae (no./m ³) in the Missouri River | 15 |
| A-1 | Distribution and abundance of fishes in the headwaters (HW), upper (UMR) and open river (OR) segments of the Mississippi River | A-1 |
| A-2 | List of Fish of the Central Ohio River (River Mile 328 – 654) | A-9 |
| A-3 | Juvenile fishes collected in seasonally inundated backwaters of the Atchafalaya River Basin during 2005-2006 | A-11 |
| A-4 | Ichthyoplankton collected during 2005-2006 in the Atchafalaya River Basin. | A-13 |

ACKNOWLEDGEMENTS

We thank Jocelyn Brown-Saracino whose comments and suggestions helped us to improve an earlier version of this report. This research was supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Wind & Water Power Program. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

1. INTRODUCTION

Hydrokinetic energy technologies have been proposed as renewable, environmentally preferable alternatives to fossil fuels for generation of electricity. Hydrokinetic technologies harness the energy of water in motion, either from waves, tides or from river currents. For energy capture from free-flowing rivers, arrays of rotating devices are most commonly proposed. The placement of hydrokinetic devices in large rivers is expected to increase the underwater structural complexity of river landscapes. Moore and Gregory (1988) found that structural complexity increased local fish populations because fish and other aquatic biota are attracted to structural complexity that provides microhabitats with steep flow velocity gradients (Liao 2007). However, hydrokinetic devices have mechanical parts, blades, wings or bars that move through the water column, posing a potential strike or collision risk to fish and other aquatic biota. Furthermore, in a setting with arrays of hydrokinetic turbines the cumulative effects of multiple encounters may increase the risk of strike.

Submerged structures associated with a hydrokinetic (HK) project present a collision risk to aquatic organisms and diving birds (Čada et al. 2007). Collision is physical contact between a device or its pressure field and an organism that may result in an injury to that organism (Wilson et al. 2007). Collisions can occur between animals and fixed submerged structures, mooring equipment, horizontal or vertical axis turbine rotors, and structures that, by their individual design or in combination, may form traps. This report defines strike as a special case of collision where a moving part, such as a rotor blade of a HK turbine intercepts the path of an organism of interest, resulting in physical contact with the organism. The severity of a strike incidence may range from minor physical contact with no adverse effects to the organism to severe strike resulting in injury or death of the organism. Harmful effects to animal populations could occur directly (e.g., from strike mortality of individuals) or indirectly (e.g., if the loss of prey species to strike reduces food for predators). Although actively swimming or passively drifting animals may collide with any of the physical structures associated with hydrokinetic devices, turbine rotors are the most likely sources for risk of strike or significant collision (DOE 2009). It is also possible that during a close encounter with a HK device no physical contact will be made between the device and the organism, either because the animal avoids the device by successfully changing its direction of movement, or by successfully evading any moving parts of the device.

Oak Ridge National Laboratory (ORNL) has been funded by the US Department of Energy (DOE) Waterpower Program to evaluate strike potential and consequences for Marine and Hydrokinetic (MHK) technologies in rivers and estuaries of the United States. We will use both predictive models and laboratory/field experiments to evaluate the likelihood and consequences of strike at HK projects in rivers. Efforts undertaken at ORNL address three objectives:

1. Assess strike risk for marine and freshwater organisms;
2. Develop experimental procedures to assess the risk and consequences of strike; and
3. Conduct strike studies in experimental flumes and field installations of hydrokinetic devices.

During the first year of the study ORNL collected information from the Federal Energy Regulatory Commission (FERC) MHK database about geographical distribution of proposed hydrokinetic projects (what rivers or other types of systems), HK turbine design (horizontal axis, vertical axis, other), description of proposed axial turbine (number of blades, size of blades, rotation rate, mitigation measures), and number of units per project. Where site specific information was available, we compared the location of proposed projects' rotors within the channel (e.g., along cutting edge bank, middle of thalweg, near bottom or in midwater) to the general locations of fish in the river (shoreline, bottom/midwater/surface of channel) to ascertain potential interactions. In addition, we are collaborating and communicating with scientists at other national laboratories and industry who are also developing information useful to this task. For example, other studies being funded by DOE include evaluations of different in-current (hydrokinetic) turbine designs for their effects on rates and severity of blade strike and likelihood of cavitation.

This report summarizes activities completed during the first year of a three-year study.

2. EFFECTS OF ROTOR BLADE STRIKE ON AQUATIC ANIMALS

An organism is said to be entrained in a river or ocean current if it is carried along at or near the velocity of the current without being able to overcome or escape such current. Entrainment in the currents may put the organisms in the path of turbine blades that are associated with conventional hydropower (CH) turbine rotors or HK projects. Nearly all of the knowledge of the effects of collisions (strike) of entrained aquatic animals with rotor blades comes from studies of CH projects. The CH studies indicated that injury and mortality from blade strike is a function of both the probability of strike and the force of the strike. Studies of survival rates of fish following entrainment and passage through CH turbines identified key factors that influence probabilities of turbine blade encounter (Eicher Associates Inc. 1987; Turnpenny et al. 2000; Čada 2001).

There have been several studies to estimate the potential of fish strike by rotating blades (e.g., Čada 1990; Ploskey and Carlson 2004; Deng et al. 2005; Ferguson et al. 2008), but most involve conventional hydroelectric turbines that are enclosed in turbine housings and afford little opportunity for flow-entrained organisms to avoid strike. It is likely that both the probability and consequences of organisms striking the rotor blade are greater for a conventional turbine than for a non-ducted HK turbine, due to the greater opportunities for organisms to avoid approaching the HK turbine rotor or moving outward from the periphery. However, passage through a conventional turbine poses only a single exposure to the rotor, whereas passage through a project consisting of large numbers of HK turbines represents a larger risk of strike that has not been investigated.

For HK projects, the seriousness of strike is presumably related to the animal's swimming ability (i.e., ability to avoid or evade the blade), water velocity, number of blades, blade design (i.e., leading edge shape), blade length and thickness, blade spacing, blade movement (rotation) rate, and the part of the rotor that the animal strikes (Wilson et al. 2007). Less is known about the magnitude of impact forces that cause injuries to most marine and freshwater organisms (Čada et al. 2005; 2006), or the swimming behavior (e.g., burst speeds) that organisms may use to avoid strike. Until such data become more widely available, studies that evaluated kinematics and performance of fish fast-start swimming during predator-prey encounters (Domenici and Blake 1997), may guide the development of relevant model parameters. In addition to direct strike, there is a potential for adverse effects due to sudden water pressure changes (including cavitation) associated with movement of the blade.

A vertical axis turbine, such as the Blue Energy Ocean Turbine depicted in Figure 1, will have the same leading edge velocity along the entire length of the blade, and during unidirectional movement fish passing a vertical axis turbine will have to face the risk of blade strike twice. On the other hand, blade velocity on a horizontal axis turbine (e.g., DEEP-Gen in Figure 1) will increase from the hub out to the tip. Rotor blade diameter and revolutions per minute are critical components of turbine design to fish. The rotor blade tip has a much higher velocity than the hub because of the greater distance that is covered in each revolution. For example, on a rotor spinning at 20 rpm, the leading edge of the blade 1 m from the center point will be traveling at a velocity of about 2 m/s – a speed that is likely to be avoidable or

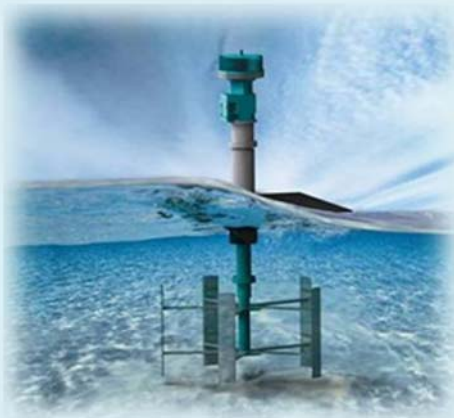
Current Energy Converters



Oscillating Hydrofoil (Stingray)
Source: The Engineering Business



Horizontal Axis Turbine (DEEP-Gen)
Source: Tidal Generation



Vertical Axis Turbine
(Blue Energy Ocean Turbine)
Source: Blue Energy



Ducted Horizontal Axis Turbine
(Open-Centre Turbine)
Source: OpenHydro

Figure 1. General types of current energy converters.
Source: DOE (2009).

undamaging to most organisms. However, a 20-m-diameter rotor spinning at 20 rpm would have a tip velocity of nearly 21 m/s. Fraenkel (2006; 2007b) described a horizontal axis turbine (Seagen; Figure 2) with a maximum rotation speed of 12 to 15 rpm, which results in a maximum blade tip velocity of 12 m/s. Wilson et al. (2007) suggested that for marine and tidal applications, rotor blades tips will likely move at or below 12 m/s because greater speeds will incur efficiency losses through cavitation. Rotors on in-river hydrokinetic devices turbines are expected to be smaller in diameter than for marine or tidal settings but operate at greater rpm.

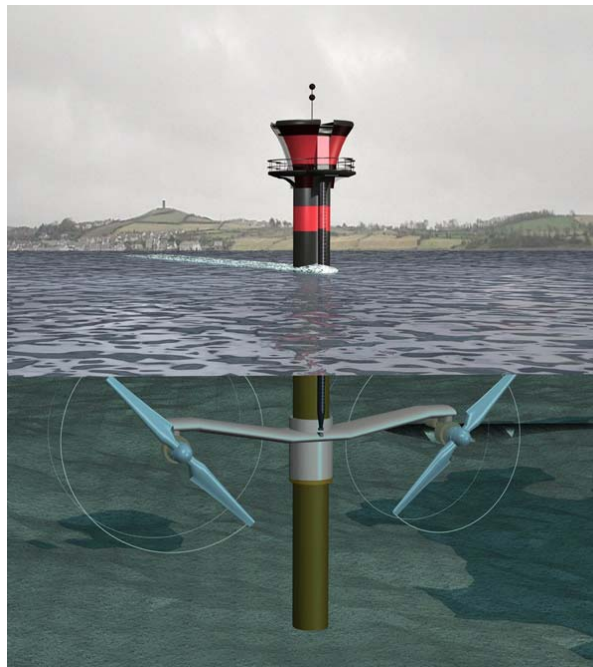


Figure 2. Artist's impression of the Seagen marine current turbine in Strangford Lough, UK.
Source: Davison and Mallows (2005).

The force of the strike is expected to be proportional to the strike velocity; consequently, the potential for injury from a strike would be greatest at the outer periphery of the rotor. In hydrokinetic turbines, the blade tip will be moving at the highest velocity and exhibit the greatest strike force, although, animals may be able to avoid the tip of an unducted rotor. As shown in Figure 3, relatively safe areas of passage through the rotor would be nearest the hub (because of low velocities) and potentially nearest the tip (because of the opportunity for the animal to move outward to avoid strike). The central zone of relatively high blade velocities and relatively less opportunity to avoid strike may be the most dangerous area (Coutant and Čada 2005). For rotors contained within ducts (Figures 4 and 5), there would be no opportunity for an organism entrained in the intake flow to escape strike by moving outward from the periphery; safe passage would depend on sensing and evading the intake flow or passing through the rotor between the blades. The identification of relatively high and low risk passage zones in HK turbines has currently experienced only limited testing (VLH 2008; FFP 2010) and remains to be further investigated in field applications.

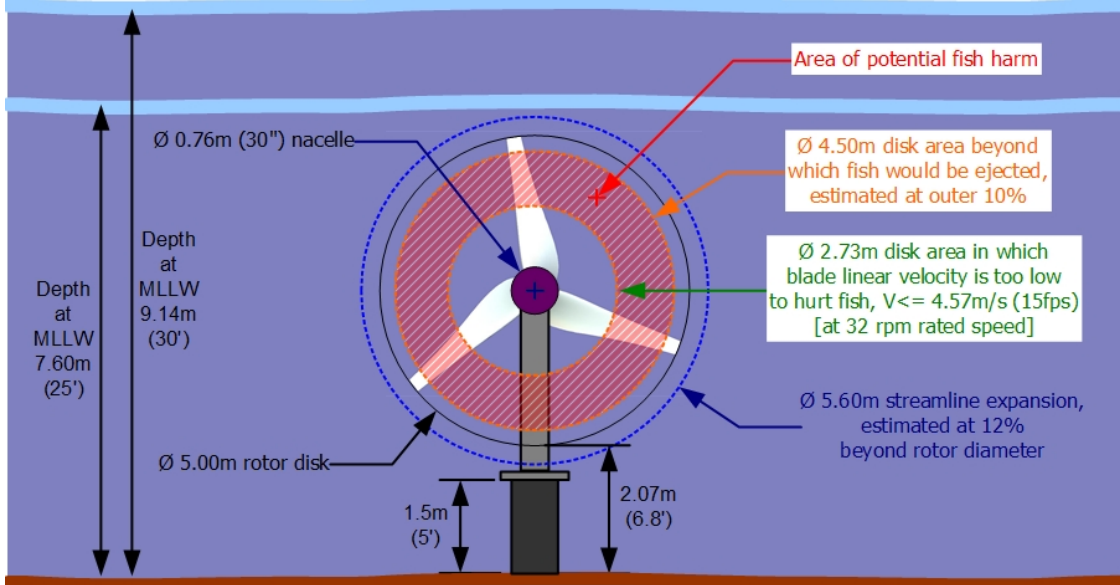


Figure 3. Predicted zone of potentially damaging strike associated with an unducted horizontal axis turbine.
Source: Coutant and Čada (2005)



Figure 4. Ducted horizontal axis hydrokinetic turbine, installed on the Mississippi River near Hastings, Minnesota.
Source: Hydro Green Energy LLC



Figure 5. Ducted horizontal axis Free Flow Power SmarTurbine™ generator for in-stream deployment at locations in the Mississippi and the Atchafalaya rivers.
Source: Free Flow Power Corporation FFP (2010)

Normandeau Associates, Inc. (2009) reported a study of survival and injury of fish that passed through a ducted HK turbine in the Mississippi River. Groups of yellow perch, bluegill, catfish, smallmouth buffalo, and bigmouth buffalo were released in front of the turbine, passed through the rotor, and were collected downstream from the turbine. Survivals at 1 hour and 48 hours after the test ranged from 98-100%. No turbine blade passage injuries were observed among either small- or large-sized fish. The authors suggested that the small number of blades (3) in the HK turbine and the low water velocity through the runner (1.7 to 3.0 m/s) may have contributed to the very low injuries and mortalities observed.

Wilson et al. (2007) described a simple model to estimate the probability of aquatic animals entering the path of a marine turbine. The model is based on the density of the animals and the water volume swept by the rotor. The volume swept by the turbine can be estimated from the radius of the rotor and the velocity of the animals and the turbine blades. They emphasized that their model predicts the probability of an animal entering the region swept by a rotor, not collisions. Entry into the path toward the rotor may lead to a collision, but only if the animal does not take evasive action or has not already sensed the presence of the turbine and avoided the encounter. Applying this simplified model (no avoidance or evasive action) to a hypothetical field of 100 turbines, each with a 2-bladed rotor 16 m in diameter, they predicted that 2 percent of the herring population and 3.6 to 10.7 percent of the porpoise population near the Scottish coast would encounter a rotating blade. At this time, there is no information about the degree to which marine animals may sense the presence of turbines, take appropriate evasive maneuvers, or suffer injury in response to a collision. Wilson et al. (2007) suggested that marine vertebrates may see or hear the device at some distance and avoid the area, or they may evade the structure by dodging or swerving when in closer range.

The potential injurious effects of turbine rotors have been compared to those of ship propellers, which are common in the aquatic environment. Fraenkel (2007a) pointed out that in contrast to ship propellers; the rotors of hydrokinetic and current energy devices are much less energetic. He estimated that a tidal turbine rotor at a good site will absorb about 4 kW/m² of power from the swept area of the current, whereas typical ship propellers release over 100 kW/m² of power into the swept area of the water column. In addition to the greater power density, a ship propeller and ship hull generate suction that can pull objects toward it, increasing the area of influence for strike (Fraenkel 2006).

3. PROPOSED FRESHWATER HK DEVELOPMENT SITES AND TURBINE DESIGNS

We collected information from the MHK database maintained by the Federal Energy Regulatory Commission (FERC) about geographical distribution of proposed hydrokinetic projects, and their categorization as inland, tidal or wave projects. As of August 2010, 116 preliminary permits had been issued to private developers to study HK projects in inland waters, the development of which would total over 6,800 MW (Figure 6). Most of these projects are proposed for the Ohio and lower Mississippi Rivers (Table 1). In addition, another 9 preliminary permits for inland projects were under consideration by FERC (Figure 7). Although several manufacturers of hydrokinetic technologies provide general descriptions of their devices, project-specific technical data describing type of hydrokinetic system, turbine design (horizontal axis, vertical axis, other), description of proposed axial turbine (number of blades, size of blades, rotation rate, mitigation measures), and number of units per project are currently not publicly available. However, it is expected that placement of hydrokinetic devices will occur in arrays, located in river sections with constant high energy potential such as found within or adjacent to the main channel. In addition, guidelines developed by the US Army Corps of Engineers for sites in the Mississippi River require (Free Flow Power 2010) that piling structures associated with hydrokinetic devices are located at least 500 feet upstream/downstream of structures, at least 200 feet away from revetment toes, and with no structures in the river bed exceeding maximum height of 20 feet below a low water reference plane (LWRP).

For inland/freshwater projects, several designs using hydrokinetic turbines have reached proof-of-concept or the field testing stage, and field testing of a vortex induced vibration (VIV) device by Vortex Hydro Energy is currently pending on approval of necessary permits from FERC. Freshwater / inland technologies that have reached the field testing stage include:

Free Flow Power (FFP) developed the SmarTurbine™ generator, a horizontal-axis ducted turbine design with a rim-mounted, permanent magnet, direct-drive generator and a 7-blade rotor disk as single moving part. These hydrokinetic turbines range from 1 meter to 3 meters in diameter and are to be installed in micro arrays, suspended from the river surface, attached to bridge abutments, maintained from barges, or suspended or attached to pylons. Commercial installations are expected to operate in river currents from 2 meters per second to 5 meters per second.

Verdant Power (Free Flow Kinetic Hydropower Systems) uses a non-ducted design with three-bladed, horizontal-axis turbines of 5-meter diameter. In river currents, the free-flow turbines are expected to operate at ~ 35 rpm, with each modular device capable of generating 60 to 80 kW. A pilot project of Verdant Power (CORE 2009) is currently under deployment in the St. Lawrence River in Cornwall, Ontario.

Hydro Green Energy, LLC (HGE), in a pilot study on hydrokinetic energy from the Mississippi River at U.S. Army Corps of Engineers Lock and Dam No. 2 in Hastings, MN, used a Kensington horizontal-axis ducted turbine with a 3-bladed rotor. The rotor of

the surface-suspended flow-through device operated at 21 rpm during a fish survival study conducted in July 2009 (Normandeau Associates, Inc. 2009).

Other Technologies - Designs using cross-flow helical turbines with either vertical or horizontal axes are also under development for river, tidal and marine applications, but technical information about projects using cross-flow turbines is still sparse (Khan et al. 2009). Vertical axis Darreius-type turbines are projected for placement in currents at ~ 2.6 m/s and rotate at > 100 rpm. Gorlov (2005) suggested that rapid rotating submerged helical type turbines would create a velocity barrier in the water column that fish would avoid, but at present no field data have been published to support such statement.

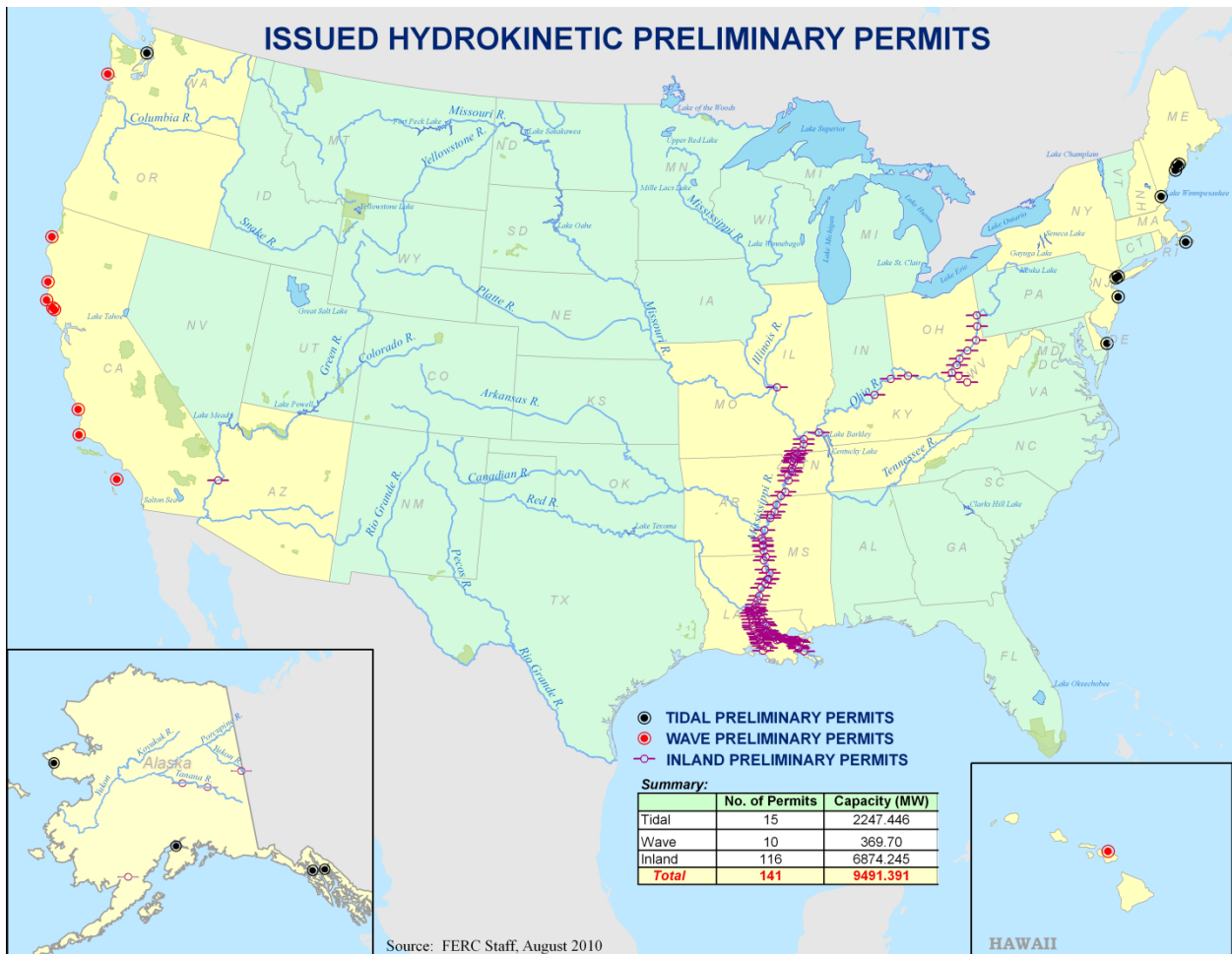


Figure 6. Preliminary permits issued by the Federal Energy Regulatory Commission for tidal, wave, and riverine hydrokinetic projects.

Source: <http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics.asp>

Table 1. Preliminary permits issued or pending for hydrokinetic projects as of July 1, 2010

| | Issued | Pending |
|-----------------|--------|---------|
| Mississippi | 78 | |
| Atchafalaya | 19 | |
| Ohio | 11 | 4 |
| Kanawha | 2 | |
| Tanana | 2 | |
| Colorado | 1 | |
| Kvichak | 1 | |
| Sakonnet | 1 | |
| Wax Lake | 1 | |
| Yukon River | 1 | |
| Tennessee River | | 3 |
| Columbia River | | 1 |
| St. Clair River | | 1 |

(Source: FERC MHK database online, 2010)

In June 2010, commercial operation began for a pontoon-mounted hydrokinetic device on the Yukon River near Eagle, Alaska. The device uses a 4-blade vertical axis *EnCurrent* turbine and operates at a maximum 22 rpm. Potential biological impact of the slow-spinning turbine on aquatic life is currently under evaluation (AP&T 2010).

For reviews of additional technologies and assessments of horizontal and vertical axis turbines for river and tidal applications for hydrokinetic energy conversion systems see DOE (2009) and Khan et al. (2009).

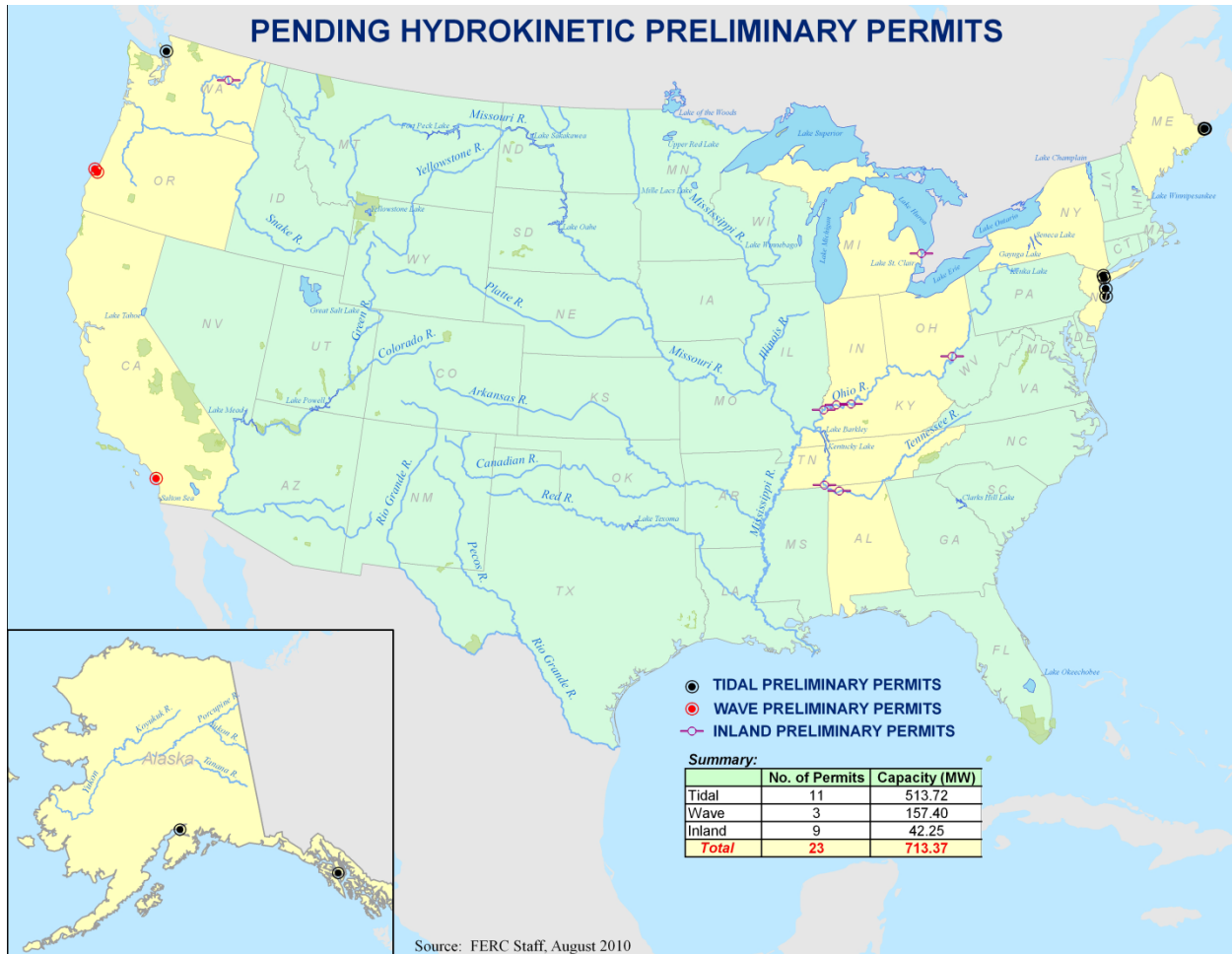


Figure 7. Preliminary permits under consideration (pending) by the Federal Energy Regulatory Commission for tidal, wave, and riverine hydrokinetic projects. Source: <http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics.asp>

4. POTENTIALLY AFFECTED FRESHWATER ORGANISMS

A review of literature on riverine aquatic biota identified freshwater taxa with potential for overlap of habitat with placement of hydrokinetic devices (Table 2). For large rivers, these groups of organisms include phytoplankton, zooplankton, ichthyoplankton, macroinvertebrates, and fish species. Phytoplankton are microscopic plants that drift in the water column that obtain their energy from photosynthesis. Zooplankton are small, weakly swimming animals that drift with river currents. Ichthyoplankton are the eggs and larvae of fish drifting in the water column. Macroinvertebrates include insects, worms and mussels, and provide an important food source to fish; normally benthic macroinvertebrates live in or on the bottom sediments, but some periodically drift with the river currents. Amphibians, reptiles, diving birds and aquatic mammals are not considered in this report as these taxa are not likely to routinely encounter blades of hydrokinetic devices.

4.1 AQUATIC HABITATS

In large rivers, aquatic habitats along the river cross section contrast in depth and water velocity. Habitat types include navigation pools, main channels and their boundaries, secondary channels, and backwater shorelines including pools on floodplains with areas of infrequent inundation (Figure 8). Flow velocity and water depth are greatest in the main channel and in navigation channels, and represent areas with the largest potential for extraction of kinetic energy. Collectively, main channels also provide the single largest continuous habitat type

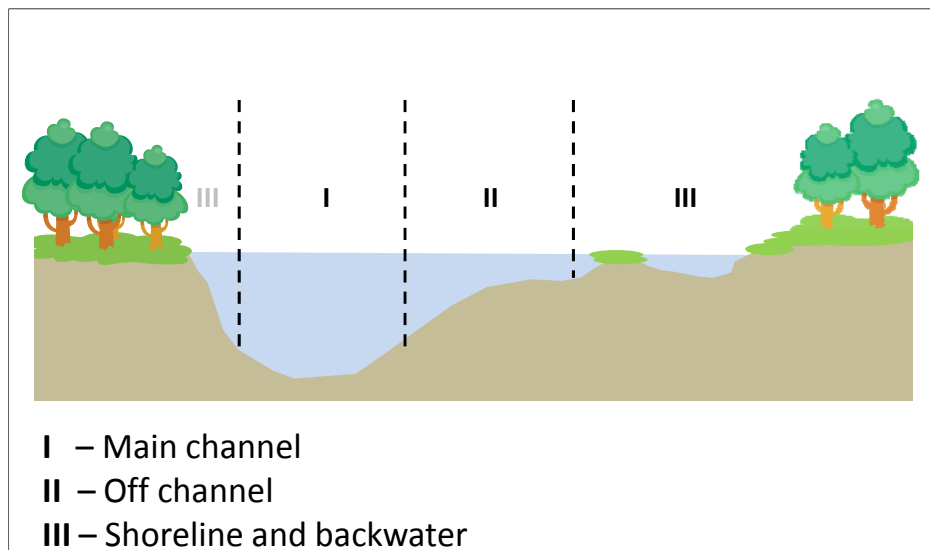


Figure 8. Simplified cross section of a river, with different aquatic habitats that contrast in water depth and flow velocity.

within river systems (Leopold et al. 1964). Lower energy environments such as secondary channels and off-channel habitat with shorelines, backwaters and floodplain pools provide important fish nurseries and temporary foraging areas (Sheaffer and Nickum 1986; Copp and

Table 2. Distribution of freshwater organisms along a cross-section of a large river

| Freshwater Organisms | Backwater, Shorelines, and Off-Channel Water | Main Channel and Main Channel Boundaries | Reference |
|-----------------------------|---|--|---|
| Phytoplankton | Evenly distributed throughout the water column | | Elliot 1970; Clifford 1972 |
| Zooplankton | Copepods and cladocerans | Rotifers | Carter et al. 1982; Hergenrader et al. 1982 |
| Benthic macroinvertebrates | Numerous orders of aquatic insects (e.g., mayflies, dragonflies, dipterans), crayfish, and mollusks (snails and clams) | Chironomids, nematodes and oligochaetes | Gammon 1977; Zimmerman 1977 |
| Fish larvae | Centrarchids Cyprinidae Cyprinodontidae | Freshwater drum Gizzard shad White bass Some catostomid larvae Common carp | Galat and Zweimuller, 2001; Sheaffer and Nickum 1986; Hergenrader et al. 1982 |
| Fish juveniles and adults | Bluegill White crappie Black crappie Common carp Gar species Bowfin Largemouth bass Spotfin shiner Emerald shiner Bullhead minnow Brook silverside Darter species Madtoms | Channel catfish Sauger/walleye Smallmouth buffalo Smallmouth bass Shovel nose sturgeon Lake sturgeon Black buffalo Highfin carpsucker Northern hogsucker Gizzard shad Goldeye Mooneye Skipjack herring White bass | Gutreuter et al. 2010; Koel, 2004; Chick et al. 2006; Barko et al. 2004; Dettmers et al. 2001 |

Penaz 1988) but due to their lower energy potential, are of less concern to kinetic energy extraction (Čada et al. 2007). Vertical stratification of the water column further distinguishes among different habitats in large rivers. Flow velocities of running water are greatest near the surface and decrease with depth and sediment load. Suspended sediment loads increase the

turbidity of water, are greatest near the substrate and limit available light for photosynthesis by phytoplankton and submerged aquatic vegetation.

4.2 FISH

Fish species richness varies significantly among different river habitats (Koel 2004). Larger river fish species require channel habitat during at least one of their life stages and several species reside in the main channel during all seasons (Galat and Zweimuller 2001; Dettmers et al. 2001; Gutreuter et al. 2010). In the main channel, abundant benthic invertebrates and zooplankton provide an important food source to riverine fish (Dettmers et al. 2001). For the upper Mississippi River, lateral distribution of fish species within the channel was found to reflect tolerances for river current velocity (Barko et al. 2004; Gutreuter et al. 2010). Barko et al. (2004) provide a list of fish species collected in the unimpounded Upper Mississippi River and denote fish species as fluvial specialist, fluvial dependent, or fluvial generalist. Many pelagic fish species reside in main-channel habitats and hold their position in the water column while feeding on material drifting to them (Dettmers et al. 2001). These pelagic species include freshwater drum, gizzard shad, goldeye, mooneye, skipjack herring and white bass, and overlap with habitat for these species may be of relevance to hydrokinetic energy production. In addition, large rivers provide pathways for species movement. Long-distance migrating species such as shad, sturgeons, salmonids, and American eel warrant further examination of risk of encounter with hydrokinetic technologies.

4.3 LARVAL FISH AND DRIFT ASSEMBLAGES

Several fish species such as freshwater drum and some Catostomidae are pelagic spawners that release their floating or semi-buoyant eggs directly in the main channel. On the other hand, larvae of centrarchids and cyprinids are more abundant in backwater areas, away from the main channel (Galat and Zweimuller 2001). In contrast to macroinvertebrates and plankton, horizontal and vertical distributions (Table 3) of densities for larval fish generally correspond to habitat distribution of adult fish, spawning time (Wolter and Sukhodolov 2008) and distribution of available spawning habitats along the river cross section (Galat and Zweimuller 2001; Holland

Table 3. Mean horizontal and vertical distribution of fish larvae (no./m³) in the Missouri River

| | Cutting Bank | Mid-Channel | Filling Bank |
|--------------------------|--------------|-------------|--------------|
| Horizontal distribution* | 1.13 | 0.4 | 0.85 |
| Vertical distribution** | | | |
| Surface | | 0.8 | |
| Mid-depth | | 0.6 | |
| Near bottom | | 0.2 | |

* Measured at 1 meter depth

** Measured in main channel

Source: Cada (1977)

1986). Free-swimming movement of larval fish is accidental until their swim bladder is filled and response of ichthyoplankton to hydraulic forces is similar to that of non-biotic suspended particles in the water column (Wolter and Sukhodolov 2008; Hergenrader et al. 1982). Fish larvae drift sampling in the Missouri River indicated densities to be lowest in mid-channel, greatest at cutting bank, and lower on filling bank habitats (Hergenrader et al. 1982). A regression model based on integrated depth sampling for larval fish indicated that in a river of 5.6 meter depth about 60 percent of all fish larvae were in the uppermost 1.8 meters of the water column (Hergenrader et al. 1982).

The horizontal and vertical distributions of phytoplankton, zooplankton and macroinvertebrate drift organisms are variable and highly dependent on current velocity and turbulence (Carter et al. 1982). In shallow and turbid rivers, macroinvertebrate drift assemblages were found evenly distributed throughout the entire water column (Elliot 1970; Clifford 1972). Gammon (1977) and Zimmerman (1977), from sampling macroinvertebrates in the Missouri River, reported vertical drift assemblage densities greater near the bottom than near the surface. Along river cross sections, densities of macroinvertebrates were greatest near shore and lower in the mid-channel section compared to main channel boundaries. Non-benthic taxa (mainly rotifers) and benthic invertebrates including chironomids, nematodes and oligochaetes provide important food sources for fish larvae in the main channel (Galat and Zweimuller 2001). For some species of the ichthyoplankton community, cut-off channels and backwater areas provide important nursery zones where larval fish feed on copepods and cladocerans suspended in the water column (Sheaffer and Nickum 1986; Copp and Penaz 1988).

Larval fish and drift assemblages are not expected to experience direct damage through blade strike if the rotation rate of the turbine rotor is low (Čada et al. 2007). However, although non-blade strike related potential for damage is not assessed in this report, small organisms entrained in water flow over a turbine blade while in passage through a hydrokinetic device may experience turbulence with potential for damage from shear stress (DOE 2009).

5. STRIKE RISK MODEL

Most blade strike research modeling to date has focused on conventional hydropower turbines. In these scenarios, fish are not able to navigate around turbines and their ability to evade rotor blade strike in the associated high-velocity flows is likely limited. Therefore, in CH turbine strike models there is little basis to account for fish ability to avoid the turbines by swimming around them, or to avoid the blades by evading them as they pass through the devices. This may not be the case for HK projects; although few studies have examined fish behavior around HK devices to date, there is emerging information to suggest that fish may be able to avoid blade strike in the slowly rotating, relatively open passages of some HK devices (Normandeau Associates, Inc. 2009).

In this section, the term “avoidance” refers to the possible ability of the fish to swim away from the swept area of the rotor. Even if the fish passes through the rotor-swept area, it may be able to evade blade strike. The term “evasion” refers to the possible ability of an entrained fish to prevent blade strike (by burst swimming or other rapid movements) as it passes through the rotor-swept area. The following blade strike equations 1 and 2 only apply to fish that have not avoided the device and are passing through the rotor-swept area.

Ferguson et al. (2008) describe blade-strike risk as “the probability of a fish of given length and traveling at a certain velocity passing through openings between turbine blades as the turbine runner rotates and the blades sweep through the water flow pathway.” Blade-strike models for hydraulic turbines associated with conventional hydropower generation were first developed by von Raben (1957). This early model (Equation 1) expressed probability of blade contact in a conventional hydropower turbine as

$$P = (L \times n \times (R/60) \times a \times \cos a') / f, \quad (1)$$

where P is the probability of blade contact,

L is the length of fish expressed in centimeters,

n is the number of blades in the turbine,

R is the number of revolutions per minute,

a is the cross-section area (m²) of water passage through the turbine expressed as turbine diameter minus area of the turbine nacelle,

a' is the blade angle described as the angle formed by water flow with the axial direction at the moment of impact with the edges of the turbine blade, and

f is the flow through the turbine expressed in m³ per second.

Subsequent refinements to this early model are based on almost identical approaches that mainly differ in terminology (Eicher et al. 1987; Turnpenny et al. 2000; Deng et al. 2005, 2007). General blade strike risk models for Kaplan type turbines were most recently reviewed by

Ploskey and Carlson (2004), and Deng et al. (2005). In a model for risk of blade strike in passage through Kaplan turbines occurrence of blade strike is dependent on probability of blade encounter and fish length relative to water length, the distance between blades which allows for movement of water, and fish passage (Turnpenny et al. 2000).

The probability (P) of a fish getting struck by a turbine blade as it passes through the rotor can be calculated using Equation 2:

$$P = L / WL, \quad (2)$$

where L is length of the fish (meters), and water length (WL), in meters = $V_{axial} / (\cos\theta \times n \times N/60)$,

with V_{axial} representing discharge (m^3/sec^{-1}) / rotor-swept area (m^2),

$\cos\theta$ is the cosine of the angle between V_{axial} and the absolute water velocity vector,

n is the number of blades on the turbine, and

N represents runner revolutions per minute.

Although these models were not explicitly developed for application to in-stream hydrokinetic turbines and do not account for swimming performance or behavior of fish, their conceptual approach appears to be a justifiable starting point for modification for evaluation of existing and proposed in-stream hydrokinetic projects. Modifications to these earlier models include expressing “f” from equation 1 as river flow (m^3/s) in the cylindrical area swept by the rotor and incorporation of variables that address swimming and behavior of fish. To calculate probability of blade encounter, knowledge is needed about the size of fish in the path of the HK runner, design parameters of the HK turbine, hydrologic conditions as described by flow velocity or river discharge, and information about whether or not fish will avoid encounter with the turbine.

Turbines of hydrokinetic devices are expected to rotate at lower speeds than observed for turbines in traditional electric power generation and hence, should pose less risk for blade-strike to fish. At present, differences in HK turbine designs pose challenges in the development of blade-strike risk models for HK technologies. Current concepts for HK turbines range in number of blades from 2 to 7 or more blades, and proposed turbines vary widely in rotor diameter and projected rotation rate (revolutions per minute) under different flow conditions. Application of equation 1 indicates that for a hypothetical scenario with a fish moving downstream through the rotor-swept area of a HK turbine, with the fish passively entrained in the current and a lack of avoidance, evasion, or attraction behavior, the probability for blade encounter increases with increasing number of turbine blades (Figure 9). Furthermore, for such a scenario the probability of blade encounter or blade strike increases with increasing length of fish (Figure 10).

At present, empirical data from field observations on fish behavior and success in avoidance or evasion of blade strike from HK technology is still largely absent, but successful avoidance of the HK project or evasion of blades by fish would lower the probability of blade encounter (Figure 11).

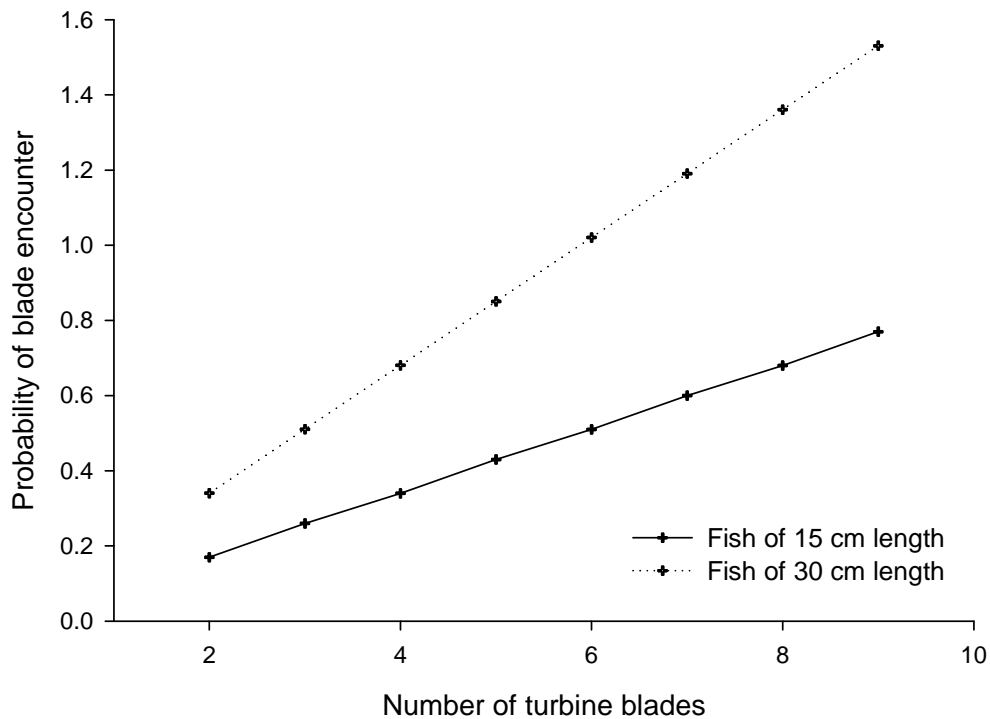


Figure 9. Increase in probability of blade encounter with increasing number of turbine blades. Encounter probabilities are derived from equation 1, and a probability of blade encounter greater than 1.0 suggests the possibility of multiple blade encounters for a single fish in passage through the rotor swept area. The hypothetical model is based on fish of 15 cm and 30 cm length, for single passage through the rotor-swept area of a 3-blade turbine with rotor diameter of 3 m, operating at 35 rpm in a river current of 1.03 meter/sec⁻¹. The model assumes no avoidance or evasive behavior of fish.

For optimal energy extraction and performance, hydrokinetic turbines are expected to operate within a range of revolutions per minute (rpm) that prevents formation of corrosive turbulence and cavitation. With fixed upper limits for rpm (and thereby fixed upper limits for axial velocity of blade rotation), flow velocity of water passing through the rotor-swept area emerges as an important variable in the prediction of blade strike risk to fish. With increasing flow velocity the risk of blade-strike to fish decreases. The decline in risk of blade strike at greater flow velocities is illustrated in Figure 12, assuming hypothetical scenarios for single passage of fishes with 15 cm and 30 cm lengths respectively, through the rotor-swept area of a 3-blade turbine with 3-meter rotor diameter operating at maximum 35 rpm.

Furthermore, fish passage through a HK device is not expected to be based on entrainment only. The ability of fish to swim at speeds (U m/sec) greater than ambient flow velocity (V_F m/sec) enables fish to move upstream and downstream within a river. Although modes of swimming, ranges in duration of swimming velocity, and capacity for maximum swimming velocity vary among fish species (Videler and Wardle 1991, Ward et al. 2003), fish swimming actively during downstream passage through the rotor-swept area of a HK turbine should experience a reduction in hypothetical risk of blade encounter. Equations 1 and 2 do not account

for fish swimming speed, but in modeling risk of blade strike to fish, a reduction in risk due to active swimming downstream can be expressed in the model using fish ground speed (U_{Gs} m/sec) as a variable that sums the swim speed of a fish and ambient flow velocity (Equation 3).

$$U_{Gs} \text{ m/sec} = U \text{ m/sec} + V_F \text{ m/sec} , \quad (3)$$

where U_{Gs} m/sec expresses the ground speed of a fish, U m/sec represents swim speed of a fish, and V_F m/sec is the flow velocity of the current.

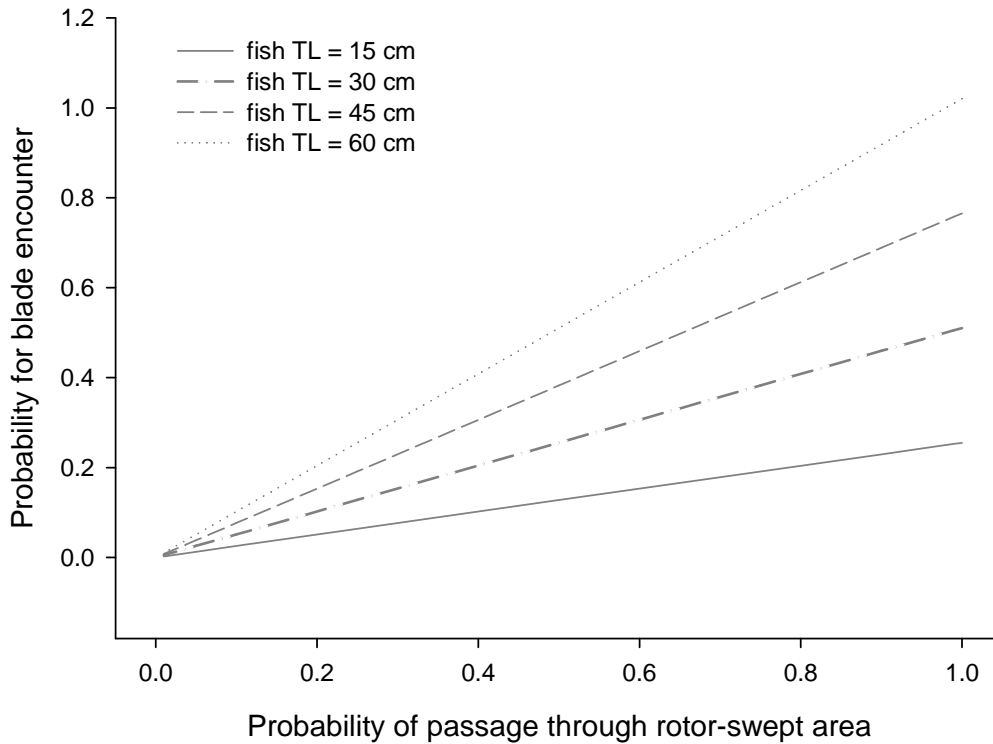


Figure 10. Probability of blade strike as a function of total length for fish passing through the rotor-swept area. For passive passage through the rotor-swept area of a hydrokinetic device the hypothesized risk of blade encounter increases with total length (TL) of a fish. The model assumes no avoidance or evasive behavior. Probabilities are derived from equation 1, for risk of blade strike to fish during single passage through the rotor-swept area of a 3-blade turbine with rotor diameter of 3 m, operating at 35 rpm in a river current of 1.03 meter/sec⁻¹.

With increasing value for U_{Gs} the hypothetical risk of blade strike during downstream movement of a fish decreases, as illustrated in an example (Figure 13) assuming increasing swim speed (U m/sec) for fishes with total length of 15 cm or 25 cm respectively, during single downstream

passage through the rotor-swept area of a 3-blade turbine with 3-meter rotor diameter operating at maximum 35 rpm, in a current with a velocity of 1.03 m/sec (V_F m/sec).

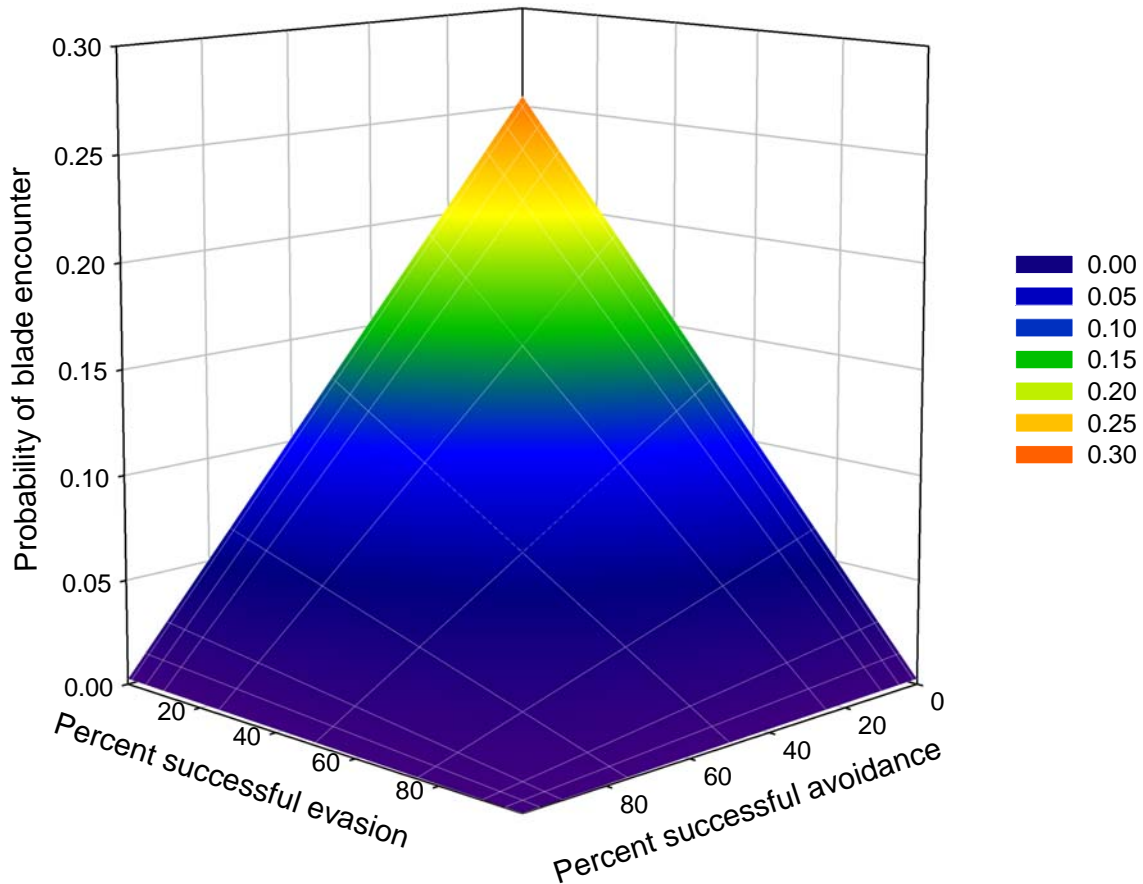


Figure 11. Hypothetical probabilities of blade encounter for a fish of 15 cm length, passively entrained in the water column during single passage through the rotor-swept area of a hydrokinetic turbine. This figure shows the effects of various values for avoidance and evasion on the probability of blade encounter (strike). The model assumes a 3-blade turbine with 3m rotor diameter, operating at 35 RPM in a river current of 1.03 meter/sec⁻¹. Probabilities for blade encounter are derived from equation 1.

The conceptual approach outlined above estimates probability of blade strike to fish during downstream passage through the rotor-swept area of a single device. However, applications for preliminary permits for installation of HK technologies submitted to FERC indicate that commercial-scale installations would involve multiple arrays with HK devices positioned along multiple transects. Hence, for fish the probability of encounter with HK technology is expected to increase with proportion of the river cross section occupied by HK devices. Furthermore, navigation through multiple transects with HK devices is expected to increase risk of blade strike.

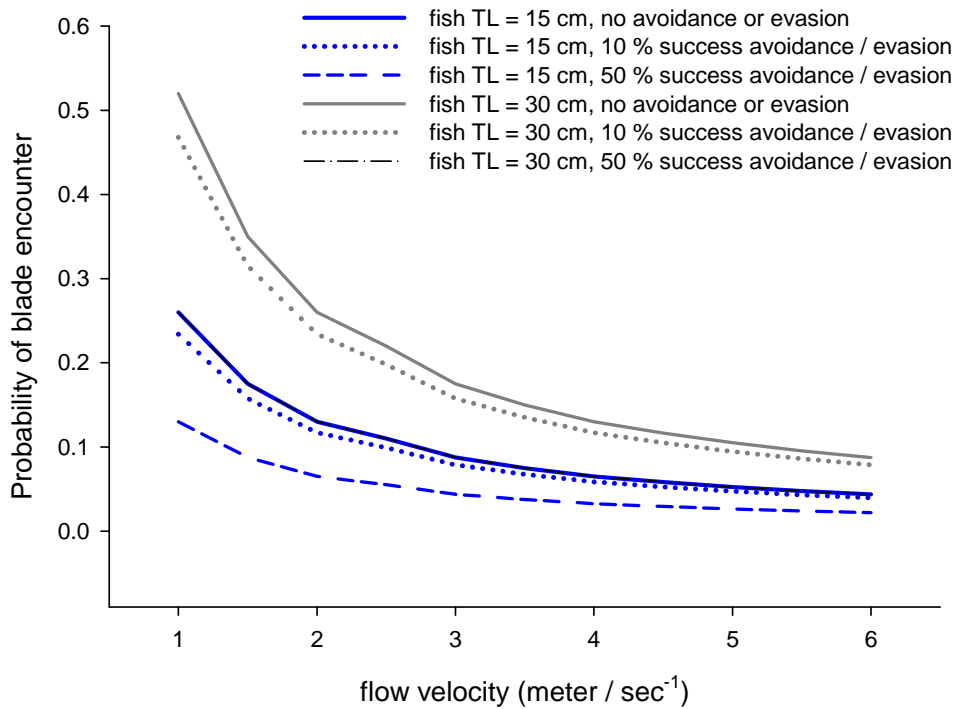


Figure 12. Decline in risk of blade encounter to fish with increase in river flow velocity. Scenarios for fish of 15 cm length (blue lines) and 30 cm length (gray lines) are shown. Solid lines indicate assumed probability of blade strike with 0% success in fish avoiding passage through the rotor-swept area or evasion of blade encounter during passage. Alternate scenarios assume 10 percent (dotted lines) and 50 percent (dashed lines) success in avoidance or evasive behavior in fish. Probabilities for blade encounter are derived from equation 1.

A conceptual model (Equation 4) for probability of fish encounter with turbine blades of HK devices was presented by Wilson et al. (2007).

$$PE = (100 \times (A_{rsa} / A_{scs})) \times (1 - P_a) \times (1 - P_e), \quad (4)$$

where PE is the probability for encounter of the area swept by the hydrokinetic turbine, A_{rsa} is the rotor swept area, A_{scs} is the area of the stream cross section, and P_a and P_e represent probabilities of avoidance and evasion, respectively.

The conceptual model superimposes a hypothetical array transect on a river cross section showing different zones of aquatic habitat (Figure 14) or densities of organisms (Figure 15). The overlay identifies habitat zones and fish species with increased risk for encounter with HK devices (Figure 16).

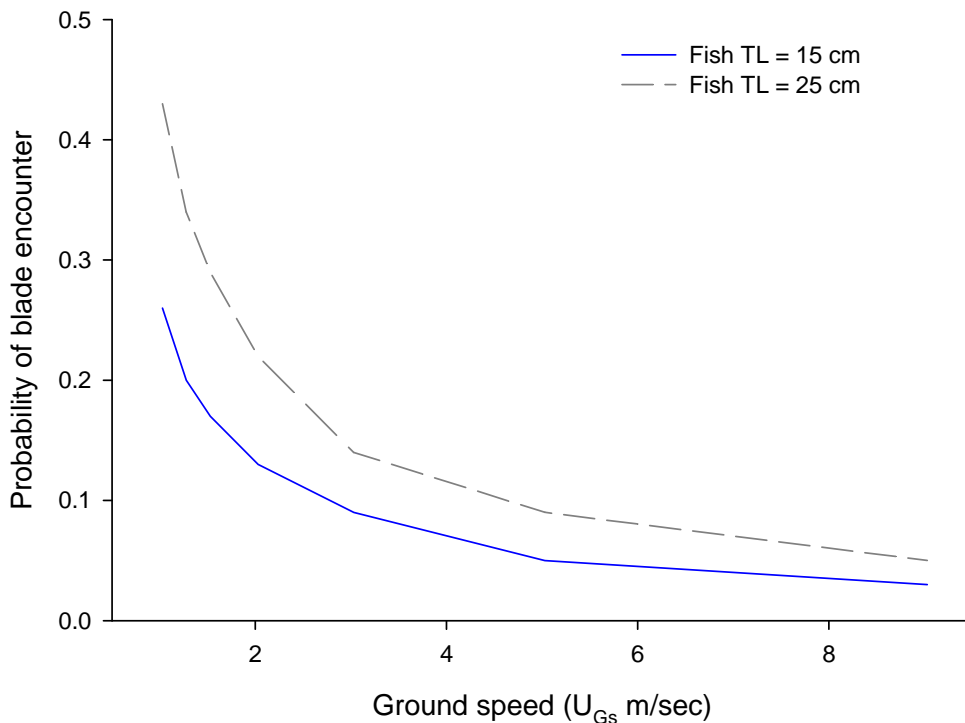


Figure 13. Increased ground speed relative to flow velocity during passage through the rotor-swept area of a HK device reduces the probability of blade encounter for fish. Ground speed of a fish (U_{Gs} in m/sec) is calculated as flow velocity (VF in m/sec) + swim velocity (U in m/sec). The above scenarios, for fish with TL = 15 cm and 25 cm respectively, assume increasing swim speed of fish but no avoidance or evasive behavior during single passage through the rotor-swept area of a 3-meter diameter turbine with a 1 meter hub and 3-bladed rotor moving at 35 rpm in unchanging 1.03 m/sec flow velocity. Probabilities for blade encounter are derived from equation 1.

The total number of HK devices per river transect, and number of transects per array in a project are expected to be dependent on site specific factors. In absence of site specific data, calculations for river cross section area occupied by HK technology are derived from a simplified geometry for a river transect decomposed into segments representing main channel, area towards left shoreline and right shoreline (Figure 17), the number of HK devices located along a single transect, and their summed rotor-swept area, which will be depended on dimensions of individual HK devices. Potential constraints to placement of HK devices include hydrology, local bathymetry, and competing river uses. Because yield for kinetic energy extraction is largest in the main channel, fish species that favor main channel habitat are expected to have greatest probability of encountering HK devices. Fixed installation of HK devices, including their support structures, will reduce area available for unrestricted movement of fish. The arrangement of HK devices in multiple transects increases probability of encounter during upstream or downstream movement of fish in large rivers, and multiple arrays of HK projects within the range of movement of individual species will further increase probability of

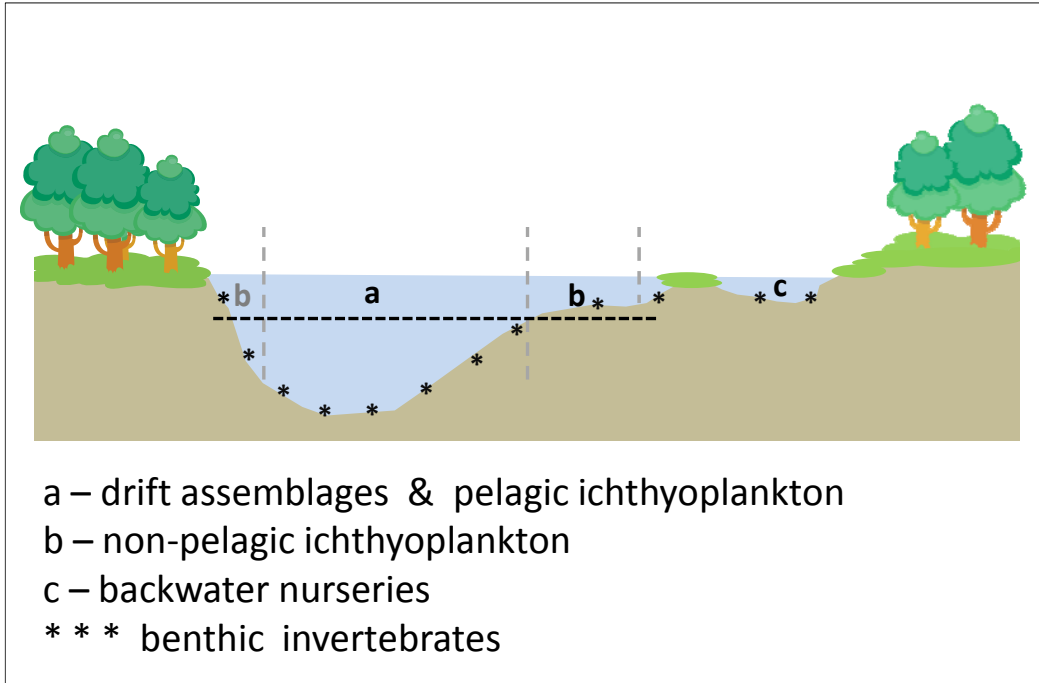


Figure 14. Distribution of plankton, macroinvertebrates and fish larvae across habitats in a large river, with > 60 percent of drift assemblage concentrated in the uppermost 1.8 meters of a hypothetical river with 5.4 meter depth.

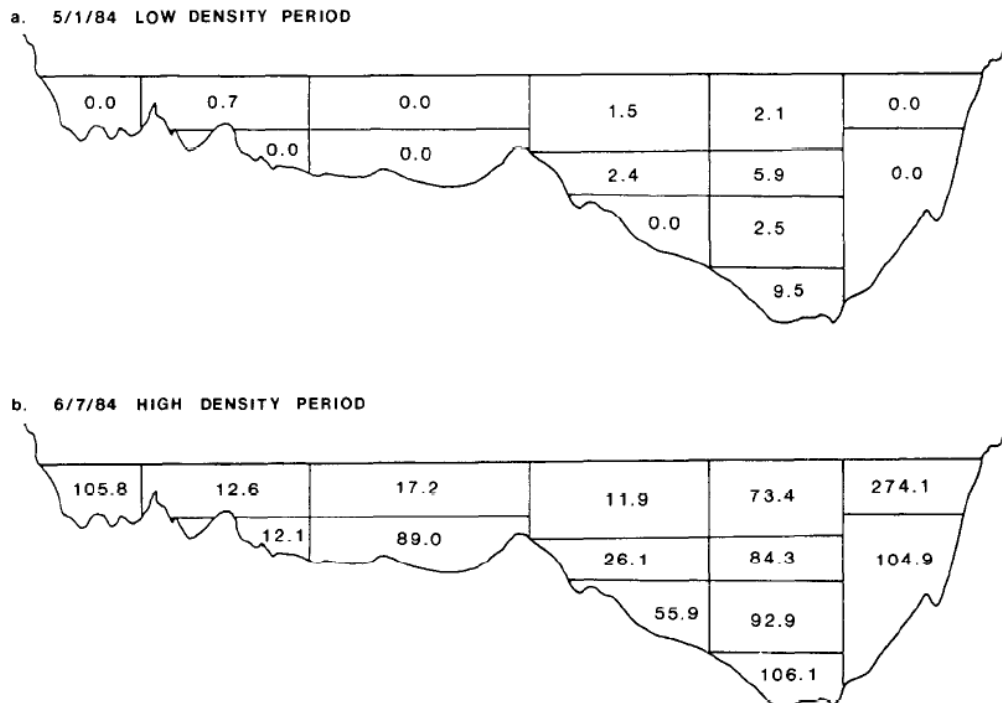


Figure 15. Densities of fish larvae (number/100 m³) in various portions of a cross section of lower Navigation Pool 5 in the Upper Mississippi River during low density (a) and high density (b) periods. From Holland (1986).

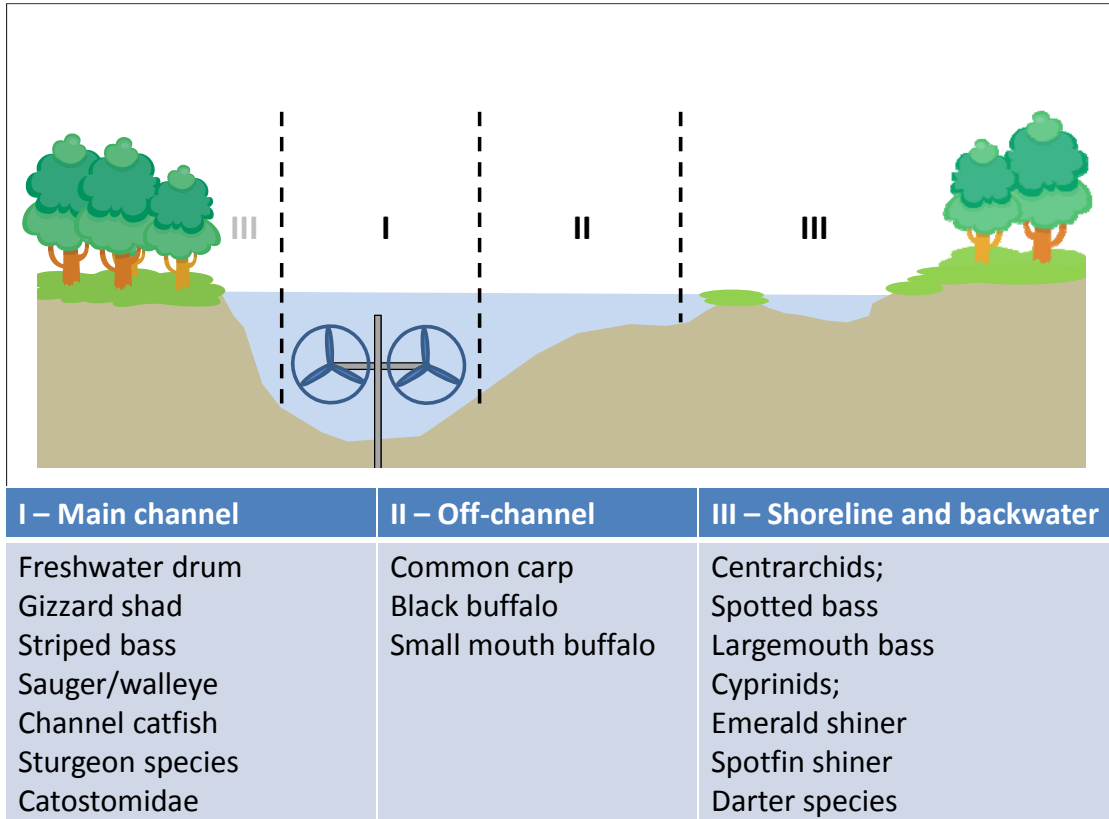


Figure 16. Conceptual overlay of a hydrokinetic array transect on a river cross section showing river habitat for different fish taxa. Hydrokinetic turbines are not shown to scale.

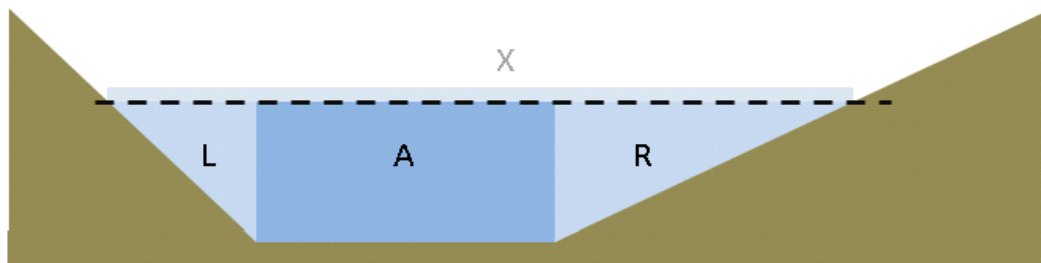


Figure 17. Simplified riverbed geometry for calculation of river cross section area, looking downstream. A, represents the main channel section with area calculated width of main channel * depth at reference river stage (indicated by dotted reference line., L, and R, represent cross section areas from the main channel border to the respective shore lines with areas calculated as $\frac{1}{2}$ distance from shoreline to boundary of main channel section * depth at reference river stage. The area X indicates increasing river cross section area for conditions when water levels exceed reference stages.

encounter. When HK project specific information about array configurations become available, the percent-area geometric model can be modified to include number of transects within a HK project array and the number of arrays within the range of movement of particular fish species in upstream/downstream movement direction (Equation 5).

$$PE_{Ar} = (Ta_{i-ii}) \times (p_d + p_u) \times (100 \times (A_{rsa} / A_{scs})) \times (1 - P_a) \times (1 - P_e), \quad (5)$$

where PE_{Ar} is the probability for encounter of rotor swept area during passage through an array of HK devices,

T represents the number of transects in arrays a_{i-ii} ,

p_d and p_u are probabilities of downstream and upstream movement of fish relative to a fixed location,

A_{rsa} , and A_{scs} represent rotor swept area and stream cross section area, respectively, and

P_a , and P_e are probabilities for project avoidance and rotor evasion.

Site fidelity and upstream or downstream movement of resident fish species are not well understood and merit further study.

Preliminary permit applications submitted to FERC include scenarios with 6 to 60+ devices for single river transects that vary in width from less than 450 m to over 950 m, but detailed information on individual river transect profiles is currently not publicly available. For large rivers, scenarios with combined rotor-swept areas of HK devices occupying more than 5 percent of total river cross section area are currently deemed unlikely, but ongoing modeling efforts will evaluate hypothetical scenarios ranging from 0.1 percent to 10 percent of stream cross sectional areas occupied by HK technology.

For a hypothetical example with the application of Equation 5 (allowing for dimensionless comparisons across different HK device designs and river cross sections), the following assumptions are presented; a resident fish species with uniform distribution across all river habitats, with limited movement range covering a single HK project array, and the array consisting of five transects. It is further assumed that each transect consists of four turbines whose swept area cumulatively represents five percent of total river cross section area at that transect, and fish have a 0.5 probability of successfully avoiding rotor blade encounter and a 0.5 probability for success in evading an approaching rotor blade. (Note that there are no published empirical data to support these hypothetical values for avoidance or evasion). For a resident fish making a single downstream passage through the array, the probability of encounter (PE_{Ar}) with a HK turbine would be (5 transects) \times (1 probability of moving downstream) \times (0.05 area of river cross section occupied by HK rotor-swept area of all rotors in a transect) \times (0.5 probability of rotor blade avoidance) \times (0.5 probability of successful evasion of approaching rotor blade) = 0.06.

Subsequently, for fish with a larger range of movement, PE_{Ar} during unidirectional movement would increase proportional to the factor Ta_{i-ii} and with changes in P_a and P_e .

The above modeling approaches outline strategies for calculation of probability of fish to encounter a HK device during upstream or downstream movement. Different fish species vary

in riverine habitat preference and it is expected that refined geometric-area modeling approaches will identify species of relevance for interactions with HK technology. Furthermore, it is acknowledged that not all encounters with HK devices will actually result in physical contact with a HK turbine blade, but in absence of results from field studies, the conceptual modeling approach can provide baselines for later comparison against empirical data as such become available.

5.1 IDENTIFIED KNOWLEDGE GAPS

To improve the assessment of potential for fish to strike HK rotors or other moving components, there is a pressing need for data that describe how fish respond behaviorally when exposed to HK technology. In particular, observations on rates of success for avoidance or evasion of blade strike are expected to contribute most in reducing model uncertainty. Furthermore, empirical data are needed on abundance of fish species within different river habitats. Data on distribution and density of pelagic species within main channel habitats will aid in refinement of modeling efforts for risk of blade strike to fish. Furthermore, existing risk models will be enhanced as more specific information on design for proposed HK projects becomes available. Several knowledge gaps have been identified;

- The lack of data on fish behavior in response to encounter with HK technology is the greatest factor of uncertainty in modeling encounter rates and probabilities for blade strike. Limited field studies (e.g., Normandeau Associates, Inc. 2009) suggest that a fish's ability to evade the HK rotor blade can considerably reduce the strike losses. Conversely, while less likely, attraction to the rotor because of generated sounds or other stimuli may increase the probability of blade encounter and/or strike losses.
- Current modeling efforts assume uniform distribution of fish across river transects and concentrate on downstream movement of fish. However, fish species vary in their preferences for flow velocity or association with different habitat types and quantitative data on fish densities is needed for species with overlap of habitat with areas suitable for extraction of kinetic energy.
- Furthermore, upstream and downstream movement of resident fish, and lateral movement among habitat types within a river cross section invite research to examine how non-migratory fish respond to placement of HK technology in the river.
- Future energy scenarios envision the deployment of HK technology in large arrays. How fish will navigate through multiple arrays of HK devices, or to what degree fish will express behavioral responses such as avoidance or escape to prevent passage through rotor swept areas is currently unknown.
- In rivers, sediment loads and turbid waters may impair the visual recognition of rotating blades and impede avoidance behavior of fish. Research is needed to examine if and how fish respond to visual cues from moving parts associated with HK technologies.
- How the placement of HK technology in river currents will alter turbulence and flow velocity of water for fish is currently not well understood. Research is needed to examine how the placement of HK technologies changes flow velocity in currents upstream and downstream of HK devices.
- Some characteristics of HK devices (e.g., noise, electromagnetic fields; alteration of water velocities and bottom habitats) may attract some species of fish or deter others.

The differential responses of fish species to these other aspects of HK operations, and the resulting influence on susceptibility to strike, invite future research efforts.

- Research is needed to examine near field and far field downstream effects of turbulence from HK devices; increased turbulence may remove fine substrate in the immediate vicinity of HK devices and increase downstream sediment deposition.
- Under different flow regimes what are relationships among probability of blade strike and increase in total fish length? Under conditions with low current velocity, fish passage through a HK device may require more time and hence pose a greater risk for blade strike. Research is needed to identify thresholds for operational parameters to minimize risk of strike during low-flow conditions.
- For ducted turbine designs, questions arise of how fish will avoid entrainment. Are there fish species or size classes where their threshold for critical swim speed would limit their ability to escape potential entrainment during HK device encounter?
- Will differences in the downstream velocity field attract fish and increase predation or will fish avoid turbulence at turbine outflow?
- How will fish respond to altered velocity fields and turbulence during upstream movement?

Furthermore, HK technology deployed from pontoons or barges will differ in design and dimension from fixed installations on pillars. Inquiries about how surface deployed HK devices contrast from fixed installations in risk potential to aquatic biota, and what fish species are most likely to be affected by surface deployed HK technologies elicit further research.

6. DISCUSSION

The identification of overlap of aquatic habitat with potential placement of hydrokinetic devices in rivers is a first step in modeling risk of encounter and risk of blade strike to riverine biota. Geometric-area model approaches indicate that position of a HK device within the river cross section, and relative position of a HK turbine within the water column are key factors in identification of potentially affected biota and determining potential for risk of blade strike to fish. For plankton and macroinvertebrate drift assemblages including larval fish, risk of blade strike from HK turbines may be of less concern than potential for injury or damage from HK turbine induced turbulence. Main channel habitats yield the largest potential for kinetic energy extraction (Figure 18) and encounters with HK devices appear most likely for pelagic main channel species that include freshwater drum, gizzard shad, channel catfish, striped bass, some large river sucker species, and sturgeon species. Species that migrate between freshwater and saltwater habitats such as salmon, shad, or eel are likely to experience increased risk for encounter with HK technologies. For fish species associated with off-channel habitat lateral movement among habitat types or habitat utilization during different life stages may also increase potential exposure to HK technologies.

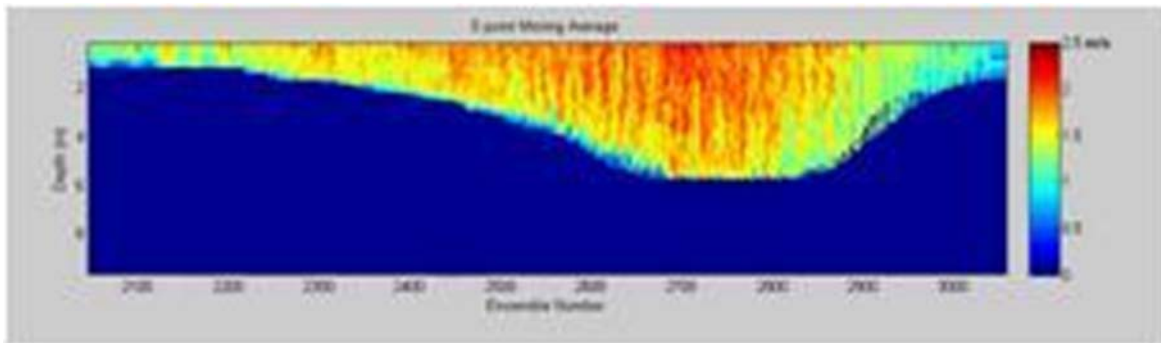


Figure 18. Example of a cross-section velocity profile for the Tanana River near Nenana, Alaska. (Source: Alaska Hydrokinetic Energy Research Center).

From the set of engineering parameters, turbine design (propeller-type turbine or cross-flow helical rotor), rotor swept area, number of blades in the HK turbine and projected rotation rate emerged as important components of future blade strike risk models. Compared to conventional hydroelectric energy production, HK turbines are expected to operate at relatively low rpm (~25-45 rpm). Preliminary modeling results suggest that probability of blade encounter during single passage through a rotor swept area is dependent on number of blades of the device, length of fish, rotor rotation rate, and river flow velocity. Arrays with multiple transects of HK devices in series or parallel arrangement are expected to pose increased risk for probability of encounter. Turbidity from high sediment loads in large rivers may impair visual orientation and avoidance or escape behavior of fish but to what cues fish will respond during navigation in vicinity of HK devices is subject of future research. However, the greatest factor of model uncertainty arises from a lack of data on fish behavior in response to exposure to HK technology.

Fish screens (Figure 19) may offer some protection from fish entrainment but are likely to decrease efficiency and power generation of a HK turbine. For large bodied river fish such as sturgeon and paddlefish, large catfish and deep bodied fishes like buffalo or carp, installation of protective screens may prove beneficial. Alternate efforts for mitigation in riverine environments are subject to future research.



Figure 19. Proposed fish screen assembly to reduce risk of blade strike, by UEK@System (Underwater Electric Kite) for the Yukon River Hydrokinetic Project. Source: Alaska Power & Telephone (AP&T), 2010.

6.1 FUTURE EFFORTS

During FY11, ORNL will advance the modeling it began in FY10 to predict encounter rates and probabilities of injury or mortality in riverine and tidal deployments of MHK devices. This model will be designed such that developers and regulators can test various operational and environmental assumptions on encounter and strike probability. Whenever possible we will incorporate the results of laboratory and field blade strike studies from the U.S. and abroad. We will also develop procedures and initiate laboratory studies for testing blade strike in laboratory flumes. If possible, this work will be coordinated with a related project to be undertaken by the Electric Power Research Institute (EPRI) and partners (including Alden Labs and the Conte Anadromous Fish Research Laboratory) which may also receive DOE Waterpower funding through the industry-led research program. We will work with these labs to increase the types of devices and the number of species being tested.

We also plan to test laboratory procedures for measuring the effects on larval fish of close encounters with MHK devices. Direct blade strike might not be necessary to injure larval fish; because of their fragile nature, larval fish may be injured by close encounters that expose them to extreme turbulence, high shear stresses, and blade-induced cavitation. Studies of the effects of

these stressors do not require a full scale device in a laboratory flume, but can be carried out in smaller test settings that replicate individual stressors.

Hence, evaluation of the probability and consequences of blade strike associated with MHK rotors could be investigated in two interrelated efforts. In one set of experiments, a scale model of a MHK rotor would be installed in a flume, and the interactions of the moving blades with large, freely swimming fish would be assessed (behavioral avoidance, evasion, or blade strike, and the injury and mortality resulting from strike). These studies would help determine whether actively swimming fish are able to avoid blade strike, as suggested by most MHK developers. In a second set of experiments, the interactions of small, weakly swimming or passively drifting juvenile fish with a fixed MHK leading edge profile will be quantified. In many aquatic systems, the large numbers of drifting fish eggs, larvae, and small juveniles may be the organisms most susceptible to rotor strike. Because of their poorly developed sensory systems and swimming abilities, small fish may not be able to avoid the rotor as they drift in a swiftly flowing current. However, their small size and mass may cause them to be swept aside in the “bow wave” of the blade, thereby avoiding injury. Laboratory experiments to assess the risk and consequences of blade strike to these largely passively drifting organisms would help define the importance of the issue at many sites.

6.1.1 EPRI/Alden Studies of Fish Interactions with Scale Model MHK Rotor

Contingent upon funding, experiments would be carried out in 2011 at the Alden Research Laboratory to quantify the risk of fish strike associated with a moving hydrokinetic rotor. Based on technology readiness level and environmental testing needs of MHK developers, candidate MHK designs include (1) Free Flow Power’s horizontal axis, ducted turbine or (2) the horizontal axis, cross-flow helical turbine designs of Alexander Gorlov and Ocean Renewable Power Company. Vortex Hydro’s VIVACE design (not a rotor, but rather a series of moving cylinders), could also be tested in a similar fashion.

Scale models of the MHK rotor would be installed in Alden’s flume, and the reactions of fish introduced upstream from the rotor would be observed, using an approach similar to that used for Alden’s studies of the Lucid spherical cross-flow rotor. Detailed, fine-scale measurements of water velocities in the vicinity of the rotor, coupled with high-speed video recordings, could be used to interpret any observed avoidance and evasion behavior. In addition to standard test conditions (e.g., lighted flume, good water quality and temperature), there would be value in testing fish responses under suboptimal conditions. For example, a fish’s ability to avoid strike or the injury resulting from strike could be compared for lighted vs. darkened conditions in the flume or for optimal water temperatures vs. cold water temperatures (which may slow the fish’s swim speeds).

Fish species could include trout or salmon that are commonly tested in blade strike studies. In order to encompass a broader range of species that might interact with MHK projects, it would be useful to also test American shad (or some other member of the Clupeidae), striped bass (or white bass or white perch), sturgeon, white suckers (or some other member of the Catostomidae), and smallmouth or largemouth bass. Within a species, testing of two or three different sizes classes would help determine whether a fish’s ability to avoid strike or its susceptibility to strike injury is influenced by its size.

Post-experiment data analysis would include comparisons of strike occurrences and injuries/mortality of control and test fish under the different test conditions. Mathematical models would be used to extrapolate the flume tests of a scale model rotor to predict effects on fish from a full-sized, prototype rotor.

6.1.2 ORNL Studies of Blade Strike in Passively Drifting Juvenile Fish

The largest numbers of fish that are likely to interact with mid-water rotors in rivers and ocean currents will be small – eggs, larvae, and juveniles that are more or less drifting with the currents. Because of their less-developed sensory and swimming abilities, these fish early life stages presumably have a poor ability to avoid blade strike and are often considered as passively drifting particles in strike models. However, some MHK developers suggest that the rotor blades create hydrodynamic disturbances (“bow waves”) in front of the leading edge that may signal fish that there is an oncoming threat (Gorlov 2010) or, in the case of very small fish, sweep them aside without blade contact (EPRI 2008). It is possible that the low mass (and low momentum) of fish early life stages will cause them to drift with the bow wave and be deflected around the blade leading edge. If verified, the result of this passive mechanism would be to reduce the strike probability for small fish in the rotor swept area.

Experiments would be carried out in 2011 at Oak Ridge National Laboratory to quantify the risk of fish strike associated with a stationary MHK blade shape fixed in a laboratory flume. Based on technology readiness level and environmental testing needs of MHK developers, candidate MHK designs include blade leading edge shapes associated with (1) Free Flow Power’s horizontal axis, ducted turbine or (2) the horizontal axis, cross-flow helical turbine designs of Alexander Gorlov and Ocean Renewable Power Company. Vortex Hydro’s VIVACE design (not a rotor, but rather a series of moving cylinders), could also be tested in a similar fashion.

A full-sized model of the MHK rotor blade leading edge profile would be installed in a flume in ORNL’s aquatics laboratory. Fish early life stages (eggs, larvae, and/or small juveniles) would be introduced into the flume upstream from the blade in such a way that they would drift with the current in a direct path toward the blade profile. High speed videos would record the paths of fish and the incidence of strike. Detailed, fine-scale measurements of water velocities in the vicinity of the blade, coupled with the high-speed video recordings, could be used to quantify and interpret any motions that depart from that of a passive water particle. Fish would be collected with fine-mesh plankton nets downstream from the blade in order to assess injury and mortality compared to controls. The incidence of strike measured in these tests would be compared to that predicted from the strike equation that assumes no avoidance or evasion of the blade by small, drifting fish. Flow velocities in the flume would be varied to simulate fish-blade interactions at different current velocities and at different distances from the hub of a rotor.

Fish species could include those with drifting or planktonic early life stages, including shad (family Clupeidae), striped bass (or white bass or white perch), white suckers (or some other member of the family Catostomidae), and members of the sunfish family (bluegill, smallmouth or largemouth bass). For most species, larvae or juveniles would be tested; especially in rivers,

most fish eggs are laid in nests or adhere to the substrate and are not susceptible to MHK blade strike.

Post-experiment data analysis would include comparison of measured strike occurrences to those predicted by the standard strike equation, with a goal of quantifying the values for avoidance and evasion. Test and control fish would be compared to evaluate whether collisions with the blade or exposures to the shear stresses associated with flow disturbances near the blade increase fish mortality. Mathematical models would be used to extrapolate the flume tests of a scale model rotor to predict effects on fish from a full-sized, prototype rotor.

7. REFERENCES

- Alaska Hydrokinetic Energy Research Center (AHERC), The University of Alaska Fairbanks. 2010. Available online: <http://www.uaf.edu/acep/facilities/alaska-hydrokinetic-energ/> (Accessed March 2011).
- Alaska Power & Telephone. 2010. Yukon River Hydrokinetic Turbine Project. Available online: <http://www.aptalaska.com/index.php?action=switchPage&pageID=95> (Accessed September 2010).
- Barko, V. A., D. P. Herzog, R. A. Hrabik & J. S. Scheibe (2004) Relationship among Fish Assemblages and Main-Channel-Border Physical Habitats in the Unimpounded Upper Mississippi River. *Transactions of the American Fisheries Society*, 133, 371-384.
- Čada, G. F. 1977. The entrainment of larval fishes at two nuclear power plants on the Missouri River in Nebraska. Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska.
- Čada, G. F. 1990. A review of studies related to the effects of propeller-type turbine passage on fish early life stages. *North American Journal of Fisheries Management* 10(4):418-426.
- Čada, G.F., J. Smith, and J. Busey. 2005. Use of pressure sensitive film to quantify sources of injury to fish. *North American Journal of Fisheries Management* 25(2):57-66.
- Čada, G.F., J.M. Loar, L. Garrison, R.K. 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.
- Čada, G.F., J. Ahlgrim, M. Bahleda, T. Bigford, S. Damiani Stavrakas, D. Hall, R. Moursund, and M. Sale. 2007. Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments. *Fisheries* 32(4):174-181.
- Carter, S. T., K. R. Bazata, and D. L. Andersen. (1982) Macroinvertebrate communities of the channelized Missouri River near two nuclear power stations. *In: Hesse L.W., G.L. Hergenrader, H.S. Lewis, et al. (Editors) The Middle Missouri River: a collection of papers on the biology with special reference to power station effects.*
- Chick, J. H., M. A. Pegg & T. M. Koel (2006) Spatial patterns of fish communities in the Upper Mississippi River System: Assessing fragmentation by low-head dams. *River Research and Applications*, 22, 413-427.
- Clifford, H. F. (1972) A year's study of drifting organisms in a brown-water stream of Alberta, Canada. *Canadian Journal of Zoology*, 50, 975-983.
- Copp, G. and M. Peñáz (1988) Ecology of fish spawning and nursery zones in the flood plain, using a new sampling approach. *Hydrobiologia*, 169, 209-224.

Coutant, C.C. and G.F. Čada. 2005. What's the future of instream hydro? *Hydro Review* XXIV(6):42-49.

Davison, A. and T. Mallows. 2005. Strangford Lough Marine Current Turbine Environmental Statement (Non-Technical Summary). Project No. 9P5161. Royal Haskoning Ltd., Edinburg, UK. Available online: <http://www.seageneration.co.uk/downloads/EIS%20Non%20Technical%20Summary.pdf>. (Accessed September 2010).

Deng, Z., T.J. Carlson, G.R. Ploskey, and M.C. Richmond. 2005. Evaluation of blade-strike models for estimating the biological performance of large Kaplan turbines. PNNL-15370. Pacific Northwest National Laboratory, Richland, WA.

Deng, Z., T. J. Carlson, G. R. Ploskey, M. C. Richmond & D. D. Dauble. 2007. Evaluation of blade-strike models for estimating the biological performance of Kaplan turbines. *Ecological Modelling*, 208, 165-176.

Dettmers, J. M., D. H. Wahl, D. A. Soluk & S. Gutreuter. 2001. Life in the Fast Lane: Fish and Foodweb Structure in the Main Channel of Large Rivers. *Journal of the North American Benthological Society*, 20, 255-265.

DOE 2009. Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies. Prepared in response to the Energy Independence and Security Act of 2007, Section 633(b). Report to Congress.

Domenici, P., and R. W. Blake. 1997. The kinematics and performance of fish fast-start swimming. *Journal of Experimental Biology*, 200(8):1165-1178.

Eicher Associates Inc. 1987. Turbine-related fish mortality: review and evaluation of studies. Rep. EPRI-AP-5480 to Electric Power Research Institute, Palo Alto, Ca.

Elliot, J. M. 1970. Methods of sampling invertebrate drift in running water. *Annalis De Limnologie* 6:133-159.

EnCurrent Hydro Turbines, New Energy Corporation Inc. 2010. Available online: <http://www.newenergycorp.ca/Portals/0/documents/datasheets/ENC.005.010.DataSheet.pdf> (Accessed March 2011).

EPRI (Electric Power Research Institute). 2008. Evaluation of the Effects of Turbine Blade Leading Edge Design on Fish Survival. EPRI, Palo Alto, CA: 2008. 1014937.

Ferguson, J. W., G. R. Ploskey, K. Leonardsson, R. W. Zabel & H. Lundqvist (2008) Combining turbine blade-strike and life cycle models to assess mitigation strategies for fish passing dams. *Canadian Journal of Fisheries and Aquatic Sciences*, 65, 1568-1585.

FERC 2010. Federal Energy Regulatory Commission, Hydrokinetic Projects. Available online: <http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics.asp>. (Accessed September 2010).

Fraenkel, P.L. 2006. Tidal current energy technologies. *Ibis* 148:145-151.

Fraenkel, P.L. 2007a. Marine current turbines: Pioneering the development of marine kinetic energy converters. Proceedings of the Institution of Mechanical Engineers, Part A: *Journal of Power and Energy*. 221(2):159-169.

Fraenkel, P.L. 2007b. Marine current turbines: Moving from experimental test rigs to a commercial technology. 26th International Conference on Offshore Mechanics & Arctic Engineering. ASME-OMAE07. 10 p.

Free Flow Power Corporation (FFP). 2010. A new generation of energy. Available online: <http://www.free-flow-power.com/Home.html> (Accessed September 2010).

Galat, D. L. & I. Zweimuller (2001) Conserving large-river fishes: is the highway analogy an appropriate paradigm? *Journal of the North American Benthological Society*, 20, 266-279.

Gammon, J. R. 1977. Measurement of entrainment and predictions of impact on the Wabash and Ohio Rivers. Pages 159-176 in L. D. Jenson, editor. Third National Workshop on Entrainment and Impingement. Ecological Analysts, Inc., Melville, New York.

Gorlov, A. (2005). Alexander's marvelous machine (Jill Davis) National Resources Defense Council. Available online: <http://www.nrdc.org/onearth/05spr/gorlov1.asp> (Accessed September 2010).

Gorlov, A. 2010. Helical turbine and fish safety. Available online: <http://www.mainetidalpower.com/project.html> (Accessed March 2011).

Gutreuter, S., J. M. Vallazza and B. C. Knights. 2010. Lateral distribution of fishes in the main-channel trough of a large floodplain river: implications for restoration. *River Research and Applications*, 26, 619-635.

Halloran, B. T. 2010. Early life history dynamics of the fish community in the Atchafalaya River basin. Ph.D. Dissertation. Louisiana State University and Agricultural and Mechanical College, Baton Rouge, Louisiana.

Hergenrader, G.L., L. G. Harrow, R. G. King, and G. Čada. 1982. Larval fishes in the Missouri River and the effects of entrainment. In: Hesse L.W., G.L. Hergenrader, H.S. Lewis, et al. (Editors) The Middle Missouri River: a collection of papers on the biology with special reference to power station effects.

Holland, L. E. (1986) Distribution of early life history stages of fishes in selected pools of the Upper Mississippi River. *Hydrobiologia*, 136, 121-130.

Hydro Green Energy, LLC. 2010. Available online: <http://www.hgenergy.com/> (Accessed September 2010).

Khan, M. J., G. Bhuyan, M. T. Iqbal and J. E. Quaicoe (2009) Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Applied Energy*, 86, 1823-1835.

Koel, T. M. (2004) Spatial variation in fish species richness of the upper Mississippi River system. *Transactions of the American Fisheries Society*, 133, 984-1003.

Liao, J. C. (2007) A review of fish swimming mechanics and behaviour in altered flows. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 362, 1973-1993.

Moore, K. M. S., and S. V. Gregory. 1988. Response of young-of-the-year cutthroat trout to manipulation of habitat structure in a small stream. *Transactions of the American Fisheries Society* 117: 162-170.

Normandeau Associates, Inc. 2009. An Estimation of Survival and Injury of Fish Passed Through the Hydro Green Energy Hydrokinetic System, and a Characterization of Fish Entrainment Potential at the Mississippi River Lock and Dam No. 2 Hydroelectric Project (FERC No. P-4306) Hastings, Minnesota. Final Report. December 2009. Available online: <http://www.normandeau.com/> (Accessed March 2011).

Ocean Renewable Power Company, LLC. 2010. Available online: <http://www.oceanrenewablepower.com/home.htm> (Accessed September 2010).

Ploskey, G.R. and T.J. Carlson. 2004. Comparison of Blade-Strike Modeling Results with Empirical Data. PNNL-14603. Pacific Northwest National Laboratory, Richland, WA.

Schramm, H. L., Jr. 2004. Status and management of Mississippi River fisheries. Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries. *Editors: Welcomme R. L. and T. Petr.*

Sheaffer, W. A. & J. G. Nickum (1986) Backwater areas as nursery habitats for fishes in pool 13 of the Upper Mississippi River. *Hydrobiologia*, 136, 131-139.

Turnpenny, A.W.H., M.H. Davis, J.M. Fleming, and J.K. Davies. 1992. Experimental studies relating to the passage of fish and shrimps through tidal power turbines. Marine and Freshwater Biology Unit, National Power, Fawley, Southampton, Hampshire, England.

Verdant Power. 2010. A world leader in renewable energy. Available online: <http://verdantpower.com/> (Accessed September 2010).

Videler, J. J., and C. S. Wardle. 1992. Fish Swimming Stride by Stride - Speed Limits and Endurance (Reviews in Fish Biology and Fisheries, Vol 1, Pg 23, 1991). *Reviews in Fish Biology and Fisheries* 2(4):358-35.

VLH (Very Low Head turbines), MJ2 Technologies S.A.R.L. 2008. Available online: <http://www.vlh-turbine.com/EN/php/Accueil.php> (Accessed March 2011).

Von Raben, K. 1957. "Regarding the problem of mutilation of fishes by hydraulic turbines." Originally published in *Die Wasserwirtschaft* (100):497. *Fisheries Research Board of Canada Translation Series*, No. 448, 1964.

Ward, D. L., A. A. Schultz, and P. G. Matson. 2003. Differences in swimming ability and behavior in response to high water velocities among native and nonnative fishes. *Environmental Biology of Fishes* 68(1):87-92.

Wilson, B., R.S. Batty, F. Daunt, and C. Carter. 2007. Collision Risks Between Marine Renewable Energy Devices and Mammals, Fish and Diving Birds. Report to the Scottish Executive. Scottish Association for Marine Science, Oban, Scotland. PA25 1QA. 110 p.

Wolter, C. & A. Sukhodolov. 2008. Random displacement versus habitat choice of fish larvae in rivers. 661-672. John Wiley & Sons, Ltd.

Zimmerman, H.J. 1977. Seasonal events in the invertebrate drift in the Mississippi River near Becker, Minnesota. M.A. Thesis. St. Cloud College, St. Cloud, Minnesota.

APPENDIX A.
FISH SPECIES IN THE MISSISSIPPI RIVER BASIN
THAT MAY BE AFFECTED BY HYDROKINETIC TURBINE STRIKE

**APPENDIX A. FISH SPECIES IN THE MISSISSIPPI RIVER BASIN
THAT MAY BE AFFECTED BY HYDROKINETIC TURBINE STRIKE**

Table A-1. Distribution and abundance of fishes in the headwaters (HW), upper (UMR) and open river (OR) segments of the Mississippi River. Fish are resident in the Mississippi River unless noted otherwise (Residence)

Source: Schramm (2004)

| Family species | Residence ¹ | HW ² | UMR ² | OR ² | Back water dependent | Riverine dependent | Probable zone ³ |
|---|------------------------|-----------------|------------------|-----------------|----------------------|--------------------|----------------------------|
| <i>Ascipenseridae</i> | | | | | | | |
| Lake sturgeon, <i>Acipenser fulvescens</i> (Rafinesque) | | | O ⁴ | R ⁴ | | Yes | MC, CB |
| Atlantic sturgeon, <i>Acipenser oxyrinchus</i> (Mitchill) | D | | | R ⁵ | | | MC, CB |
| Pallid sturgeon, <i>Scaphirhynchus albus</i> (Forbes and Richardson) | | | R | O | | Yes | MC, CB |
| Shovelnose sturgeon, <i>Scaphirhynchus platyrhynchus</i> (Rafinesque) | | | O | O | | Yes | MC, CB |
| <i>Polyodontidae</i> | | | | | | | |
| Paddlefish, <i>Polyodon spathula</i> (Walbaum) | | | O | O | | Yes | MC, CB, BW |
| <i>Lepisosteidae</i> | | | | | | | |
| Alligator gar, <i>Atractosteus spatula</i> (Lacepede) | | | | R | Yes | | BW |
| Spotted gar, <i>Lepisosteus oculatus</i> (Winchell) | | | U | O | Yes | | BW |
| Longnose gar, <i>Lepisosteus osseus</i> (Linnaeus) | | | O | C | Yes | | MC, CB, BW |
| Shortnose gar, <i>Lepisosteus platostomus</i> (Rafinesque) | | H1 | C | C | Yes | | MC, CB, BW |
| <i>Amiidae</i> | | | | | | | |
| Bowfin, <i>Amia calva</i> (Linnaeus) | | R | C | O | Yes | | BW |
| <i>Anguillidae</i> | | | | | | | |
| American eel, <i>Anguilla rostrata</i> (Lesueur) | D | R | O | U | | | CB |
| <i>Hiodontidae</i> | | | | | | | |
| Goldeye, <i>Hiodon alosoides</i> (Rafinesque) | | | U | O | | | CB |
| Mooneye, <i>Hiodon tergisus</i> (Lesueur) | | | O | U/R | | | CB |
| <i>Clupeidae</i> | | | | | | | |
| Alabama shad, <i>Alosa alabamae</i> (Jordan and Everman) | D | | | R | | | MC, CB |
| Skipjack herring, <i>Alosa chrysochloris</i> (Rafinesque) | | | O/R | C | | | MC, CB, BW |
| Gizzard shad, <i>Dorosoma cepedianum</i> (Lesueur) | | A | A | A | Yes | | MC, CB, BW |
| Threadfin shad, <i>Dorosoma petenense</i> (Günther) | | | U | A | Yes | | CB, BW |
| <i>Salmonidae</i> | | | | | | | |
| Cisco, <i>Coregonus artedii</i> (Lesueur) | | R | R | | | | BW |
| <i>Umbridae</i> | | | | | | | |
| Central mudminnow, <i>Umbra limi</i> (Kirtland) | | U | O | | Yes | | BW |
| <i>Esocidae</i> | | | | | | | |
| Grass pickerel, <i>Esox americanus vermiculatus</i> (Lesueur) | | | R | R | Yes | | BW |
| Northern pike, <i>Esox lucius</i> (Linnaeus) | | O | O | | Yes | | BW |
| Muskellunge, <i>Esox masquinongy</i> (Mitchill) | | O/U | | | Yes | | BW |
| Chain pickerel, <i>Esox niger</i> (Lesueur) | | | | R ⁵ | Yes | | BW |
| <i>Cyprinidae</i> | | | | | | | |
| Central stoneroller, <i>Campostoma anomalum</i> (Rafinesque) | | R | R | H2 ⁶ | | | MC, CB |
| Goldfish, <i>Carassius auratus</i> (Linnaeus) | I | | U | R | Yes | | BW |

Table A-1 (continued)

| Family species | Resi- dence ¹ | HW ² | UMR ² | OR ² | Back water dependent | Riverine dependent | Probable zone ³ |
|---|-----------------------------|-----------------|------------------|-----------------|----------------------------|-----------------------|-------------------------------|
| Grass carp, <i>Ctenopharyngodon idella</i> (Valenciennes) | I | | U | U | | Yes | MC, CB, BW |
| Bluntnose shiner, <i>Cyprinella camura</i> (Jordan and Meek) | P | | | H2 | | | CB |
| Red shiner, <i>Cyprinella lutrensis</i> (Baird and Girard) | | | O | C/O | Yes | | CB, BW |
| Spotfin shiner, <i>Cyprinella spiloptera</i> (Cope) | | C | C | R | | | CB, BW |
| Blacktail shiner, <i>Cyprinella venusta</i> (Girard) | | | | O | | | CB, BW |
| Steelcolor shiner, <i>Cyprinella whipplei</i> (Girard) | P | | | R | | | CB, BW |
| Common carp, <i>Cyprinus carpio</i> (Linnaeus) | I | C | A | C | Yes | | CB, BW |
| Gravel chub, <i>Erimystax x-punctatus</i> (Hubbs and Crowe) | | | | R | | | CB, BW |
| Western silvery minnow, <i>Hybognathus argyritis</i> (Girard) | | | | R | | | BW |
| Brassy minnow, <i>Hybognathus hankinsoni</i> (Hubbs) | | U | R | | | | CB |
| Cypress minnow, <i>Hybognathus hayi</i> (Jordan) | | | | R | Yes | | BW |
| Mississippi silvery minnow, <i>Hybognathus nuchalis</i> (Agassiz) | | | U/R | O | Yes | | CB, BW |
| Plains minnow, <i>Hybognathus placitus</i> (Girard) | | | | U/R | | Yes | MC, CB |
| Clear chub, <i>Hybopsis winchelli</i> (Girard) | | | | R ⁵ | | | CB |
| Silver carp, <i>Hypophthalmichthys molitrix</i> (Valenciennes) | I | | C/O | C | | | CB |
| Bighead carp, <i>Hypophthalmichthys nobilis</i> (Richardson) | I | | O | O | | | CB |
| Striped shiner, <i>Luxilus chrysocephalus</i> (Rafinesque) | P | | | R | | | CB |
| Common shiner, <i>Luxilus cornutus</i> (Mitchill) | | C | O/R | | | | MC, CB, BW |
| Ribbon shiner, <i>Lythrurus fumeus</i> (Evermann) | P | | | R | | | BW |
| Redfin shiner, <i>Lythrurus umbratilis</i> (Girard) | P | | R | H2 | | | CB, BW |
| Speckled chub, <i>Macrhybopsis aestivalis</i> (Girard) | | | O | C | | | CB |
| Sturgeon chub, <i>Macrhybopsis gelida</i> (Girard) | | | | U/R | | | CB |
| Sicklefin chub, <i>Macrhybopsis meeki</i> (Jordan and Everman) | | | | U/R | | | CB |
| Silver chub, <i>Macrhybopsis storeriana</i> (Kirtland) | | | C/O | C/O | | | CB, BW |
| Pearl dace, <i>Margariscus margarita</i> (Cope) | | R | | | | | MC, CB, BW |
| Black carp, <i>Mylopharyngodon piceus</i> (Richardson) | I | | | R | | | CB, BW |
| Hornyhead chub, <i>Nocomis biguttatus</i> (Kirtland) | | O | R | | | | CB |
| Golden shiner, <i>Notemigonus crysoleucas</i> (Mitchill) | | O | C/O | U | Yes | | BW |
| Pallid shiner, <i>Notropis amnis</i> (Hubbs and Greene) | | | R | | | | CB |
| Emerald shiner, <i>Notropis atherinoides</i> (Rafinesque) | | A | A | A | | | CB, BW |

Table A-1 (continued)

| Family species | Resi- dence ¹ | HW ² | UMR ² | OR ² | Back water dependent | Riverine dependent | Probable zone ³ |
|---|-----------------------------|-----------------|------------------|-----------------|----------------------------|-----------------------|-------------------------------|
| River shiner, <i>Notropis blennioides</i> (Girard) | | | C | C | | | CB, BW |
| Bigeye shiner, <i>Notropis boops</i> (Gilbert) | P | | | R | | | CB |
| Ghost shiner, <i>Notropis bethlemi</i> (Meek) | | | R | U/R | Yes | | CB, BW |
| Bigmouth shiner, <i>Notropis dorsalis</i> (Agassiz) | | P | O | O/R | R | | CB |
| Blackchin shiner, <i>Notropis heterodon</i> (Cope) | | U | O/R | | Yes | | BW |
| Blacknose shiner, <i>Notropis heterolepis</i> (Eigenmann and Eigenmann) | | U | R | | | | BW |
| Spottail shiner, <i>Notropis hudsonius</i> (Clinton) | | U | U | R | | | CB |
| Longnose shiner, <i>Notropis longirostris</i> (Hay) | | | | U ⁵ | | Yes | MC, CB |
| Ozark minnow, <i>Notropis nubilis</i> (Forbes) | P | | R | R | | | CB |
| Chub shiner, <i>Notropis potteri</i> (Hubbs and Bonham) | | | | R | | | CB |
| Rosyface shiner, <i>Notropis rubellus</i> (Agassiz) | P | | R | | | | CB |
| Silverband shiner, <i>Notropis shumardi</i> (Girard) | | | R | O | | | CB, BW |
| Sand shiner, <i>Notropis stramineus</i> (Cope) | P | R | O | U ⁵ | | | CB |
| Weed shiner, <i>Notropis texanus</i> (Girard) | | | O | U | Yes | | BW |
| Mimic shiner, <i>Notropis volucellus</i> (Cope) | | R | C | O | | | CB, BW |
| Channel shiner, <i>Notropis wickliffi</i> (Trautman) | | | C/O | O | | | MC, CB |
| Pugnose minnow, <i>Opsopoeodus emiliae</i> (Hay) | | | O | O | Yes | | BW |
| Suckermouth minnow, <i>Phenacobius mirabilis</i> (Girard) | | | R | R | | | CB, BW |
| Northern redbelly dace, <i>Phoxinus eos</i> (Cope) | | C | | | | | CB |
| Southern redbelly dace, <i>Phoxinus erythrogaster</i> (Rafinesque) | | P | | H1 | H2 | | CB |
| Finescale dace, <i>Phoxinus neogaeus</i> (Cope) | | R | | | | | CB, BW |
| Bluntnose minnow, <i>Pimephales notatus</i> (Rafinesque) | | P | O | O | U | | BW |
| Fathead minnow, <i>Pimephales promelas</i> Rafinesque | | C/U | U | R | Yes | | BW |
| Bullhead minnow, <i>Pimephales vigilax</i> (Baird and Girard) | | R | O | O | Yes | | BW |
| Flathead chub, <i>Platygobio gracilis gracilis</i> (Richardson) | | | | R | | Yes | CB |
| Eastern blacknose dace, <i>Rhinichthys atratulus</i> (Hermann) | P | U | R | | | Yes | CB |
| Longnose dace, <i>Rhinichthys cataractae</i> (Valenciennes) | | C/O | R | | | Yes | CB |
| Creek chub, <i>Semotilus atromaculatus</i> (Mitchill) | | O | R | | | Yes | MC, CB |
| Catostomidae | | | | | | | |
| River carpsucker, <i>Carpionodes carpio</i> (Rafinesque) | | | C | A | | Yes | CB, BW |
| Quillback, <i>Carpionodes cyprinus</i> (Lesueur) | | R | C | U | | | CB, BW |
| Highfin carpsucker, <i>Carpionodes velifer</i> (Rafinesque) | | | O/U | R | | | CB, BW |
| White sucker, <i>Catostomus commersoni</i> (Lacepède) | | C | C | | | | MC, CB, BW |

Table A-1 (continued)

| Family species | Resi- dence ¹ | HW ² | UMR ² | OR ² | Back water dependent | Riverine dependent | Probable zone ³ |
|---|-----------------------------|-----------------|------------------|------------------|----------------------------|-----------------------|-------------------------------|
| Blue sucker, <i>Cycleptus elongatus</i> (Lesueur) | | | O | O | | Yes | MC, CB |
| Creek chubsucker, <i>Erimyzon oblongus</i> (Mitchill) | | | | U | | | BW |
| Lake chubsucker, <i>Erimyzon succetta</i> (Lacepède) | | | | U | | | BW |
| Northern hog sucker, <i>Hypentelium nigricans</i> (Lesueur) | | O | R | | | | CB |
| Smallmouth buffalo, <i>Ictiobus bubalus</i> (Rafinesque) | | | C/O | A/C | Yes | | MC, CB, BW |
| Bigmouth buffalo, <i>Ictiobus cyprinellus</i> (Valenciennes) | | O | C | C/O | Yes | | CB, BW |
| Black buffalo, <i>Ictiobus niger</i> (Rafinesque) | | | U/R | U | Yes | | CB, BW |
| Spotted sucker, <i>Minytrema melanops</i> (Rafinesque) | | | C/O | U/R ⁵ | Yes | | CB, BW |
| Silver redhorse, <i>Moxostoma anisurum</i> (Rafinesque) | | O | C/O | H2 | | | CB, BW |
| River redhorse, <i>Moxostoma carinatum</i> (Cope) | | | O/R | R | | | CB |
| Golden redhorse, <i>Moxostoma erythrum</i> (Rafinesque) | | | O | | | | MC, CB |
| Shorthead redhorse, <i>Moxostoma macrolepidotum</i> (Lesueur) | | C | C/O | U ⁷ | | | MC, CB |
| Greater redhorse, <i>Moxostoma valenciennesi</i> (Jordan) | | O | R | | | Yes | MC, CB, BW |
| Ictaluridae | | | | | | | |
| White catfish, <i>Ameiurus catus</i> (Linnaeus) | P | | | H3 | | | |
| Black bullhead, <i>Ameiurus melas</i> (Rafinesque) | | R | O | U | Yes | | BW |
| Yellow bullhead, <i>Ameiurus natalis</i> (Lesueur) | | R | O | U | Yes | | BW |
| Brown bullhead, <i>Ameiurus nebulosus</i> (Lesueur) | | R | O | | Yes | | BW |
| Blue catfish, <i>Ictalurus furcatus</i> (Lesueur) | | | O | A | | | MC, CB |
| Channel catfish, <i>Ictalurus punctatus</i> (Rafinesque) | | O | C | C | | | CB, BW |
| Mountain madtom, <i>Noturus eleutherus</i> (Jordan) | | | | H1 | | Yes | CB |
| Stonecat, <i>Noturus flavus</i> (Rafinesque) | | R | R | O | | Yes | CB |
| Tadpole madtom, <i>Noturus gyrinus</i> (Mitchill) | | R | O | U/R | Yes | | BW |
| Freckled madtom, <i>Noturus nocturnus</i> (Jordan and Gilbert) | | | R | O/U | | | BW |
| Northern madtom, <i>Noturus stigmosus</i> (Taylor) | | | | H2 | | | CB, BW |
| Flathead catfish, <i>Pylodictis olivaris</i> (Rafinesque) | | R | C/O | A | | | MC, CB |
| Aphredoderidae | | | | | | | |
| Western pirate perch, <i>Aphredoderus sayanus</i> (Gilliams) | | | R | R | Yes | | BW |
| Percopsidae | | | | | | | |
| Trout-perch, <i>Percopsis omiscomaycus</i> (Walbaum) | | O | O | | Yes | | BW |
| Gadidae | | | | | | | |
| Burbot, <i>Lota lota</i> (Linnaeus) | | O | R | | | | CB, BW |

Table A-1 (continued)

| Family species | Resi- dence ¹ | HW ² | UMR ² | OR ² | Back water dependent | Riverine dependent | Probable zone ³ |
|---|-----------------------------|-----------------|------------------|-----------------|----------------------------|-----------------------|-------------------------------|
| Fundulidae | | | | | | | |
| Golden topminnow, <i>Fundulus chrysotus</i> (Günther) | P | | | R | Yes | | BW |
| Banded killifish, <i>Fundulus diaphanus</i> (Le Sueur) | | R | H1 | | | | |
| Starhead topminnow, <i>Fundulus dispar</i> (Agassiz) | P | | R | R | | | BW |
| Blackstripe topminnow, <i>Fundulus notatus</i> (Rafinesque) | | | O | O | Yes | | BW |
| Blackspotted topminnow, <i>Fundulus olivaceus</i> (Storer) | | | | O | Yes | | BW |
| Poeciliidae | | | | | | | |
| Western mosquitofish, <i>Gambusia affinis</i> (Baird and Girard) | | | O | O | Yes | | BW |
| Atherinidae | | | | | | | |
| Brook silverside, <i>Labidesthes sicculus</i> (Cope) | | O | C/O | C/O | | | BW |
| Inland silverside, <i>Menidia beryllina</i> (Cope) | | | | O | | | CB, BW |
| Gasterosteidae | | | | | | | |
| Brook stickleback, <i>Culaea inconstans</i> (Kirtland) | | R | R | | | | MC, CB |
| Cottidae | | | | | | | |
| Mottled sculpin, <i>Cottus bairdi</i> (Girard) | | R | | | | | |
| Percichthyidae | | | | | | | |
| White bass, <i>Morone chrysops</i> (Rafinesque) | | R | C | C | | | CB, BW |
| Yellow bass, <i>Morone mississippiensis</i> (Jordan and Everman) | | | R/O | O | | | BW |
| Striped bass, <i>Morone saxatilis</i> (Walbaum) ⁷ | D | | | O | | | MC, CB |
| Centrarchidae | | | | | | | |
| Rock bass, <i>Ambloplites rupestris</i> (Rafinesque) | | C | C/O | | Yes | | BW |
| Shadow bass, <i>Ambloplites arriomus</i> (Viosca) | P | | | U ⁵ | | | BW |
| Flier, <i>Centrarchus macropterus</i> (Lacepü de) | | | | O | Yes | | BW |
| Banded pygmy sunfish, <i>Elassoma zonatum</i> (Jordan) | | | | R ⁵ | Yes | | BW |
| Green sunfish, <i>Lepomis cyanellus</i> (Rafinesque) | | R | C/O | U | Yes | | BW |
| Pumpkinseed, <i>Lepomis gibbosus</i> (Linnaeus) | | R | C/O | | Yes | | BW |
| Wormouth, <i>Lepomis gulosus</i> (Cuvier) | | | O/U | C/O | Yes | | BW |
| Orangespotted sunfish <i>Lepomis humilis</i> (Girard) | | | O | O | Yes | | BW |
| Bluegill, <i>Lepomis macrochirus</i> (Rafinesque) | | O | A | C | Yes | | BW |
| Longear sunfish, <i>Lepomis megalotis</i> (Rafinesque) | | | | U | Yes | | BW |
| Redear sunfish, <i>Lepomis microlophus</i> (Günther) | | | | U | Yes | | BW |
| Bantam sunfish, <i>Lepomis symmetricus</i> (Forbes) | | | | O ⁵ | Yes | | BW |
| Smallmouth bass, <i>Micropterus dolomieu</i> (Lacepü de) | | C | O | | | | CB, BW |
| Spotted bass, <i>Micropterus punctulatus</i> (Rafinesque) | P | | | R | | | CB, BW |
| Largemouth bass, <i>Micropterus salmoides</i> (Lacepü de) | | O | C | C | Yes | | BW |
| White crappie, <i>Pomoxis annularis</i> (Rafinesque) | | R | C | C | Yes | | BW |
| Black crappie, <i>Pomoxis nigromaculatus</i> (Lesueur) | | O | C | O/U | Yes | | BW |

Table A-1 (continued)

| Family species | Residence ¹ | HW ² | UMR ² | OR ² | Back water dependent | Riverine dependent | Probable zone ³ |
|--|------------------------|-----------------|------------------|-----------------|----------------------|--------------------|----------------------------|
| Percidae | | | | | | | |
| Western sand darter, <i>Ammocrypta clara</i> (Jordan and Meek) | P | | O | R | | Yes | CB, BW |
| Crystal darter, <i>Crystallaria asprella</i> (Jordan) | P | | R | R | | Yes | CB |
| Mud darter, <i>Etheostoma asprigene</i> (Forbes) | | | O/R | O | | | BW |
| Rainbow darter, <i>Etheostoma caeruleum</i> (Storer) | P | | R | R | | | CB |
| Bluntnose darter, <i>Etheostoma chlorosoma</i> (Hay) | | | R | U | | | BW |
| Iowa darter, <i>Etheostoma exile</i> | | | R | | | | |
| Fantail darter, <i>Etheostoma flabellare</i> (Rafinesque) | P | | R | | | Yes | CB |
| Swamp darter, <i>Etheostoma fusiforme</i> (Girard) | | | | U ⁵ | Yes | | BW |
| Slough darter, <i>Etheostoma gracile</i> (Girard) | | | | U | | | BW |
| Johnny darter, <i>Etheostoma nigrum</i> Rafinesque | | O | O | R ⁵ | | | CB, BW |
| Cypress darter, <i>Etheostoma proeliare</i> (Hay) | P | | | O ⁵ | | | BW |
| Missouri saddled darter, <i>Etheostoma te trazonum</i> (Hubbs and Black) | P | | | R ⁵ | | | |
| Banded darter, <i>Etheostoma zonale</i> (Cope) | P | | R | | | | |
| Yellow perch, <i>Perca flavescens</i> (Mitchill) | | O | C/O | | Yes | | CB, BW |
| Log perch, <i>Percina caprodes</i> (Rafinesque) | | O | C/O | R ⁵ | Yes | | CB, BW |
| Gilt darter, <i>Percina evides</i> (Jordan and Copeland) | P | | H1 | | | | CB |
| Blackside darter, <i>Percina maculata</i> (Girard) | | C | R | | | | |
| Saddleback darter, <i>Percina vigil</i> (Hay) | | | | U | | | CB |
| Slenderhead darter, <i>Percina phoxocephala</i> (Nelson) | | | R | R ⁵ | | | CB |
| River darter, <i>Percina shumardi</i> (Girard) | | | O | O/U | | | CB |
| Sauger, <i>Stizostedion canadense</i> (Smith) | | R | C | O | | | CB |
| Walleye, <i>Stizostedion vitreum</i> (Mitchill) | | O | C | U/R | | | CB, BW |
| Sciaenidae | | | | | | | |
| Freshwater drum, <i>Aplodinotus grunniens</i> (Rafinesque) | | R | A | A | | Yes | CB, BW |
| Mugilidae | | | | | | | |
| Striped mullet, <i>Mugil cephalus</i> (Linnaeus) | M | | | O | | | CB |
| Petromyzontidae | | | | | | | |
| Chestnut lamprey, <i>Ichthyomyzon castaneus</i> (Girard) | | | O/U | O/R | | | MC, CB |
| Silver lamprey, <i>Ichthyomyzon unicuspis</i> (Hubbs and Trautman) | | | O | R | | | MC, CB |
| American brook lamprey, <i>Lampetra appendix</i> (DeKay) | | | R | | | | MC, CB, BW |

Table A-1 (continued)

¹All fish in this table are considered residents unless designated with one of the following letters: D – Diadromous; I – Introduced; M - Marine; P - Peripheral (typically occupies tributary streams and rivers but may temporarily enter the Mississippi River).

²A - Abundant in all river surveys. C - Common in most surveys. O - Occasionally collected; not generally distributed but local concentrations may occur. U - Uncommon, does not usually appear in survey samples. R - Rare. H1 - Taxon has been collected in the Mississippi River but no records of collection since 1978 (Fremling et al. 1989). H2 - Taxon reported as present by Warren et al. (2000) but abundance not known. H3 - Taxon presumed by Warren et al. (2000) to be present but not verified by collection records.

³MC - Main Channel is the portion of the river that contains the thalweg and the navigation channel; water is relatively deep and the current, although varying temporally and spatially, is persistent and relatively strong. CB - Channel Border is the zone from the main channel to the riverbank. Compared to MC, the CB is a zone of slower current, shallower water, and greater habitat heterogeneity. The channel border includes secondary channels and sloughs, islands and their associated sandbars, dikes and dike pools, and natural and revetted banks. BW – Backwater zone includes lentic habitats lateral to the channel border that are connected to the river for at least some time in most years. The backwater zone includes abandoned channels (including floodplain lakes) severed from the river at the upstream or both ends, lakes lateral to the channel border, ephemeral floodplain ponds, borrow pits created when levees were built, and the floodplain itself during overbank stages.

⁴Occasional occurrence in UMR; rare occurrence in OR attributed to stocking.

⁵Not listed as present in the open-river reach of the Mississippi River by Warren et al. (2000).

⁶Warren et al. (2000) list Mississippi stoneroller (*C. a. pullum*) as present in the open-river reach of the Mississippi River.

⁷Warren et al. (2000) list Pealip redhorse (*M. m. pisolabrum*) as present in the open-river reach of the Mississippi River.

Table A-2. List of Fish of the Central Ohio River (River Mile 328 – 654)

Source: <http://www.fallsoftheohio.org/OhioRiverFishList.html>

| | | | |
|------------------------------------|---|--|---|
| Bass – Crappie Family | | Darters | |
| Largemouth Bass | Micropterus salmoides | Banded Darter | Etheostoma zonale |
| Rock Bass | Ambloplites rupestris | Crystal Darter | Ammocrypta asperella |
| Smallmouth Bass | Micropterus dolomieu | Dusky Darter | Percina sciera |
| Spotted Bass | Micropterus punctulatus | Eastern Sand Darter | Ammocrypta pellucida |
| Striped Bass | Morone saxatilis * | Fantail Darter | Etheostoma flabellare † |
| White Bass | Morone chrysops | Greenside Darter | Etheostoma blennioides † |
| Yellow Bass | Morone mississippiensis | Johnny Darter | Etheostoma nigrum |
| Black Crappie | Pomoxis nigromaculatus | Orangethroat Darter | Etheostoma spectabile |
| White Crappie | Pomoxis annularis | Rainbow Darter | Etheostoma caeruleum |
| Bowfin | | River Darter | Percina shumardi |
| Bowfin | Amia calva | Slenderhead Darter | Percina phoxocephala |
| Carp Family | | Stripetail Darter | Etheostoma kennicotti |
| Bigmouth Buffalo | Ictiobus cyprinellus | Variagate Darter | Etheostoma variatum |
| Black Buffalo | Ictiobus niger | Drum | |
| Smallmouth Buffalo | Ictiobus bubalus | Freshwater Drum | Aplodinotus grunniens † |
| Bighead Carp | Hypophthalmichthys nobilis | Eel | |
| Carp | Cyprinus carpio | American Eel | Anguilla rostrata |
| Grass Carp | Ctenopharyngodon idella | Gar | |
| Silver Carp | Hypophthalmichthys molitrix | Alligator Gar | Lepisosteus spatula |
| River Carpsucker | Carpiodes carpio † | Longnose Gar | Lepisosteus osseus |
| Lake Chubsucker | Erimyzon sucetta | Shortnose Gar | Lepisosteus platostomus † |
| Goldfish | Carassius auratus * | Spotted Gar | Lepisosteus oculatus |
| Northern Hogsucker | Hypentelium nigricans | Minnow-like: Chubs, Minnows and Shiners | |
| Quillback | Carpiodes cyprinus | Bigeye Chub | Hybopsis amblops † |
| Black Redhorse | Moxostoma duquesnei † | Cheek Chub | Semotilus atromaculatus |
| Golden Redhorse | Moxostoma erythrurum † | Hornyhead Chub | Nocomis biguttatus |
| Greater Redhorse | Moxostoma valenciennesi | River Chub | Nocomis micropogon |
| River Redhorse | Moxostoma carinatum | Silver Chub | Hybopsis storeriana |
| Shortnose Redhorse | Moxostoma macrolepidotum | Speckled Chub | Hybopsis aestivalis |
| Silver Redhorse | Moxostoma anisurum † | Streamline Chub | Hybopsis dissimilis |
| Blue Sucker | Cycleptus elongatus † | Blacknose Dace | Rhinichthys atraculatus |
| Highfin Sucker | Carpiodes velifer † | Redside Dace | Clinostomus elongatus |
| Spotted Sucker | Mintytrema melanops † | Bluntnose Minnow | Pimephales notatus † |
| White Sucker | Catostomus commersoni | Bullhead Minnow | Pimephales vigilax |
| Catfish Family | | Fathead Minnow | Pimephales promelas |
| Black Bullhead | Icatulurus melas | Silverjaw Minnow | Ericymba buccata |
| Brown Bullhead | Icatulurus nebulosus | Silvery Minnow | Hybognathus nuchalis |
| Yellow Bullhead | Icatulurus natalis | Suckermouth Minnow | Phenacobius mirabilis |
| Blue Catfish | Icatulurus furcatus | Bigeye Shiner | Notropis boops |
| Channel Catfish | Icatulurus punctatus † | Common Shiner | Notropis cornutus |
| Flathead Catfish | Pylodictis olivaris † | Emerald Shiner | Notropis atherinoides |
| White Catfish | Icatulurus catus | Ghost Shiner | Notropis buechanani |
| Brindled Madtom | Noturus miurus | Golden Shiner | Notemigonus crysoleucas |
| Mountain Madtom | Noturus eleuthurus | Mimic Shiner | Notropis volucellus |
| Tadpole Madtom | Noturus gyrinus | Ribbon Shiner | Notropis fumeus |
| Stonecat | Noturus flavus † | River Shiner | Notropis blenniuis |
| Codfish | | Rosefin Shiner | Notropis ardens |
| American Burbot | Lota lota | Rosyface Shiner | Notropis rubellus |
| | | Sand Shiner | Notropis stamineus |
| | | Silver Shiner | Notropis photogenis |
| | | Spotfin Shiner | Notropis spiloterus |
| | | Spottail Shiner | Notropis hudsonius |
| | | Steelcolor Shiner | Notropis whipplei |
| | | Striped Shiner | Notropis chrysocephalus |

Table A-2 (continued)

| | | |
|--|--|---|
| Miscellaneous Minnow-type Fish | | Sauger – Walleye |
| Common Stoneroller | Campostoma anomolum | Sauger Stizostedion canadense |
| Blackstripe Topminnow | Fundulus notatus | Walleye Stizostedion vitreum vitreum |
| Brook Silverside | Labidesthes sicculus | |
| Mosquito Fish | Gambusia affinis | Sculpin |
| Pirateperch | Aphredoderus sayanus | Mottled Sculpin Cottus caroliniae |
| Troutperch | Percopsis omiscomaycus | |
| Lamprey | | Shad Family |
| American Brook Lamprey | Lampetra appendix | Alabama Shad Alosa alabamae |
| Ohio Lamprey | Ichthyomyzon bdellium | Alewife Alosa pseudoharengus* |
| Silver Lamprey | Ichthyomyzon unicuspis | Skipjack Shad Alosa chrysochloris t |
| | | American Shad Alosa sapidissima* |
| | | American Gizzard Shad Dorosoma cepedianum |
| | | Threadfin Shad Dorosoma petense |
| Mooneyes | | Sturgeon |
| Goldeye | Hiodon alosoides t | Lake Sturgeon Acipenser fulvescens |
| Mooneye | Hiodon tergisus t | Shovelnose Sturgeon Scaphirohynchus platorhynchus |
| Paddlefish | | Sunfish |
| Paddlefish | Polyodon spathula | Bluegill Lepomis macrochirus |
| | | Pumpkinseed Lepomis gibbosus |
| Perch | | Green Sunfish Lepomis cyanellus |
| Logperch | Percina caprodes t | Longear Sunfish Lepomis megalotis |
| Yellow Perch | Perca flavescens | Orangespotted Sunfish Lepomis humilis |
| | | Redear Sunfish Lepomis microlophus |
| Pike Group | | Warmouth Lepomis gulosus |
| Muskellunge | Esox masquinongy | Oceanic (Freshwater Tolerant) |
| Grass Pickerel | Esox americanus vermiculatus | Coho Salmon Oncorhynchus kisutch* |
| Northern Pike | Esox lucius* | Atlantic Rainbow Smelt Osmerus mordax |
| | | Sea Trout Salmo trutta* |

Table A-3. Juvenile fishes collected in seasonally inundated backwaters of the Atchafalaya River Basin during 2005-2006
From Halloran (2010)

| Taxa | 2005 | | | | | | | 2006 | | | | | | |
|-----------------------------------|------|-----|-----|-----|-----|-----|-----|------|-----|-----|-----|-----|-----|--|
| | Feb | Mar | Apr | May | Jun | Jul | Aug | Feb | Mar | Apr | May | Jun | Jul | |
| Aphredoderidae | | | | | | | | | | | | | | |
| <i>Aphredoderus sayanus</i> | 1 | | 7 | 1 | | | | | | | | | | |
| Ameiuridae | | | | | | | | | | | | | | |
| <i>Ameiurus natalis</i> | | | | | | | | | | | | 1 | | |
| Atherinidae | | | | | | | | | | | | | | |
| <i>Labidesthes sicculus</i> | | | | | | | | | | | | | 1 | |
| Catostomidae | | | 1 | | | | | | | | | | | |
| Centrarchidae | | | | | | | | | | | | | | |
| <i>Centrarchus macropterus</i> | | | | 5 | | | | | | | | | | |
| <i>Lepomis cyanellus</i> | | | 1 | 3 | | | | | | | 2 | 7 | | |
| <i>Lepomis gulosus</i> | | | | | | 2 | 1 | | | | | 12 | 13 | |
| <i>Lepomis macrochirus</i> | 3 | | 1 | 9 | 12 | 19 | 5 | | | | | | 1 | |
| <i>Lepomis marginatus</i> | | | | | | | | | | | | | 1 | |
| <i>Lepomis miniatus</i> | | | | | 1 | | 3 | | | | | | 1 | |
| <i>Lepomis</i> spp. | | | | 1 | 3 | 1 | 3 | 1 | | | | | | |
| <i>Lepomis symmetricus</i> | | | | | | | | | | | | 9 | 29 | |
| <i>Micropterus punctulatus</i> | | | | | | | | | | | 1 | | | |
| <i>Micropterus salmoides</i> | | | 8 | 137 | 1 | | | | | 15 | | 2 | | |
| <i>Micropterus</i> spp. | | | 7 | 24 | 2 | | | | 63 | 1 | | | | |
| <i>Pomoxis annularis</i> | | | | 1 | | | | | | | | | 2 | |
| <i>Pomoxis nigromaculatus</i> | | | 6 | 3 | | | | | | 2 | | | | |
| <i>Pomoxis</i> spp. | | | 7 | 1 | | | | | 4 | | | | | |
| Clupeidae | | | | | | | | | | | | | | |
| <i>Dorosoma cepedianum</i> | | | | | | 1 | | | | | | 1 | | |
| Cyprinidae | | | | | | | | | | | | | | |
| <i>Lythrus fumeus</i> | | | | | | | 2 | | 5 | | | | | |
| <i>Notropis</i> spp. | | | | | | | 1 | | | | | | | |
| Esocidae | | | | | | | | | | | | | | |
| <i>Esox americanus americanus</i> | 2 | 1 | | | | | | | | | | | | |
| Fundulidae | | | | | | | | | | | | | | |
| <i>Fundulus</i> spp. | | | | | | | | | 1 | | | 7 | 1 | |
| Percidae | | | 253 | 4 | 2 | 4 | | | | | | | | |
| Syngnathidae | | | | | | | | | | | | | | |
| <i>Syngnathus scovelli</i> | | | 5 | 3 | | 1 | | | | | | | | |
| Monthly total | 6 | 1 | 296 | 192 | 21 | 28 | 15 | 1 | 73 | 18 | 3 | 41 | 47 | |

**Table A-4. Ichthyoplankton collected during 2005-2006 in the Atchafalaya River Basin
From Halloran (2010)**

| Taxa | 2005 | | | | | | | | 2006 | | | | | | | |
|------------------------------|------|-----|-----|-----|-----|-----|-----|-----|------|-----|------|-----|------|-----|-----|--|
| | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Feb | Mar | Apr | May | Jun | Jul | Aug | |
| Aphredoderidae | | | | | | | | | | | | | | | | |
| <i>Aphredoderus sayanus</i> | | | | | | | | | | | | | | | | |
| Atherinidae | | | | | | | | | | | | | | | | |
| <i>Labidesthes sicculus</i> | | | | | | | | | | | | | | 1 | | |
| <i>Menidia beryllina</i> | | | | 2 | | | | | | | | | | | | |
| Catostomidae | 1 | | 11 | 5 | 10 | | | | 18 | 21 | 20 | | | | | |
| Centrarchidae | | | | | | | | | | | | | | | | |
| <i>Ambloplites</i> spp. | | | | | | | | | 4 | | | | | | | |
| <i>Lepomis</i> spp. | 1 | | 39 | 177 | 384 | 266 | 190 | 3 | 3 | 2 | 63 | 40 | 900 | 145 | 12 | |
| <i>Micropterus</i> spp. | | 3 | | 1 | | | | | 8 | 9 | 1 | | 1 | | | |
| <i>Pomoxis</i> spp. | 2 | 6 | 38 | 1 | | | 3 | | 48 | 68 | 38 | 3 | | | | |
| Clupeidae | | | | | | | | | | | | | | | | |
| <i>Dorosoma</i> spp. | 1 | | 336 | 650 | 119 | 102 | 5 | 1 | 1 | 325 | 8365 | 680 | 3768 | 268 | 3 | |
| Cyprinidae | | 1 | 4 | | 21 | | | | 6 | 3 | 29 | 46 | | | | |
| Fundulidae | | | | | | | | | | | | | | | | |
| <i>Fundulus</i> spp. | | | | | | | | | | | | | | | | |
| Hidonidae | | | | | | | | | | | | | | | | |
| <i>Hidon</i> spp. | | | | | | | | | | | | | 1 | | | |
| Moronidae | | | | | | | | | | | | | | | | |
| <i>Morone</i> spp. | | | | | | | | | | | | | | | | |
| Percidae | | 2 | 39 | 2 | | | | | | 1 | 1 | | | | 1 | |
| Sciaenidae | | | | | | | | | | | | | | | | |
| <i>Aplodinotus grunniens</i> | | | 11 | 1 | 1 | | | | | | | 3 | 1 | | | |
| Unknown | | | | | | | | | | | 1 | | | | | |

INTERNAL DISTRIBUTION

- | | |
|---------------------|---|
| 1. M. S. Bevelhimer | 6. J. W. Saulsbury |
| 2. G. F. Cada | 7. P. E. Schweizer |
| 3. G. K. Jacobs | 8. G. P. Zimmerman |
| 4. L. Liang | 9. ORNL Office of Technical Information and Classification |
| 5. M. J. Peterson | |

EXTERNAL DISTRIBUTION

10. Jocelyn Brown-Saracino, U.S. Department of Energy, Office of Wind and Hydropower Technology Program, Forrestal Building, EE-2B, 1000 Independence Avenue, S.W., Washington, DC 20585