State of Understanding: Risk of Blade Strike from Current Energy Converters

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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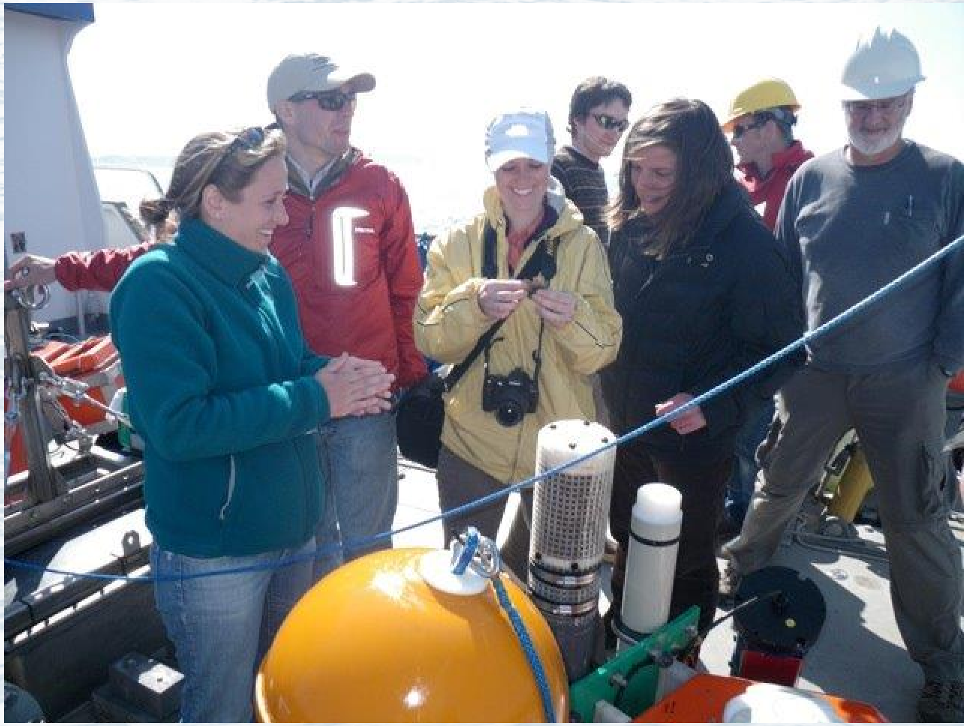
Jocelyn Brown-Saracino

Biologist

US Department of Energy

Wind and Water Power Technologies Office

Jocelyn Brown-Saracino



- Biologist with research expertise in marine mammalogy and the ecology of marine reserves
- Currently leads the DOE Wind and Water Power environmental research portfolio, including research on environmental effects of land-based wind, offshore wind, MHK, and hydropower technologies
- Worked for over last five years establishing MHK environmental research priorities, designing research portfolio, and managing environmental research projects, including numerous modeling, field, and laboratory studies on risk of strike from tidal turbines.

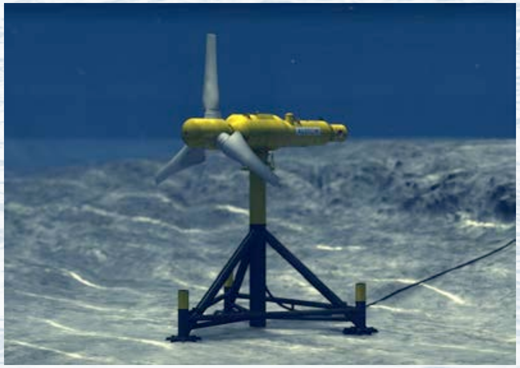
Potential Direct and Indirect Effects of MHK Devices

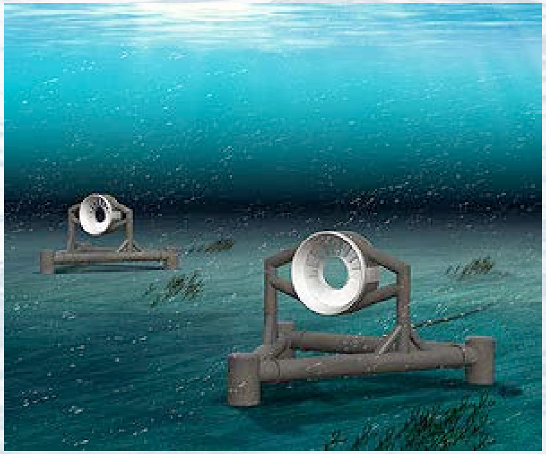
- Strike (tidal)
- Entanglement
- Changes to movement/use patterns
- Reefing
- Benthic habitat changes

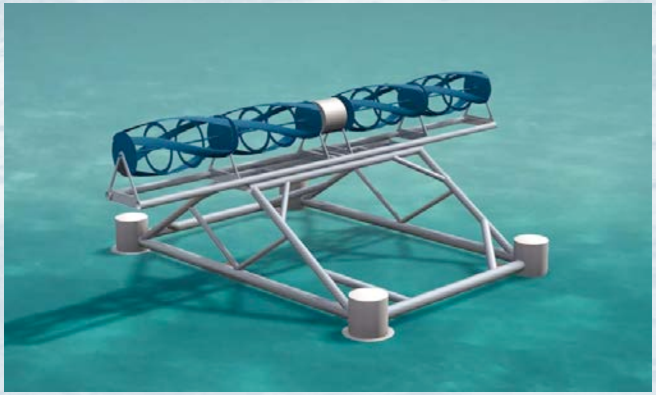
The Concern

- While varied in design, most current energy converters, including tidal turbines, have moving blades used to capture kinetic energy from moving water.

- This design structure, informed in part by historical issues regarding fish injury and mortality from hydropower turbines, informed concerns regarding strike injury and mortality from tidal turbines







Framing Strike Risk

Individual Risk = Probability x Consequence

Population risk dependent on vulnerability of population

What is the probability of being struck? (Individual)

Probability of Encounter – Will the organism encounter a turbine?

- Where is the device in the water column relative to a species' swimming patterns, presence, and abundance?
- Do organisms respond to the turbine in such a way as to increase or decrease their risk of strike?

Avoidance—What is the chance an organism will avoid the turbine (macro-scale) or the rotor swept area (RSA) (micro-scale) entirely?

Evasion—What is the chance, that failing to avoid the RSA, the organism will be able to time their passage through the turbine in such a way as to avoid being struck?

If a strike event occurs, what are the consequences? (Individual)

What is the force associated with the event?

What are the biophysical consequences of strike?

Depends on organism in question and location of strike and will likely vary with turbine design type

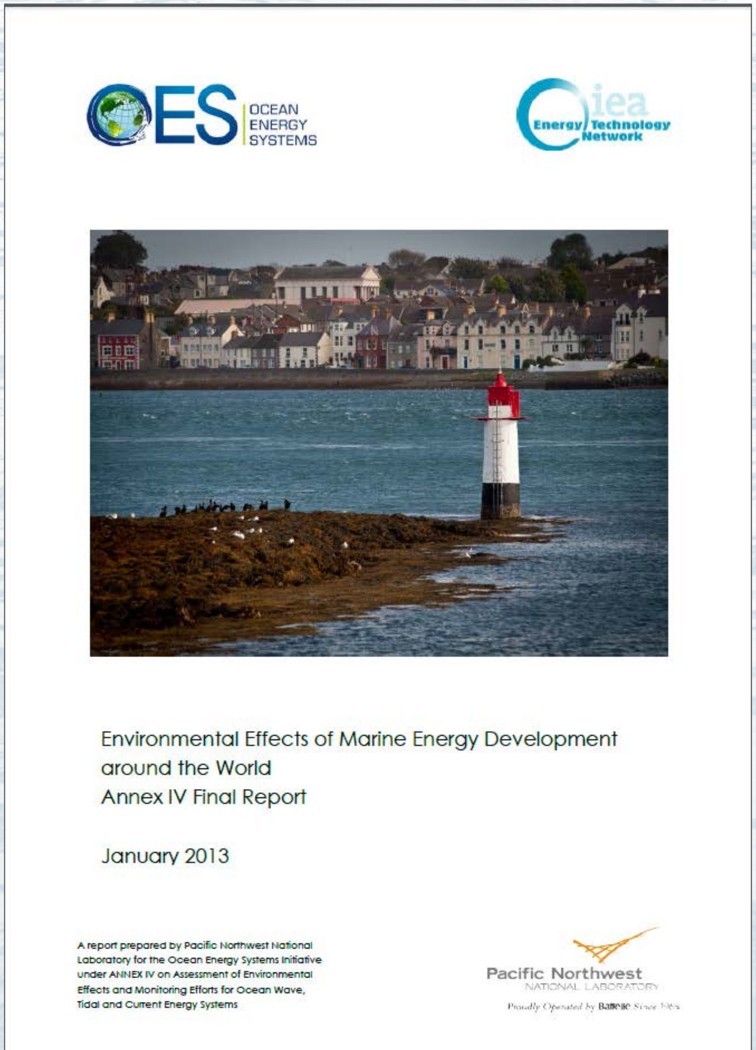
Is there a resultant population level effect? (Moving from individuals to populations.)

Many studies only look at a component of risk—important to note and contextualize.

Measured and Observed Impacts for Deployed MHK Systems

Known Known

Note much of this information take from IEA OES Annex IV Final Report:
http://www1.eere.energy.gov/water/pdfs/annex_iv_report.pdf


OES OCEAN ENERGY SYSTEMS

iea Energy Technology Network

Environmental Effects of Marine Energy Development around the World
Annex IV Final Report

January 2013

A report prepared by Pacific Northwest National Laboratory for the Ocean Energy Systems Initiative under ANNEX IV on Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal and Current Energy Systems

Pacific Northwest NATIONAL LABORATORY

Tethys Database:
http://tethys.pnnl.gov

Crossover from Other Industries

Known Known

Hydropower Comparisons

•Report by EPRI comparing fish mortality mechanisms between the two technology types:

"Fish passing through the blade sweep of a hydrokinetic turbine **experience a much less harsh physical environment than do fish entrained through conventional hydro turbines**. The design and operation of conventional turbines results in high flow velocities, abrupt changes in flow direction, relatively high runner rotational and blade speeds, rapid and significant changes in pressure, and the need for various structures throughout the turbine passageway that can be impacted by fish (e.g., walls, stay vanes, wicket gates, flow straighteners). Most, if not all, of these conditions do not occur or are not significant factors for hydrokinetic turbines. Furthermore, compared to conventional hydro turbines, **hydrokinetic turbines typically produce relatively minor changes in shear, turbulence, and pressure levels from ambient conditions in the surrounding environment.**"

http://tethys.pnnl.gov/sites/default/files/publications/Jacobson_et_al_2012.pdf

•Further avoidance ability is a critical difference between the two systems

Ship Propeller Comparisons

•F = m * a

•Propellers have external energy source, tidal turbines moving with flow of current

•If using propeller to inform risk, make sure that strike forces are comparable

Predictive Modeling Example

Environmental Effects of Hydrokinetic turbines on Fish: Desktop and Laboratory Flume Studies (EPRI, Conte, Alden)

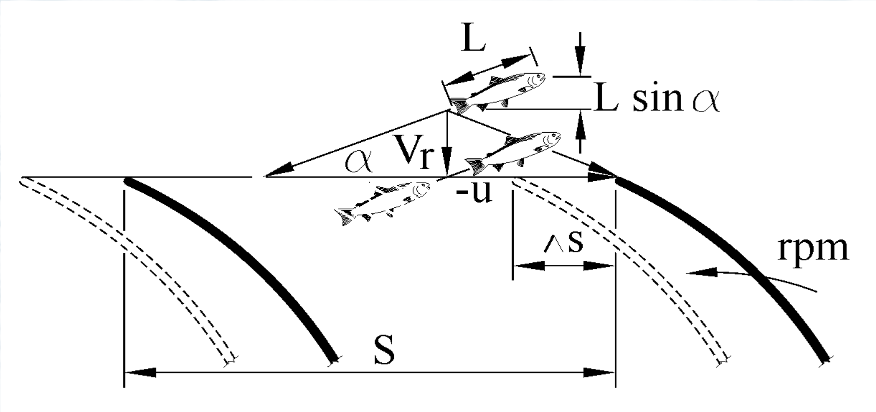
- http://mhk.pnl.gov/sites/default/files/publications/Jacobson_et_al_2012.pdf

Only examined fish passing through rotor swept area

$P_s = n\,[L\sin\alpha]N/60V_r$ (dimensionless)

where:

P_s	=	probability of strike
n	=	runner rpm
n	=	number of leading edges (blades)
L	=	fish length
α	=	angle of absolute inflow
V_r	=	radial component of inflow velocity



Measured and Observed Impacts for Deployed MHK Systems: Fish Strike Models

Known Known

Past and Current Fish Strike Models:

- Numerous approaches to modeling fish strike, ranging from models adopted from hydropower to CFD models
- Most of these models do not incorporate avoidance or evasion rates
  - Tend to model fate of fish that DO pass through turbines, rather than the likelihood that any fish passing through an area will encounter a turbine, fail to avoid it, and fail to evade strike

Models informed by field data under development:

- ELAM model using data informed by mobile hydro-acoustic surveys at the ORPC Cobscook project
- Model being developed by ORNL using data from Verdant East River project

Measured and Observed Impacts for Deployed MHK Systems: Fish Laboratory Data – Survival Rates

Known Known

Flume Studies

- Environmental Effects of Hydrokinetic turbines on Fish: Desktop and Laboratory Flume Studies (EPRI, Conte, Alden)
  http://tethys.pnnl.gov/publications/environmental-effects-hydrokinetic-turbines-fish-desktop-and-laboratory-flume-studies
- Evaluation of Behavior and Survival of Fish Exposed to an Axial Flow Turbine (EPRI, ONRL, Alden)
  http://tethys.pnnl.gov/publications/evaluation-behavior-and-survival-fish-exposed-axial-flow-hydrokinetic-turbine

Species	FFP Ducted axial flow	Lucid Spherical	Welka Axial Flow	Encurrent Vertical Axis
Rainbow Trout	>97%	>98%	>99%	- -
Hybrid Striped Bass	>91%*	- -	- -	- -
White Sturgeon	100%	- -	- -	- -
Largemouth Bass	- -	- -	>99%	- -
Juvenile Atlantic Salmon	- -	- -	- -	Same as control
American Shad	- -	- -	- -	Same as control

*High delayed mortality during one of 3 trials conducted with bass at low. Thought to likely be an experimental artifact. Turbine survival of bass at this velocity is likely higher than was calculated (most likely about 100% based on the results of tests at the higher velocity).

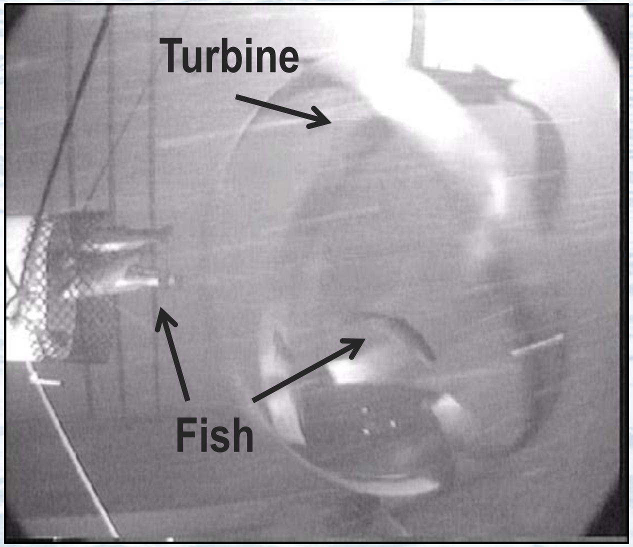
Measured and Observed Impacts for Deployed MHK Systems: Fish Laboratory Data – Avoidance Rates

Known Known

Flume Studies

- Evaluation of Behavior and Survival of Fish Exposed to an Axial Flow Turbine (EPRI, ONRL, Alden)
  - Avoidance in both light and dark conditions

http://tethys.pnnl.gov/publications/evaluation-behavior-and-survival-fish-exposed-axial-flow-hydrokinetic-turbine



Species	% Avoidance	
	Day	Night
Rainbow Trout (small)	>86%	>98%
Rainbow Trout (large)	>95%	>98%
Hybrid Striped Bass	>32%	>65%
White Sturgeon	>87%	>87%

- This second study combined avoidance and survival rates to predict survival
  - Survival rates close to 100% for fish species tested encountering the Free Flow Power turbine
  - Encounter rates not included here, which would make survival rates higher still

Measured and Observed Impacts for Deployed MHK Systems: Fish Field Data – Hastings Project, MN

Known Known

Device Type: Hydro Green Energy Turbine

Location: Tailrace of existing Hydroelectric dam on Mississippi River

Date: 2009

Organism(s) of Interest: yellow perch (*Perca flavescens*), bluegill, catfish, smallmouth buffalo (*Ictiobus bubalus*), and bigmouth buffalo (*Ictiobus niger*)

Methods:

•Fish outfitted with radio-frequency tags and balloon tags that inflated after passage through the turbine

•Fish introduced directly upstream of turbine and retrieved downstream after passage through turbine

• Mortality and injury assessed 1h and 48h after retrieval

Key Findings:

•Survival was ≥99% after 48 hours

•Only one yellow perch sustained injury (total n = 396)

- Balloon tag possibly dragged into a chain driven mechanism of the turbine

Report: http://tethys.pnnl.gov/publications/estimation-survival-and-injury-fish-passed-through-hydro-green-energy-hydrokinetic

Photo source: http://hgenergy.com/index.php/projects/hastings-project/

Figure 3-1. Bluegill with HI-Z Turb N' Tags (HI-Z tags) and radio tag attached before (top photo) and after passage (bottom photo) through the HGE hydrokinetic turbine at the Mississippi Lock and Dam No. 2 Hydroelectric Project.

Photo source: http://tethys.pnnl.gov/publications/estimation-survival-and-injury-fish-passed-through-hydro-green-energy-hydrokinetic

Measured and Observed Impacts for Deployed MHK Systems: Fish Field Data – Gorlov Helical Turbine, Mozambique

Known Known

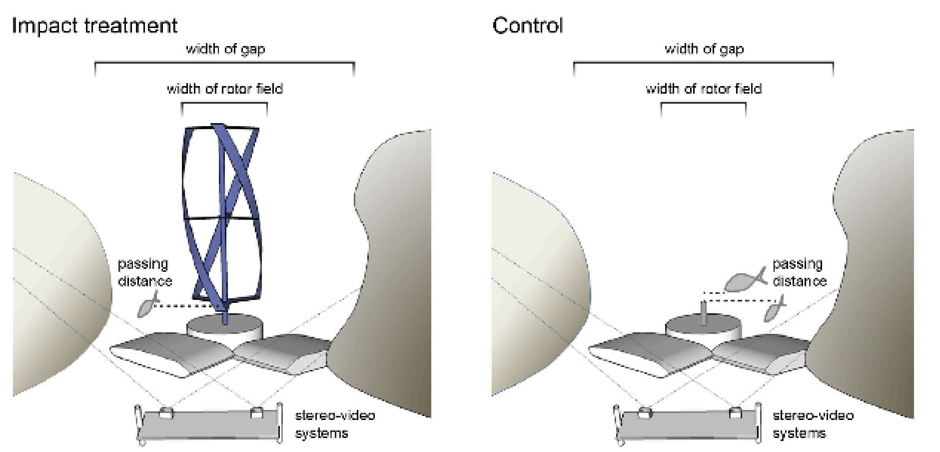


Figure 1. Experimental set-up for impact and control sampling. Fish movements were recorded by remote stereo-video systems and categorized as 'rotor passages' if swimming through the rotor field (0.7 m wide) and as 'gap passages' if swimming through the gap (2 m wide). The gap included the whole cross-area between the two rock formations, that is, both the rotor field and the space between rotor and rocks. Measurements of fish length and the closest distance (dotted horizontal lines) between passing fish and the rotor centre were computed for fish passing within the camera stereo-field (illustrated as overlapping camera fields of view).

doi: 10.1371/journal.pone.0084141.g001

From: Hammar et al. 2013

http://tethys.pnnl.gov/sites/default/files/publications/Hammar_et_al._2013.pdf

- Fish naturally occurring subtropical tidal channel in Mozambique
- Turbine rotation up to 70 rpm
- Stereo-optical camera set up
- Fish movements were recorded with and without the rotor in place.
- No fish collided with the rotor, only a few passed through rotor blades.
- Fish movements through are reduced when rotor present, increased with current speed.
- Effects differed by fish species.

Measured and Observed Impacts for Deployed MHK Systems: Fish Field Data – EMEC, Scotland

Known Known

Device Type: Series of OpenHydro 6m ducted tidal turbines

Location: European Marine Energy Centre (EMEC)

Date: since 2006

Organism(s) of Interest: Fish, Pollack (*Pollachius pollachius)*

Methods:

•Video observation using natural light

•Hundreds of hours of video footage have been collected at the face of the OpenHydro turbines

Key Findings:

•Pollack was only species detected in vicinity - observed aggregating in shoals near the device

•Pollack abundance significantly inversely associated with velocity

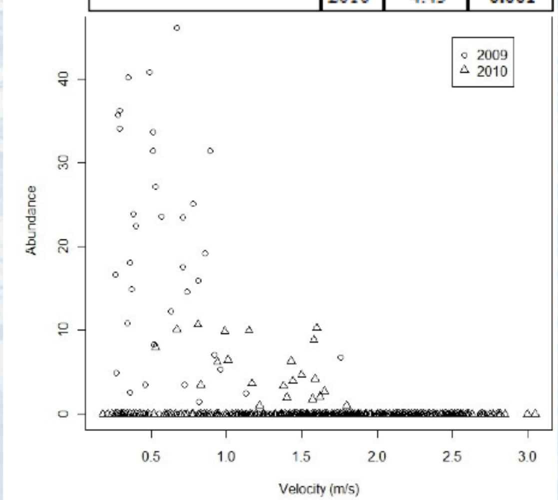
– No fish present at flow rates above 1.2 m/s in 2009 and 1.7 m/s in 2010.

•No collision or entrainment observed

•Fish only present at low tidal states

Abstract: http://tethys.pnnl.gov/publications/situ-ecological-interactions-deployed-tidal-energy-device-observational-pilot-study

Explanatory Variable	Year	F	p-value
Tidal Velocity	2009	38.31	< 0.001
	2010	4.45	0.001



Source: http://tethys.pnnl.gov/sites/default/files/2011-08-29-4-Sue-Barr.pdf

Measured and Observed Impacts for Deployed MHK Systems: Fish Field Data – Cobscook Bay, ME

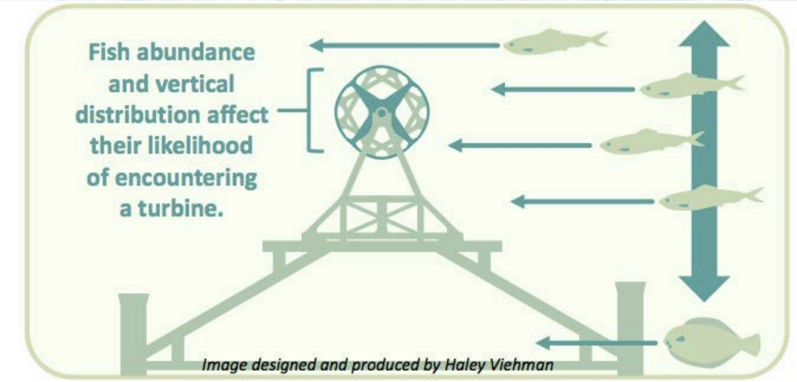
Known Known

Device type: ORPC turbine
Location: Cobscook Bay, ME
Organism(s) of Interest: Fish
Methods:

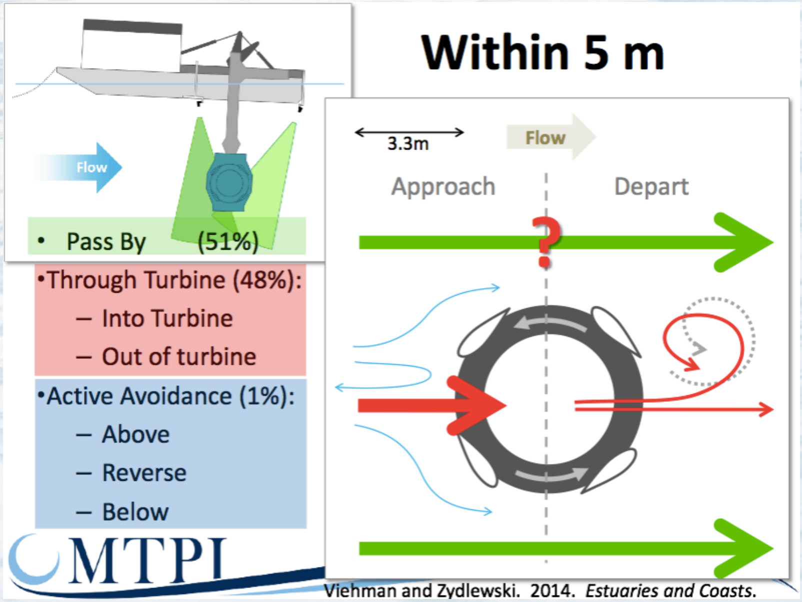
- Single-beam hydroacoustic technology to collect pre-deployment data on the presence and vertical distribution of fishes.
- DIDSON cameras to look at fish behavior around turbine

Key Findings:

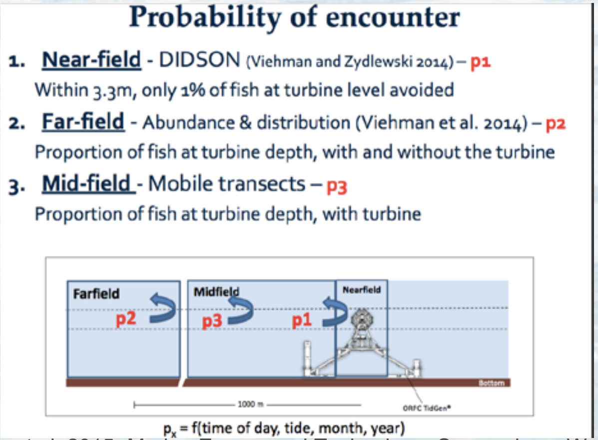
- Based on three years of data, fish density usually highest near the sea floor (below the depth of the turbine)
  - Varies with seasons
- Small fraction of fish seen actively avoiding, but 35% fewer fish went through turbines when spinning
- Fewer schools passed through turbines than ind. fish
- Possible that larger fish avoid turbine further away, but yet to be proven



Viehman 2015. International Network for Offshore Renewable Energy Annual Symposium. Halifax, NS, Canada.



Viehman and Zydlewski 2015. Estuaries and Coasts



Shen et al. 2015. Marine Energy and Technology Symposium. Washington, D.C.

Images source: http://tethys.pnnl.gov/sites/default/files/Annex-IV-Presentation-Bay-of-Fundy_Gayle.pdf

Measured and Observed Impacts for Deployed MHK Systems: Fish Field Data – East River, NY

Known Known

Device Type: Six tidal turbines from Verdant Power

Location: Roosevelt Island Tidal Energy (RITE) project, East River, NY, 10 m depth

Date: Fall 2008

Organism(s) of Interest: Resident & Migratory Fish

Methods:

- Combined two acoustic cameras, dubbed a Vessel-mounted Aimable Monitoring System (VAMS)
  - Downward-looking SBT and a DIDSON system oriented towards a turbine to observe fish movement and behavior
- VAMS deployed for three 15–17 hour periods

Key Findings:

- Resident and migratory fish avoided the areas where turbines were located and tended to prefer inshore, slower moving waters
- Fish behavior primarily influenced by the natural tidal currents and secondarily by presence of the operating turbines
- Few fish present while turbines were operating, when the flow velocity increased to greater than 0.8 m/s
  - Typical turbine cut-in velocities of 0.7 to 1.0 m/s.
- Limited observations showed fish passing by the rotating turbines following the hydrodynamics of the system
  - Indicated fish were able to detect and successfully pass around operating turbines

Putting it together: Field data to inform fish strike models

- As part of their permitting conditions, Verdant was asked to establish strike risk for Atlantic Sturgeon, an ESA listed sp.

- Verdant worked with scientists at *Kleinschmidt developed a Tidal Turbine-Fish Interaction Model based on encounter data for Atlantic Sturgeon*

- VEMCO receivers

- Atlantic Cooperative Telemetry Network, thousands
- of Atlantic sturgeon tagged along the East Coast

Image courtesy of C. Tomichek.

Information source for this and subsequent Atlantic Sturgeon slides: Talk by C. Tomichek, International Marine Energy Conference, 4/15.
Chris.Tomichek@KleinschmidtGroup.com

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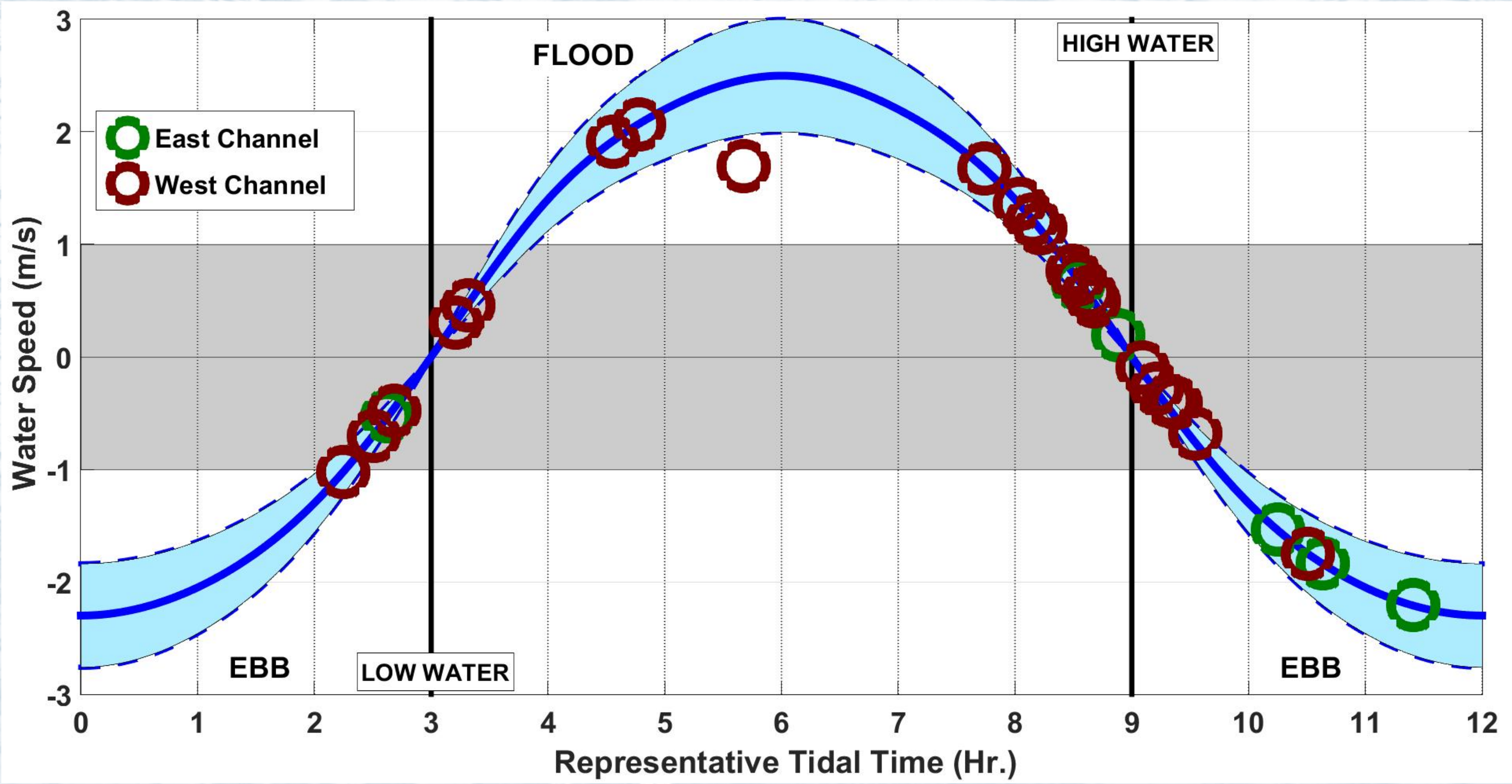
Putting it together: Field data to inform fish strike models

Known Known

Atlantic sturgeon detections May 2011 to July 2014



Graph courtesy of C. Tomichek., IMREC 2015

Putting it together: Field data to inform fish strike models

- 2D strike probability model developed

$$P_{Strike} = \sum_{V_W=0}^{V_{W,Max}} P1 \cdot P2 \cdot P3 \cdot P4 \cdot P5 \cdot P6 \cdot P7$$

P1: Probability of Blade Rotation
P2: Distribution of Water Velocity over the Tidal Cycle
P3: Fish Distribution (East vs. West Channel)
P4: Turbine Rotor Area
P5: Blade Interaction with Fish
P6: Fish Distribution (At Different Velocities)
P7: Avoidance Behavior

Information source: Talk by C. Tomichek, International Marine Energy Conference, 4/15.

Putting it together: Field data to inform fish strike models

Known Known

- P1 - Probability of Blade Rotation – based on velocity
- P2: Distribution of Water Velocity over the Tidal Cycle – based on measured flow rates
- P3: Distribution between West and East Channel, originally assumed to be 0.5. 3 years of data: 21 sturgeon detected in West Channel (88%) and 6 in East Channel (22%)
- P4: Turbine Rotor Area – based on % of cross section of channel occupied by turbine (0.0066)
- P5: Probability of blade/fish interaction
  - Strike model that includes:
    - the speed of the fish approaching the turbine
    - the length of the fish
    - the rotational speed of the turbine blades
    - the angle that the fish is approaching the turbine
- P6: Fish distribution at different water velocities
  - Originally assumed to be even
  - 22% of all sturgeon detections within 45 minutes of slack tide, below cut-in speed, thus out of strike risk
  - 1 of 27 sturgeon detected at the peak of the tide cycle
- P7 is conservatively assumed to be 1; meaning no avoidance behavior by fish.
  - Multi-beam sonar data collected in 2012 being analyzed by ONRL will be used to inform

Original strike probability P_{Strike} = 0.086%

Using updated using site data P_{Strike} = 0.032%

Note this is assuming no avoidance behavior

Information source: Talk by C. Tomichek, International Marine Energy Conference, 4/15.

Measured and Observed Impacts for Deployed MHK Systems: Marine Mammal Field Data—Strangford Lough, Ireland

Known Known

Device Type: Marine Current Turbine's SeaGen turbine

Location: Strangford Lough, Ireland (Special Area of Conservation)

Organism(s) of Interest: Seals (gray and harbor), harbor porpoises

Methods:

•To eliminate strike risk to marine mammals, turbine shut down during daylight hours when marine mammals were sighted nearby by marine observers and after dark

•Distances and protocols triggering shutdown were reduced over time

•Role of marine mammal observers was augmented and then replaced by a sonar unit

Key Findings:

•At start of project, turbines shut down on average three times per 24 hours of operation; later in project, shutdown occurred less than once per 24 hours of operation

•Shutdowns more frequent on ebb tide than flood tide

•Turbine shutdown procedures did not allow for observations of direct interactions of the animals with turbine blades

•Seal telemetry data showed that seals transited farther away from the center of the Narrows after SeaGen installation, suggesting avoidance of the turbine

•Now moving towards continuous operation

Source: http://www.seageneration.co.uk/environmentalaspects.php

Source: http://www.seageneration.co.uk/environmentalaspects.php

Measured and Observed Impacts for Deployed MHK Systems: Marine Mammal Modeling

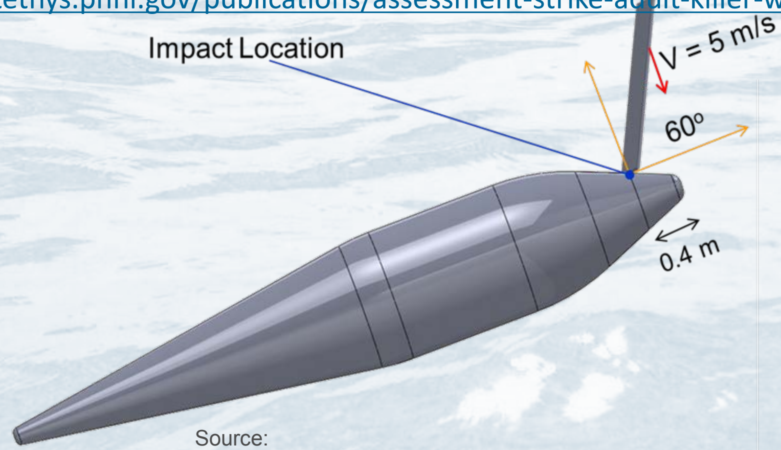
Known Known

Risk = probability x consequence

Assessment of Strike of Adult Killer Whales by an OpenHydro Tidal Turbine Blade (SNL, PNNL)

- Provided estimate of worst-case scenario results of blade strike
- Concluded that interaction likely to result in bruising or minor laceration under worst case scenario
- Study did not account for aspects of whale behavior nor provide detailed information about the strengths of specific whale tissues
- This analysis may not be generally applicable to encounters between other species of animals and other turbine designs
  - Work on this question ongoing

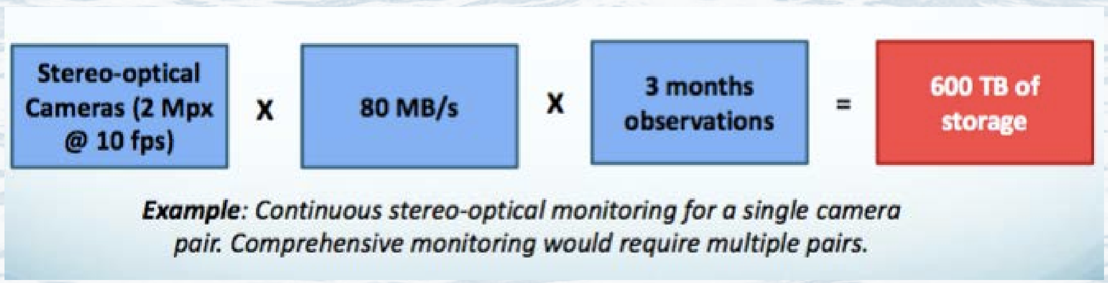
http://tethys.pnnl.gov/publications/assessment-strike-adult-killer-whales-openhydro-tidal-turbine-blade



Source: http://tethys.pnnl.gov/sites/default/files/publications/OpenHydro_Whale_Strike_Assessment_Final.pdf

Measurement Technologies

- Currently no COTS technologies ideal for monitoring collision in the near field.
  - Optical systems – light dependent, risk of biofouling, data intensive
  - Active acoustic systems result in clutter around blade surface that makes collision events hard to detect, data intensive, survivability issues in high energy environments, species ID difficult
  - PAM only detect vocalizing organism
  - Accelerometers in research stage with regards to discerning animal strike



From: http://tethys.pnnl.gov/sites/default/files/Annex-IV-Presentation-Bay-of-Fundy_Polagye.pdf

- Processing data lengthy and expensive
- Most promising solutions likely integrated instrumentation packages.
  - Packages under development by University of Washington and NERC, but in research phase of development and testing
- **Note: Strike monitoring has been and will be very expensive. May be more appropriate for research to inform broader understanding of risk, rather than aiming for continuous monitoring at projects**.
- More information: http://tethys.pnnl.gov/sites/default/files/publications/Instrumentation_Workshop_Final_1_2014_0.pdf

What do we know, what questions remain, and how do we move forward?

Known Unknown

- No observations to date of strike injury or mortality in the field from tidal turbines, but some limitations on monitoring to date
- General agreement among the scientific community that strike events are likely to be rare
- Rareness of strike events will make them inherently hard to observe and to prove out monitoring technologies (sample size issues)

What do we know, what questions remain, and how do we move forward?

Known
Unknown

- Some differences in variables such as fish presence at different flow rates, passage through turbines under dark conditions
- Different types of turbines have different rotor-tip speeds and strike forces, thus understanding the properties of a specific turbine is important in predicting strike
- Site flow rates will also affect rotational velocity and thus strike force
- Understanding how arrays of turbines affect fish avoidance ability a remaining question, though high survival rates for fish passing through turbines is promising
- Research to better understand avoidance rates, coupled with predictive modeling may be the optimal course of action

Thank you

Questions:

Jocelyn.Brown-Saracino@ee.doe.gov