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ORNL/TM-2011/133

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

May 2011

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UT-BATTELLE
ORNL-27 (4-00)

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ORNL/TM-2011/133

Environmental Sciences Division

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

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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

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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

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.

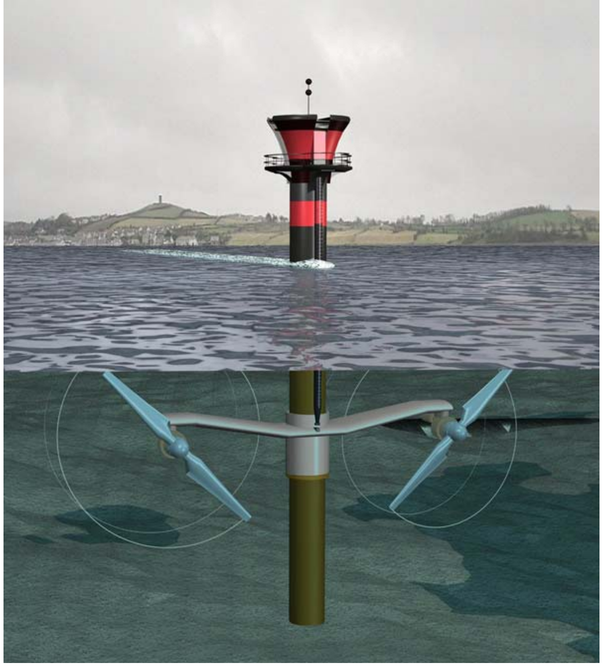


Figure 2. Artist's impression of the Seagen marine current turbine in Strangford Lough, UK. Source: Davison and Mallows (2005).

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.

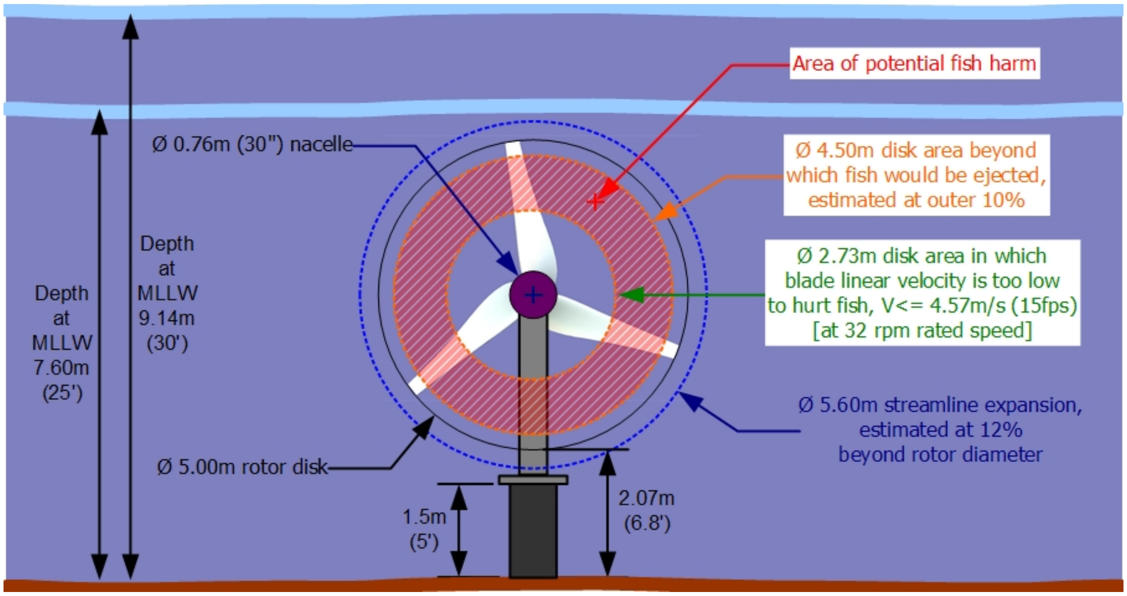


Figure 3. Predicted zone of potentially damaging strike associated with an unducted horizontal axis turbine.
Source: Coutant and Čada (2005)

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/m^2 of power from the swept area of the current, whereas typical ship propellers release over 100 kW/m^2 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

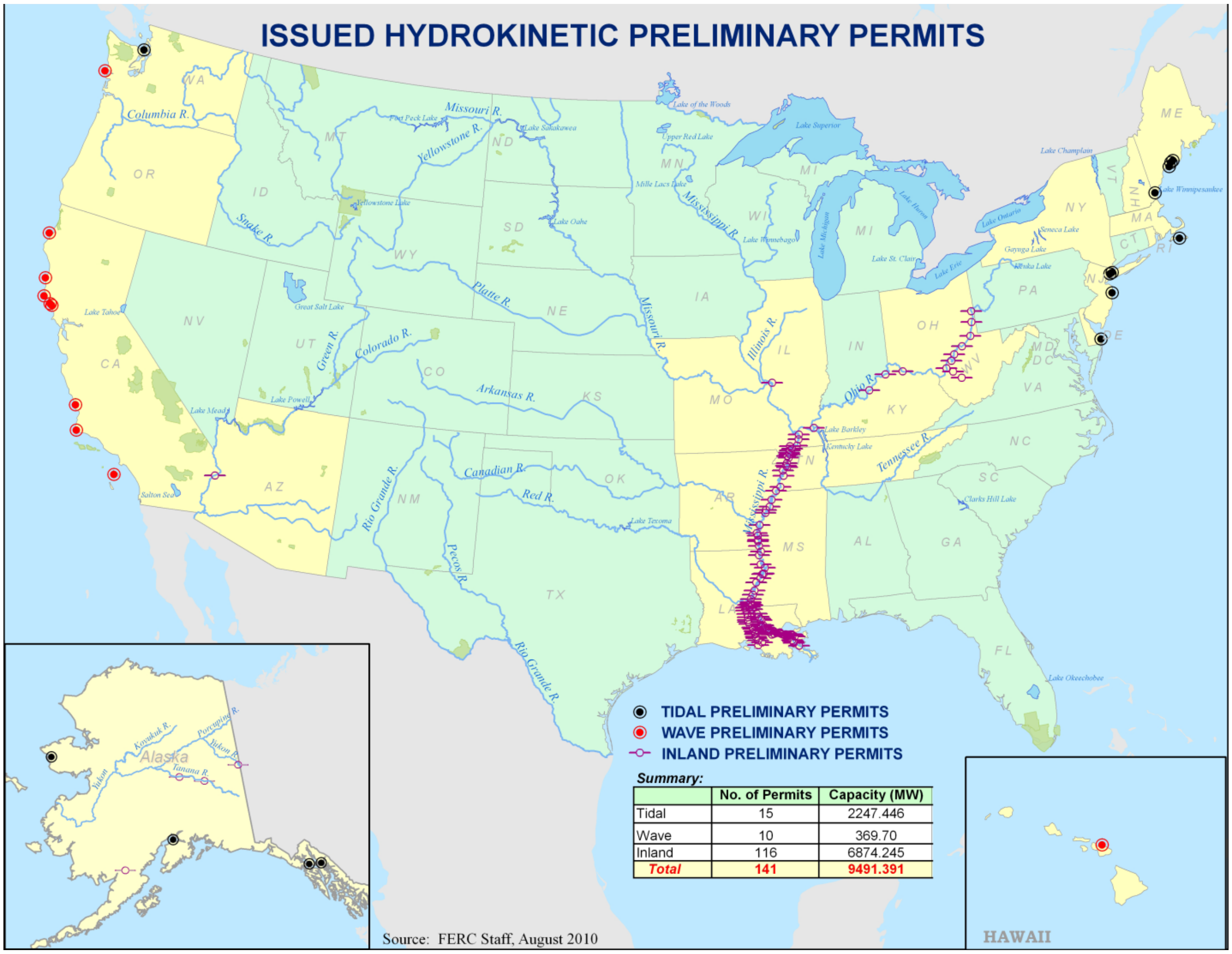
We collected information from the MHK database maintained by the Federal Energy Regulatory Commission (FERC) about geographical distribution of proposed hydrokinetic projects, and their categorization as inland, tidal or wave projects. As of August 2010, 116 preliminary permits had been issued to private 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.



Summary:

	No. of Permits	Capacity (MW)
Tidal	15	2247.446
Wave	10	369.70
Inland	116	6874.245
Total	141	9491.391

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

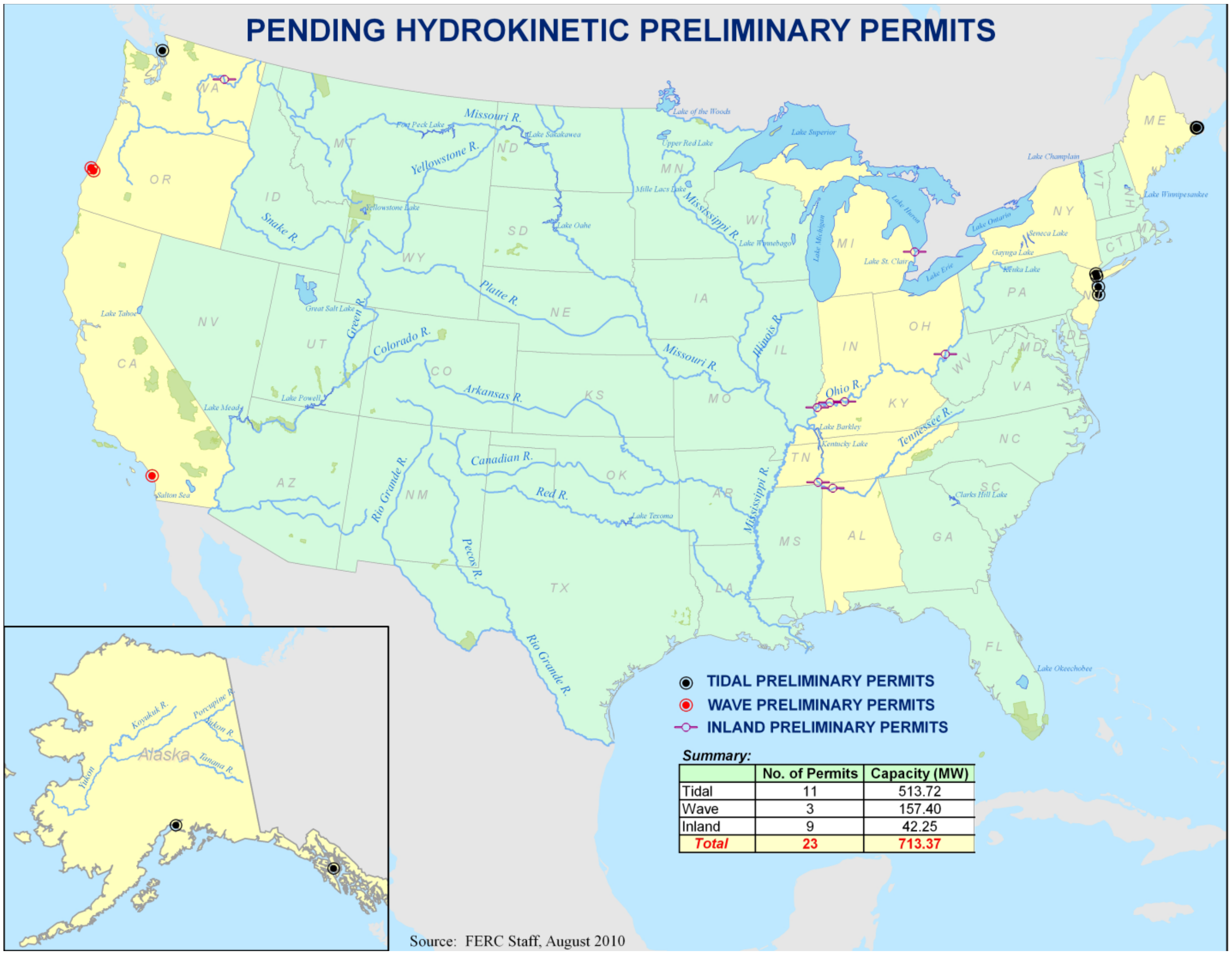
Table 1. Preliminary permits issued or pending for hydrokinetic projects as of July 1, 2010

	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).



Summary:

	No. of Permits	Capacity (MW)
Tidal	11	513.72
Wave	3	157.40
Inland	9	42.25
Total	23	713.37

Source: FERC Staff, August 2010

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 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

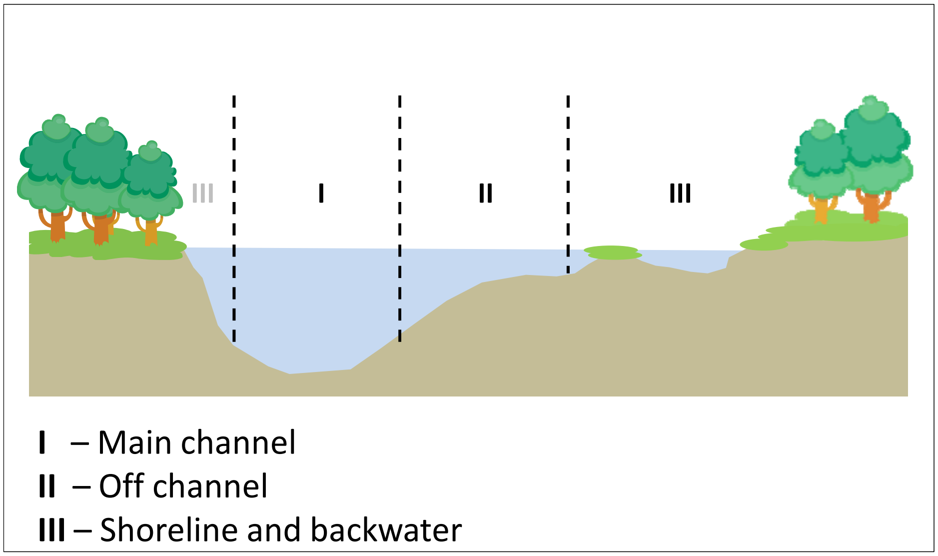


Figure 8. Simplified cross section of a river, with different aquatic habitats that contrast in water depth and flow velocity.

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; ergenrader 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./m^3) 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 marcoinvertebrates 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

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

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 (m^2) 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 m^3 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:

$$P = L / WL, \tag{2}$$

where L is length of the fish (meters), and water length (WL), in meters = V axial / (cosΘ × n × N/60),
with V axial representing discharge (m^3 /sec^{-1}) / rotor-swept area (m^2),
cosΘ 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).

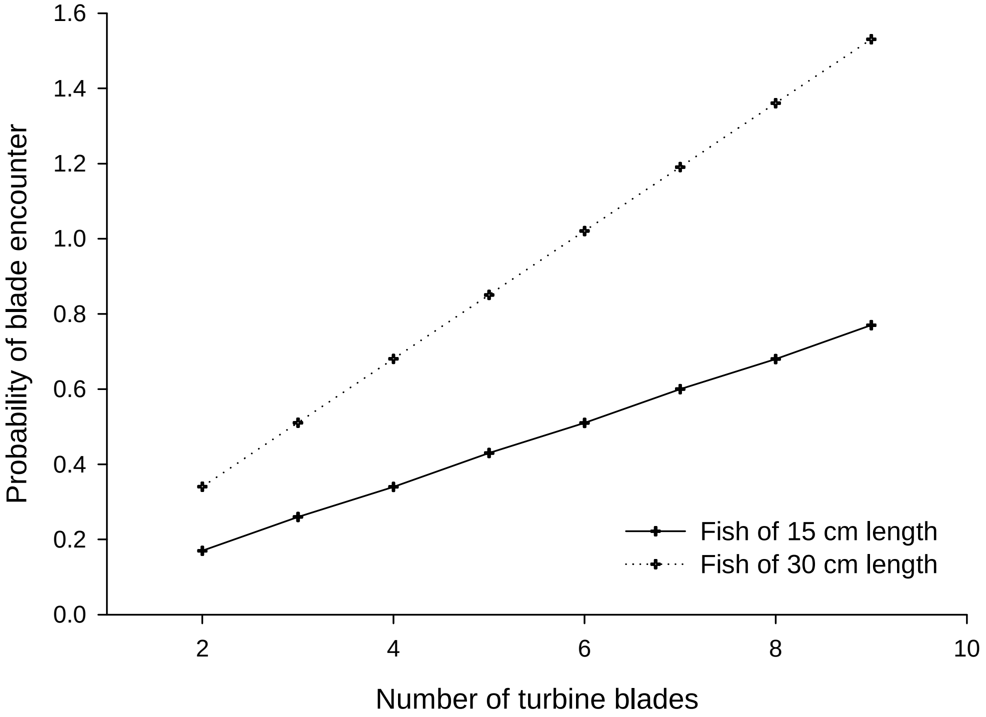


Figure 9. Increase in probability of blade encounter with increasing number of turbine blades. Encounter probabilities are derived from equation 1, and a probability of blade encounter greater than 1.0 suggests the possibility of multiple blade encounters for a single fish in passage through the rotor 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).

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

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.

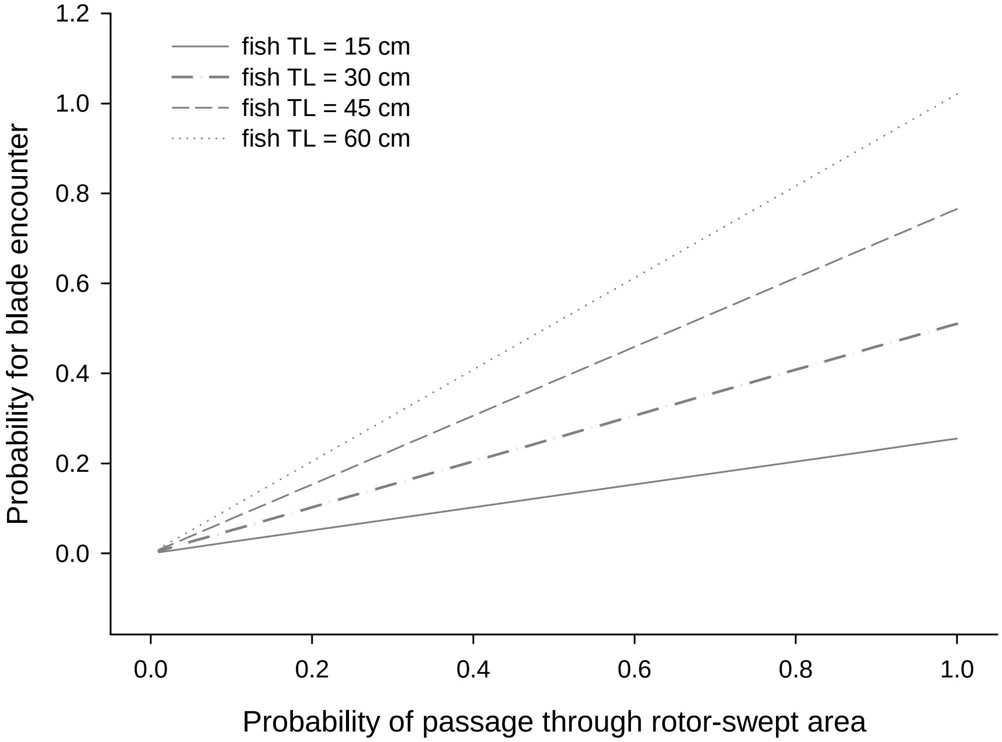


Figure 10. Probability of blade strike as a function of total length for fish passing through the rotor-swept area. For passive passage through the rotor-swept area of a hydrokinetic device the hypothesized risk of blade encounter increases with total length (TL) of a fish. The model assumes no avoidance 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).

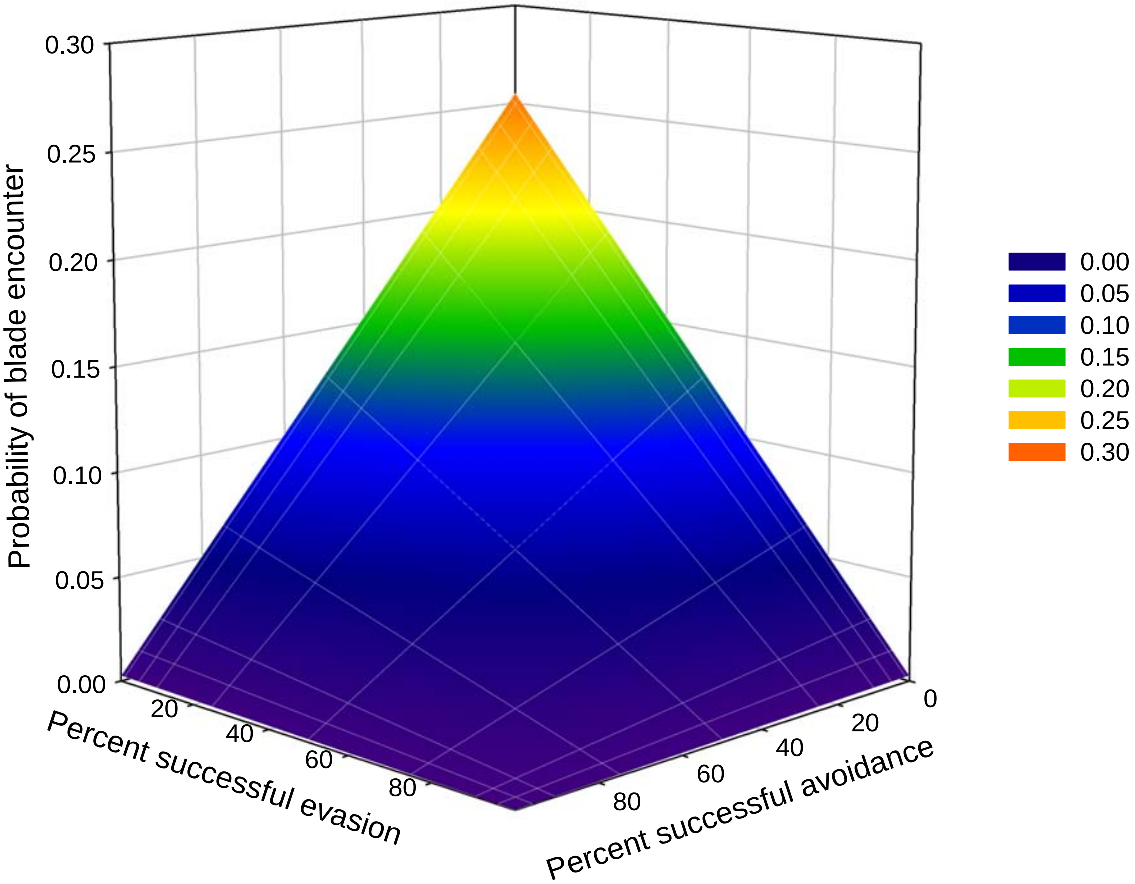


Figure 11. Hypothetical probabilities of blade encounter for a fish of 15 cm length, passively entrained in the water column during single passage through the rotor-swept area of a hydrokinetic turbine. This figures shows the effects of various values for avoidance and evasion on the probability of blade 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.

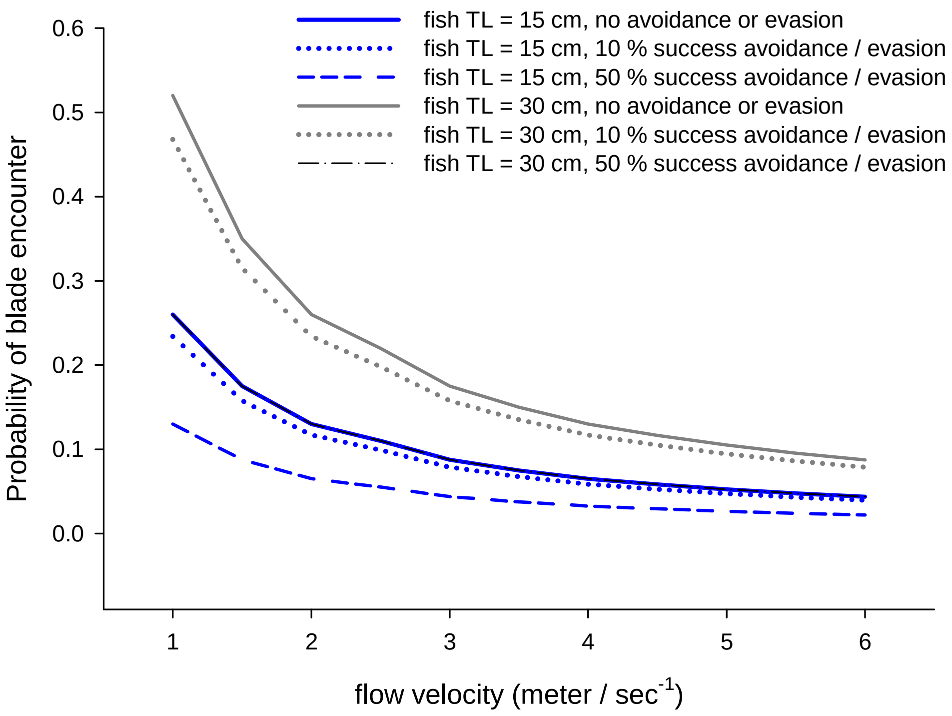


Figure 12. Decline in risk of blade encounter to fish with increase in river flow velocity. Scenarios for fish of 15 cm length (blue lines) and 30 cm length (gray lines) are shown. Solid lines indicate assumed probability of blade strike with 0% success in fish avoiding passage through the rotor-swept 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).

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

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).

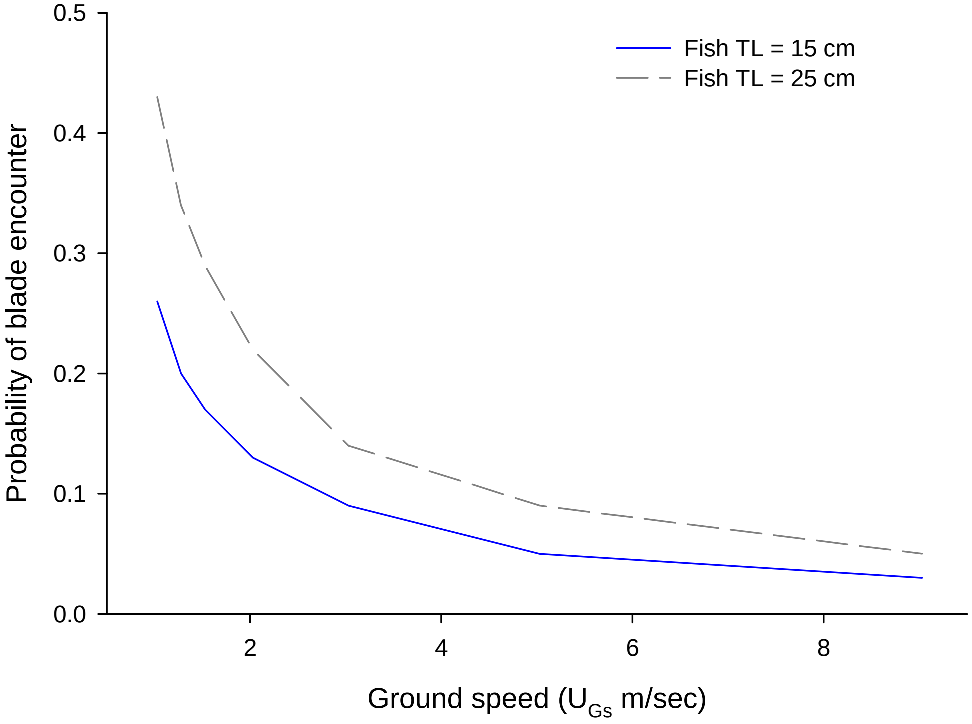


Figure 13. Increased ground speed relative to flow velocity during passage through the rotor-swept area of a HK device reduces the probability of blade encounter for fish. Ground speed of a fish (U_{Gs} in m/sec) is calculated as flow velocity (VF in m/sec) + swim velocity (U in m/sec). The above scenarios, 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

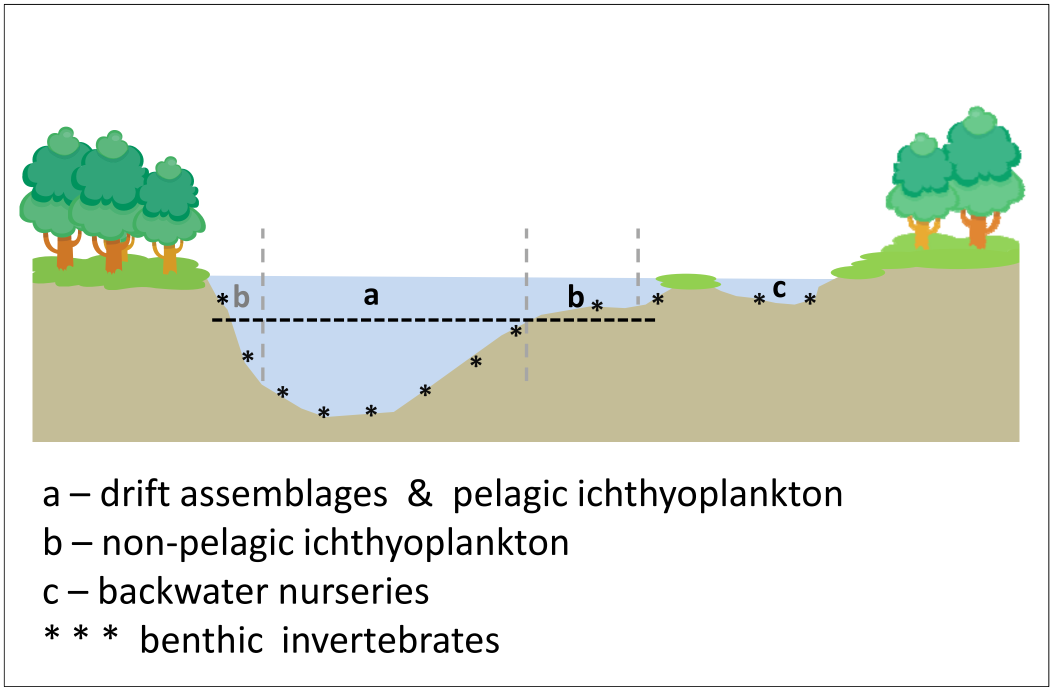


Figure 14. Distribution of plankton, macroinvertebrates and fish larvae across habitats in a large river, with > 60 percent of drift assemblage concentrated in the uppermost 1.8 meters of a hypothetical river with 5.4 meter depth.

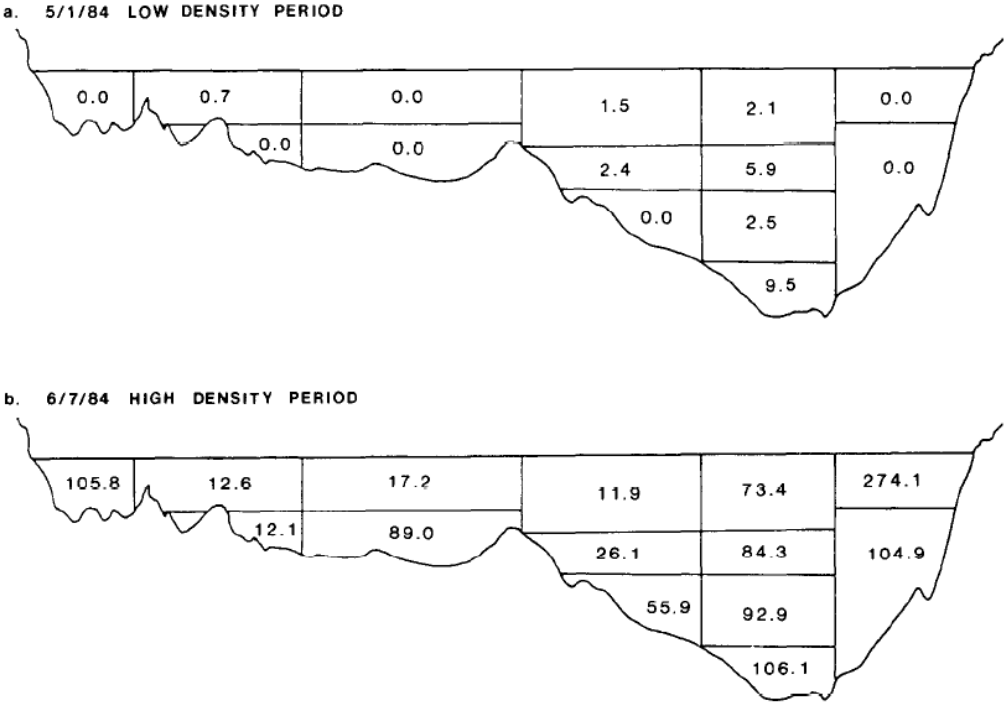
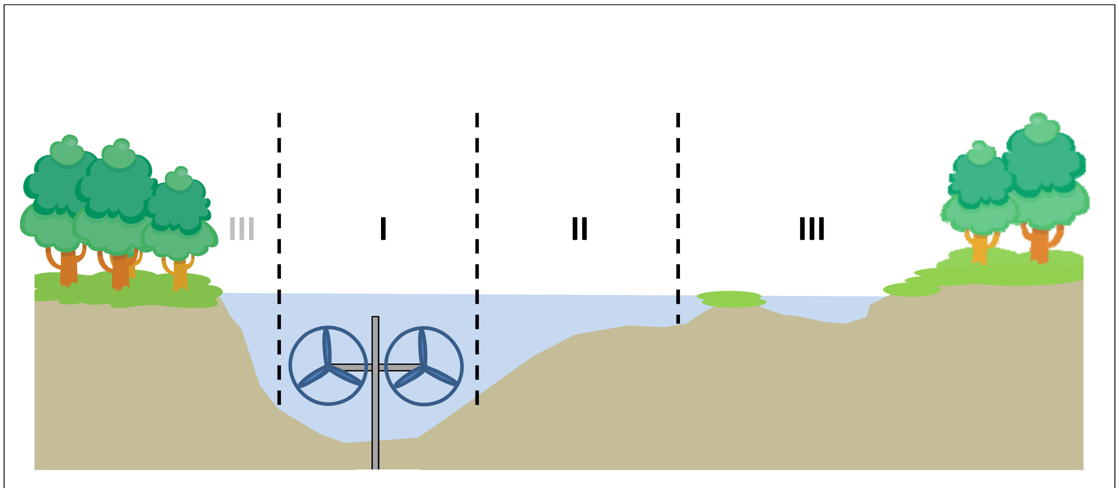


Figure 15. Densities of fish larvae (number/100 m^3) in various portions of a cross section of lower Navigation Pool 5 in the Upper Mississippi River during low density (a) and high density (b) periods. From Holland (1986).



I – Main channel	II – Off-channel	III – Shoreline and backwater
Freshwater drum	Common carp	Centrarchids;
Gizzard shad	Black buffalo	Spotted bass
Striped bass	Small mouth buffalo	Largemouth bass
Sauger/walleye		Cyprinids;
Channel catfish		Emerald shiner
Sturgeon species		Spotfin shiner
Catostomidae		Darter species

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.

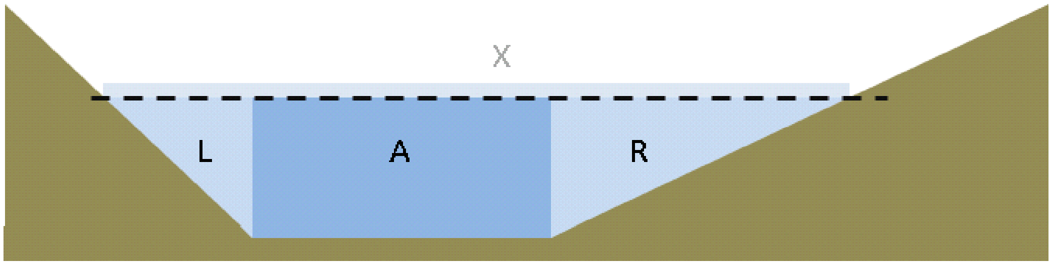


Figure 17. Simplified riverbed geometry for calculation of river cross section area, looking downstream. A, represents the main channel section with area calculated width of main channel * depth at reference river stage (indicated by dotted reference line., L, and R, represent cross section areas from the main channel border to the respective shore lines with areas calculated as ½ 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).

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

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 $a_{i\text{-}ii}$,
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) × (1 probability of moving downstream) × (0.05 area of river cross section occupied by HK rotor-swept area of all rotors in a transect) x (0.5 probability of rotor blade avoidance) x (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 $Ta_{i\text{-}ii}$ 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 salmons, 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.

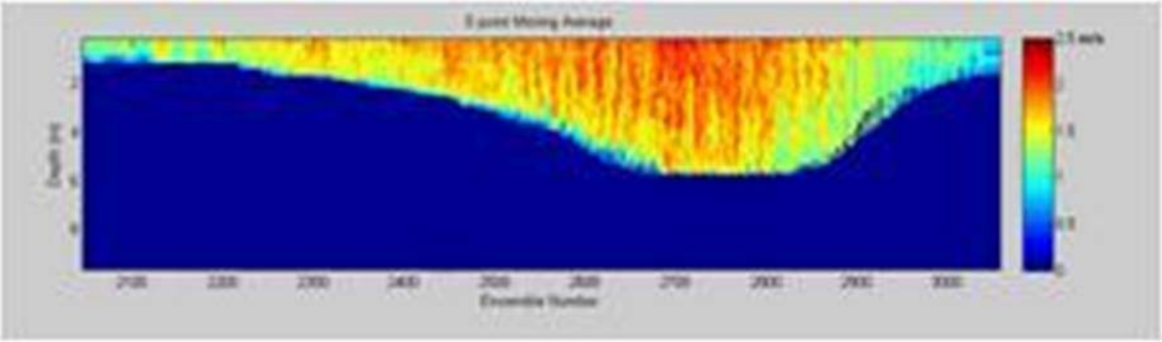


Figure 18. Example of a cross-section velocity profile for the Tanana River near Nenana, Alaska. (Source: Alaska Hydrokinetic Energy Research Center).

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.

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

Table A-1 (continued)

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

Table A-1 (continued)

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

Table A-1 (continued)

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

Table A-1 (continued)

Family species	Residence[1]	HW[2]	UMR[2]	OR[2]	Back water dependent	Riverine dependent	Probable zone[3]
Fundulidae							
Golden topminnow, *Fundulus chrysotus* (Günther)	P			R	Yes		BW
Banded killifish, *Fundulus diaphanus* (Le Sueur)		R	H1				
Starhead topminnow, *Fundulus dispar* (Agassiz)	P		R	R			BW
Blackstripe topminnow, *Fundulus notatus* (Rafinesque)			O	O	Yes		BW
Blackspotted topminnow, *Fundulus olivaceus* (Storer)				O	Yes		BW
Poeciliidae							
Western mosquitofish, *Gambusia affinis* (Baird and Girard)			O	O	Yes		BW
Atherinidae							
Brook silverside, *Labidesthes sicculus* (Cope)		O	C/O	C/O			BW
Inland silverside, *Menidia beryllina* (Cope)				O			CB, BW
Gasterosteidae							
Brook stickleback, *Culaea inconstans* (Kirtland)		R	R				MC, CB
Cottidae							
Mottled sculpin, *Cottus bairdi* (Girard)		R					
Percichthyidae							
White bass, *Morone chrysops* (Rafinesque)		R	C	C			CB, BW
Yellow bass, *Morone mississippiensis* (Jordan and Everman)			R/O	O			BW
Striped bass, *Morone saxatilis* (Walbaum)[7]	D			O			MC, CB
Centrarchidae							
Rock bass, *Ambloplites rupestris* (Rafinesque)		C	C/O		Yes		BW
Shadow bass, *Ambloplites ariommus* (Viosca)	P			U[5]			BW
Flier, *Centrarchus macropterus* (Lacepüde)				O	Yes		BW
Banded pygmy sunfish, *Elassoma zonatum* (Jordan)				R[5]	Yes		BW
Green sunfish, *Lepomis cyanellus* (Rafinesque)		R	C/O	U	Yes		BW
Pumpkinseed, *Lepomis gibbosus* (Linnaeus)		R	C/O		Yes		BW
Warmouth, *Lepomis gulosus* (Cuvier)			O/U	C/O	Yes		BW
Orangespotted sunfish *Lepomis humilis* (Girard)			O	O	Yes		BW
Bluegill, *Lepomis macrochirus* (Rafinesque)		O	A	C	Yes		BW
Longear sunfish, *Lepomis megalotis* (Rafinesque)				U	Yes		BW
Redear sunfish, *Lepomis microlophus* (Günther)				U	Yes		BW
Bantam sunfish, *Lepomis symmetricus* (Forbes)				O[5]	Yes		BW
Smallmouth bass, *Micropterus dolomieu* (Lacepüde)		C	O				CB, BW
Spotted bass, *Micropterus punctulatus* (Rafinesque)	P			R			CB, BW
Largemouth bass, *Micropterus salmoides* (Lacepüde)		O	C	C	Yes		BW
White crappie, *Pomoxis annularis* (Rafinesque)		R	C	C	Yes		BW
Black crappie, *Pomoxis nigromaculatus* (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, *Ammocrypta clara* (Jordan and Meek)	P		O	R		Yes	CB, BW
Crystal darter, *Crystallaria asprella* (Jordan)	P		R	R		Yes	CB
Mud darter, *Etheostoma asprigene* (Forbes)			O/R	O			BW
Rainbow darter, *Etheostoma caeruleum* (Storer)	P		R	R			CB
Bluntnose darter, *Etheostoma chlorosoma* (Hay)			R	U			BW
Iowa darter, *Etheostoma exile*			R				
Fantail darter, *Etheostoma flabellare* (Rafinesque)	P		R			Yes	CB
Swamp darter, *Etheostoma fusiforme* (Girard)				U[5]	Yes		BW
Slough darter, *Etheostoma gracile* (Girard)				U			BW
Johnny darter, *Etheostoma nigrum* Rafinesque		O	O	R[5]			CB, BW
Cypress darter, *Etheostoma proeliare* (Hay)	P			O[5]			BW
Missouri saddled darter, *Etheostoma tetrazonum* (Hubbs and Black)	P			R[5]			
Banded darter, *Etheostoma zonale* (Cope)	P		R				
Yellow perch, *Perca flavescens* (Mitchill)		O	C/O		Yes		CB, BW
Log perch, *Percina caprodes* (Rafinesque)		O	C/O	R[5]	Yes		CB, BW
Gilt darter, *Percina evides* (Jordan and Copeland)	P		H1				CB
Blackside darter, *Percina maculata* (Girard)		C	R				
Saddleback darter, *Percina vigil* (Hay)				U			CB
Slenderhead darter, *Percina phoxocephala* (Nelson)			R	R[5]			CB
River darter, *Percina shumardi* (Girard)			O	O/U			CB
Sauger, *Stizostedion canadense* (Smith)		R	C	O			CB
Walleye, *Stizostedion vitreum* (Mitchill)		O	C	U/R			CB, BW
Sciaenidae							
Freshwater drum, *Aplodinotus grunniens* (Rafinesque)		R	A	A		Yes	CB, BW
Mugilidae							
Striped mullet, *Mugil cephalus* (Linnaeus)	M			O			CB
Petromyzontidae							
Chestnut lamprey, *Ichthyomyzon castaneus* (Girard)			O/U	O/R			MC, CB
Silver lamprey, *Ichthyomyzon unicuspis* (Hubbs and Trautman)			O	R			MC, CB
American brook lamprey, *Lampetra appendix* (DeKay)			R				MC, CB, BW

Table A-1 (continued)

[1] All 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).

[2] A - 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.

[3] MC - 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.

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

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

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

[7] Warren 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

Largemouth Bass	*Micropterus salmoides*
Rock Bass	*Ambloplites rupestris*
Smallmouth Bass	*Micropterus dolomieui*
Spotted Bass	*Micropterus punctulatus*
Striped Bass	*Morone saxatilis**
White Bass	*Morone chrysops*
Yellow Bass	*Morone mississippiensis*
Black Crappie	*Pomoxis nigromaculatus*
White Crappie	*Pomoxis annularis*

Bowfin

Bowfin	*Amia calva*

Carp Family

Bigmouth Buffalo	*Ictiobus cyprinellus*
Black Buffalo	*Ictiobus niger*
Smallmouth Buffalo	*Ictiobus bubalus*
Bighead Carp	*Hypophthalmichthys nobilis*
Carp	*Cyprinus carpo*
Grass Carp	*Ctenopharyngodon idella*
Silver Carp	*Hypophthalmichthys molitrix*
River Carpsucker	*Carpiodes carpio* t
Lake Chubsucker	*Erimyzon sucetta*
Goldfish	*Carassius auratus**
Northern Hogsucker	*Hypentelium nigricans*
Quillback	*Carpiodes cyprinus*
Black Redhorse	*Moxostoma duquesnei* t
Golden Redhorse	*Moxostoma erythrurum* t
Greater Redhorse	*Moxostoma valenciennesi*
River Redhorse	*Moxostoma carinatum*
Shortnose Redhorse	*Moxostoma macrolepidotum*
Silver Redhorse	*Moxostoma anisurum* t
Blue Sucker	*Cycleptus elongatus* t
Highfin Sucker	*Carpiodes velifer* t
Spotted Sucker	*Minytrema melanops* t
White Sucker	*Catostomus commersoni*

Catfish Family

Black Bullhead	*Icatulurus melas*
Brown Bullhead	*Icatulurus nebulosus*
Yellow Bullhead	*Icatulurus natalis*
Blue Catfish	*Icatulurus furcatus*
Channel Catfish	*Icatulurus punctatus* t
Flathead Catfish	*Pylodictis olivaris* t
White Catfish	*Icatulurus catus*
Brindled Madtom	*Noturus miurus*
Mountain Madtom	*Noturus eleuthurus*
Tadpole Madtom	*Noturus gyrinus*
Stonecat	*Noturus flavus* t

Codfish

American Burbot	*Lota lota*

Darters

Banded Darter	*Etheostoma zonale*
Crystal Darter	*Ammocrypta asperella*
Dusky Darter	*Percina sciera*
Eastern Sand Darter	*Ammocrypta pellucida*
Fantail Darter	*Etheostoma flabellare* t
Greenside Darter	*Etheostoma blennioides* t
Johnny Darter	*Etheostoma nigrum*
Orangethroat Darter	*Etheostoma spectabile*
Rainbow Darter	*Etheostoma caeruleum*
River Darter	*Percina shumardi*
Slenderhead Darter	*Percina phoxocephala*
Stripetail Darter	*Etheostoma kennicotti*
Variegate Darter	*Etheostoma variatum*

Drum

Freshwater Drum	*Aplodinotus grunniens* t

Eel

American Eel	*Anguilla rostrata*

Gar

Alligator Gar	*Lepisosteus spatula*
Longnose Gar	*Lepisosteus osseus*
Shortnose Gar	*Lepisosteus platostomus* t
Spotted Gar	*Lepisosteus oculatus*

Minnow-like: Chubs, Minnows and Shiners

Bigeye Chub	*Hybopsis amblops* t
Cheek Chub	*Semotilus atromaculatus*
Hornyhead Chub	*Nocomis biguttatus*
River Chub	*Nocomis micropogon*
Silver Chub	*Hybopsis storeriana*
Speckled Chub	*Hybopsis aestivalis*
Streamline Chub	*Hybopsis dissimilis*
Blacknose Dace	*Rhinichthys atraculatus*
Redside Dace	*Clinostomus elongatus*
Bluntnose Minnow	*Pimephales notatus* t
Bullhead Minnow	*Pimephales vigilax*
Fathead Minnow	*Pimephales promelas*
Silverjaw Minnow	*Ericymba buccata*
Silvery Minnow	*Hybognathus nuchalis*
Suckermouth Minnow	*Phenacobius mirabilis*
Bigeye Shiner	*Notropis boops*
Common Shiner	*Notropis cornutus*
Emerald Shiner	*Notropis atherinoides*
Ghost Shiner	*Notropis buchanani*
Golden Shiner	*Notemigonus crysoleucas*
Mimic Shiner	*Notropis volucellus*
Ribbon Shiner	*Notropis fumeus*
River Shiner	*Notropis blennius*
Rosefin Shiner	*Notropis ardens*
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	
Common Stoneroller	_Campostoma anomolum_
Blackstripe Topminnow	_Fundulus notatus_
Brook Silverside	_Labidethes sicculus_
Mosquito Fish	_Gambusia affinis_
Pirateperch	_Aphredoderus sayanus_
Troutperch	_Percopsis omiscomaycus_
Lamprey	
American Brook Lamprey	_Lampetra appendix_
Ohio Lamprey	_Ichthyomyzon bdellium_
Silver Lamprey	_Ichthyomyzon unicuspis_
Mooneyes	
Goldeye	_Hiodon alosoides_ t
Mooneye	_Hiodon tergisus_ t
Paddlefish	
Paddlefish	_Polyodon spathula_
Perch	
Logperch	_Percina caprodes_ t
Yellow Perch	_Perca flavescens_
Pike Group	
Muskellunge	_Esox masquinongy_
Grass Pickerel	_Esox americanus vermiculatus_
Northern Pike	_Esox lucius_*
Sauger – Walleye	
Sauger	_Stizostedion canadense_
Walleye	_Stizostedion vitreum vitreum_
Sculpin	
Mottled Sculpin	_Cottus carolinae_
Shad Family	
Alabama Shad	_Alosa alabamae_
Alewife	_Alosa pseudoharengus_*
Skipjack Shad	_Alosa chrysochloris_ t
American Shad	_Alosa sapidissima_*
American Gizzard Shad	_Dorosoma cepedianum_
Threadfin Shad	_Dorosoma petense_
Sturgeon	
Lake Sturgeon	_Acipenser fulvescens_
Shovelnose Sturgeon	_Scaphirohynchus platorhychus_
Sunfish	
Bluegill	_Lepomis macrochirus_
Pumpkinseed	_Lepomis gibbosus_
Green Sunfish	_Lepomis cyanellus_
Longear Sunfish	_Lepomis megalotis_
Orangespotted Sunfish	_Lepomis humilis_
Redear Sunfish	_Lepomis microlophus_
Warmouth	_Lepomis gulosus_
Oceanic (Freshwater Tolerant)	
Coho Salmon	_Oncorhynchus kisutch_*
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)

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

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

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

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