Hydrokinetic Power Review

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PREFACE

The work described here was performed during the period October 2009 through April 2010 with funding from the U.S. Army Corps of Engineers Engineer Research and Development Center, Vicksburg Mississippi, under the direction of Jeff Lillycrop and Lyndell Hales. The Contract Number was W912HZ-09-P-0441.

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EXECUTIVE SUMMARY

North America has significant in-stream energy resources, and hydrokinetic electric power technologies to harness those resources are becoming available. Hydrokinetic electric power is generated by turbines capturing the energy of naturally flowing water – stream flows, tidal flows, or wave motion – without impounding the water.

Hydrokinetic power generation offers the potential to make a significant contribution to U.S. electricity needs by adding as much as 20,000 to 30,000 MW to the present 75,000 MW of hydroelectric power generation capacity. About a third of that potential occurs as in-stream generation in tidal and non-tidal rivers and in estuaries. Among its attractive features, hydrokinetic operations do not contribute to greenhouse gas emissions or other air pollution and because the installations are underwater, they have less visual aesthetic impact than wind turbines.

The Corps of Engineers mission to provide safe, sustainable, and effective Federal navigation projects requires a careful examination of hydrokinetic installation effects on navigation. Possible effects include increased risk of waterborne vessel accidents, including collisions with hydrokinetic structures, and environmental effects that impinge on navigation projects' safety, sustainability, and effectiveness.

The presence of hydrokinetic turbines and their support structure(s) present at least the potential to adversely affect navigation and the waterway ecosystem. If a vessel were to strike a hydrokinetic installation both the hydrokinetic equipment and the vessel would be damaged. Outside of collisions or restricting waterway traffic, constriction of a waterway by an installation may affect water level and currents, and thus navigability, and alter sedimentation patterns, either increasing or decreasing channel dredging requirements, all of concern to waterway operators and users.

The first U.S. hydrokinetic installations are on the Mississippi River just below Hastings, MN, and in the East River, New York City. The Federal Energy Regulatory Commission (FERC) has issued permits for over 140 studies of potential hydrokinetic installations in 15 states from coast to coast.

The hydrokinetic method of extracting energy from flows converts the kinetic energy of flow to mechanical shaft power by a propeller-like device which generates electrical current by a dynamo (or generator) attached to the shaft in a manner analogous to a wind turbine. Power generated is proportional to the speed of the current cubed. Thus the available power depends primarily on the speed of the current. The minimum current required to operate a hydrokinetic

device is typically 2-4 knots (4-7 fps) and optimum currents are in the 5-7 knot (8-12 fps) range. Water depth affects site selection, since rotor diameter is dependent on adequate water level above the installed device. For these reasons, hydrokinetic devices work best in locations with relatively steady flow throughout the year and without extended periods of low water level.

Discussions of hydrokinetic energy's environmental impacts often cite an upper limit of 10 to 20 percent on energy extraction from a cross-section stream power. Results from our simple hydrodynamic analysis show that a single installation extracting up to 20 percent of the kinetic energy from a single tidal or non-tidal flow cross section can be expected to have a small, but not insignificant effect on flow depths, velocities, and energy available for other purposes downstream, upstream, or both. In general, the changes can be characterized as slowing the flow speed and changing water level by small amounts, although cumulative effects of hydrokinetic extraction over considerable channel lengths can be substantial.

Precise resolution of the magnitude of these effects must be addressed by more sophisticated computations in multi-dimensional numerical models applied on a site-specific basis. However, from these results we anticipate that installation of hydrokinetic generators in tidal and non-tidal waterways can:

- Decrease flow speeds
- Alter water levels
- Cause localized bed scour around the installation (near field)
- Increase sediment deposition elsewhere(far field)
- Alter salinity intrusion in estuaries
- Alter water quality
- Altered transport patterns
- Alter habitats
- Increase vessel accidents

The degree, direction, and cumulative effects of these changes plus site conditions will dictate whether a specific site is suitable for hydrokinetic electricity generation or not.

The likelihood of a vessel striking a hydrokinetic installation depends on the configuration and site conditions. For installations shallower than vessel draft lying outside lateral channel limits, a rate of 0.32 rammings per year per mile of channel is a reasonable estimate for the Mississippi River until more rigorous studies can be made. For installations below channel design depth a risk-based study of the combined probability of low water conditions and vessel motion will be required to estimate the number of accidents.

We recommended that the Corps of Engineers review applications for hydrokinetic installations based on:

- Ratio of total energy loss to energy generation for various hydrokinetic installations defined by large scale lab experiments
- Site-specific 3-dimensional numerical model study of each proposed installation with energy extraction based on equipment performance and above extraction ratio
- Consideration of individual and cumulative environmental near field and far field effects on water level, flow speed, sedimentation, salinity intrusion, water quality, and habitat
- Site-specific probabilities of vessels striking the installation or suffering another accident in trying to avoid the installation.

1. INTRODUCTION

1.1 Purpose

The purpose of this work is to identify and describe potential areas of concern related to placement of hydrokinetic turbines near navigation facilities in waterways of the United States.

This document reviews the available information on hydrokinetic installations, describes how they might be used in U.S. waterways, and examines the possible effects on safe and efficient passage of waterborne commerce in Federal waterways.

1.2 Background

Hydrokinetic electric power is generated by turbines capturing the energy of naturally flowing water – stream flows, tidal flows, or wave motion – without impounding the water.

While hydrokinetic turbines do not require impounding dams, the presence of the turbines and their support structure(s) present at least the potential to adversely affect navigation and the waterway ecosystem. If a vessel were to strike a hydrokinetic installation both the hydrokinetic equipment and the vessel would be damaged. Outside of collisions or restricting waterway traffic, constriction of a waterway by an installation may affect water level and currents, and thus navigability, and alter sedimentation patterns, either increasing or decreasing channel dredging requirements, all of concern to waterway operators and users.

The first U.S. hydrokinetic installations are on the Mississippi River just below Hastings, MN, and in the East River, New York City. The Federal Energy Regulatory Commission (FERC) has issued permits for over 140 studies of potential hydrokinetic installations in 15 states from coast to coast. (See Figure 1-1) Therefore, an assessment of navigation concerns is in order.

1.3 Approach

We reviewed the existing literature and databases of information on hydrokinetics and considered common designs to identify potential waterway and navigation effects of hydrokinetic installations that capture the energy of flowing water, both coastal and inland. Capturing the energy contained in near-shore and off-shore waves is thought to have the greatest energy production potential among hydrokinetic options, but is considered only briefly here. We performed simple hydrodynamic calculations to better explore the effects of energy extraction, and considered how energy extraction might affect the Corps' navigation mission.

In 2009 the U.S. Department of Energy released a report on the environmental effects of hydrokinetic technology and mitigation of adverse effects through adaptive management. Some of the salient points of that report and the workshop held for the report are listed here, but rather than quote extensively from it, a copy of that report is provided as a companion to this document.

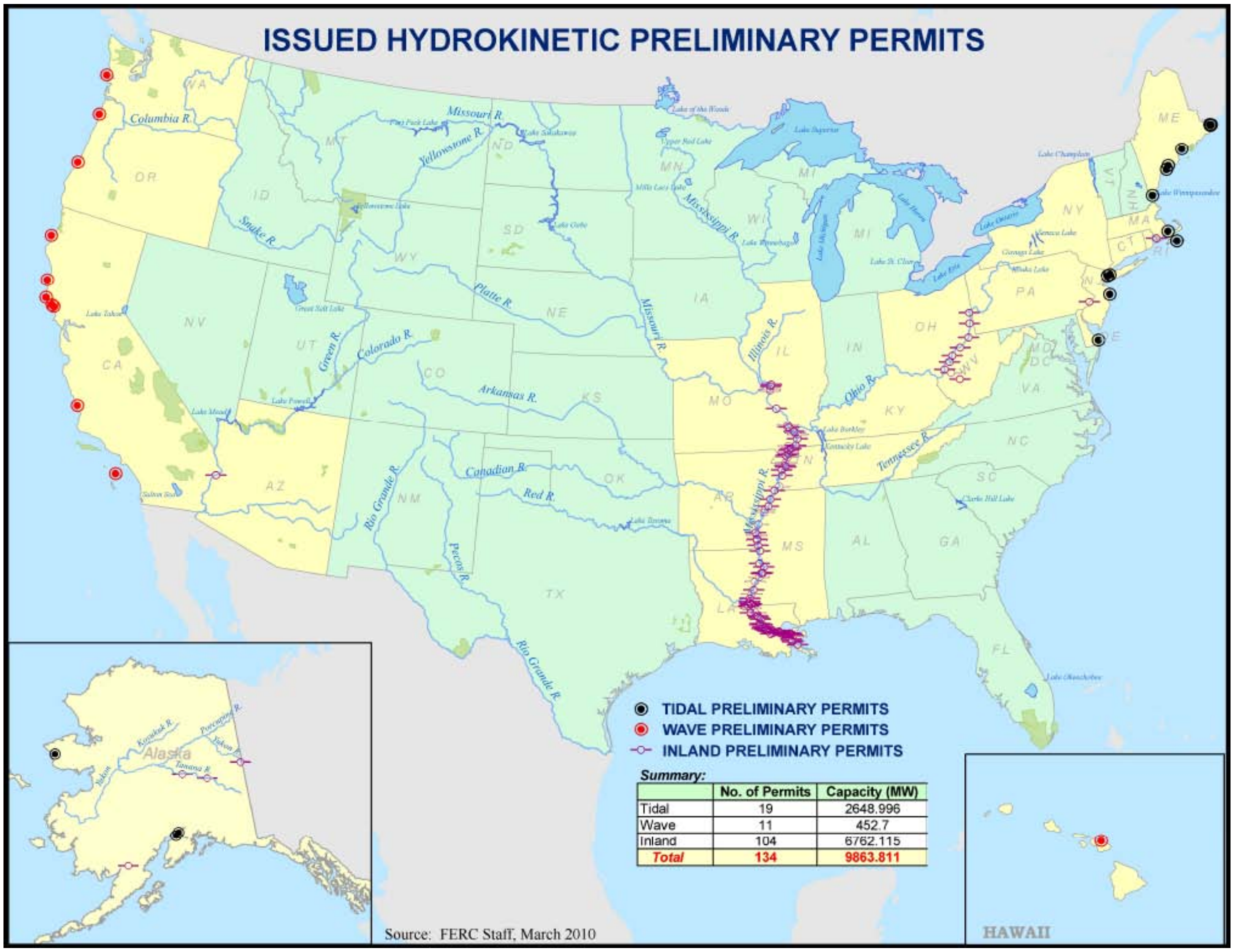


Figure 1-1. Map of FERC Permits in 2009. (Source: FERC, 2010. Used with permission)

2. HYDROKINETIC POWER

2.1 Introduction

The use of water power dates back thousands of years to the water wheels of Greece, Persia, and China, which used the energy in falling water to grind grain. These traditional uses typically captured power by tapping the potential energy of water – allowing it to fall from some height to hit and turn a wheel. Interest in harnessing energy from ocean surface waves began in the United States in the 1800's, now we are presented with a new method for generation of hydropower, one that harnesses the kinetic energy of the oceans and rivers without traditional dams or diversions.

In the United States, the Department of Energy (DOE) includes tidal in-stream, river in-stream, ocean current, and constructed waterways as hydrokinetic energy resources. In the same way, the Electric Power Research Institute (EPRI) through its Ocean Energy Program incorporates all of these as well as offshore wind and hybrid ocean wave and wind energy devices.

> *State and federal policymakers across the U.S. have begun to support hydrokinetic energy development through legislative and funding means: ocean energy had been considered eligible resource for credit under renewable electricity standards in sixteen states, and for federal renewable energy production tax credits, as expanded in the Energy Policy Act of 2005* (Union of Concern Scientists, 2009).

Although there are uncertainties about the economic feasibility and environmental issues related to this new technology, there is also abundant physical potential which fires enthusiasm among commercial developers. Developers have filed for permits to examine 55 proposed sites on the Mississippi River between St. Louis, MO and New Orleans, LA. There are 22 such sites on the Ohio River, and 27 on the Missouri. Similar projects are also being proposed on rivers in Alaska, Michigan, Minnesota, Maine, and New York. Pilot hydrokinetic power installations have been constructed in the Mississippi River near Hastings, Minnesota, and New York Harbor's East River.

2.2 Hydrokinetic Power Generation

The hydrokinetic method of extracting energy from flows converts the kinetic energy of flow to mechanical shaft power by a propeller-like device and generates electrical current with a dynamo (or generator) attached to the shaft, similar to a wind turbine. The power generated will be proportional to the density of the water and to the velocity cubed. Thus the available power depends primarily on the speed of the current.

The minimum current required to operate a hydrokinetic device is typically 2-4 knots (3.4-6.8 fps) and optimum currents are in the 5-7 knot (8.4-12.0 fps) range. *Water depth affects site selection, since rotor diameter is dependent on adequate water level above the installed device. For these reasons, hydrokinetic devices work best in locations with relatively steady flow throughout the year and without extended periods of low water level* (Lockard D., 2009).

2.3 Hydrokinetic Technologies

The technologies developed to generate energy from waves and currents, called hydrokinetic energy conversion devices, are generally categorized as either wave energy converters (WECs) or rotating devices.

Wave Energy Converters (WECs) utilize the motion of two or more bodies relative to each other. One of these bodies, called the displacer, is acted on by the waves. The second body, the reactor, moves in response to the displacer.

While there are a number of designs and configurations of WECs, the four most commonly are:

- *Oscillating Water Column (OWC):* Waves enter and exit a partially submerged collector from below, causing the water column inside the collector to rise and fall. The changing water level acts like a piston as it drives air that is trapped in the device above the water into a turbine, producing electricity via a coupled generator.

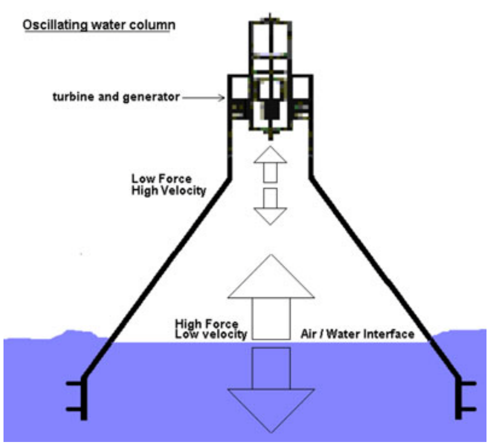


Figure 2-1. An oscillating water column wave energy converter
(Source: George, 2009. Used with permission)

Point Absorber: Utilizes wave energy from all directions at a single point by using the vertical motion of waves to act as a pump that pressurizes seawater or an internal fluid, which drives a turbine. This type of device has many possible configurations. One configuration, called a hose pump point absorber, consists of a surface-floating buoy anchored to the sea floor, with the turbine device as part of the vertical connection. The wave-induced vertical motion of the buoy causes the connection to expand and contract, producing the necessary pumping action. Energy capture and electricity generation by point absorbers can be maximized by designs that create device-wave resonance.

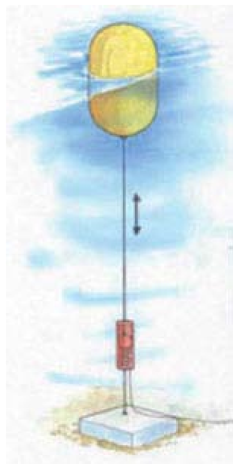


Figure 2-2. Point absorber wave energy converter.
(Source: EPRI, 2007. Used with permission)

- *Attenuator:* It is also known as heave-surge devices; the jointed floating structures are aligned parallel to the wave direction and generate electricity by riding the waves. The device, anchored at each end, utilizes passing waves to set each section into rotational motion relative to the next segment. Their relative motion, concentrated at the joints between the segments, is used to pressurize a hydraulic piston that drives fluids through a motor, which turns the coupled generator.

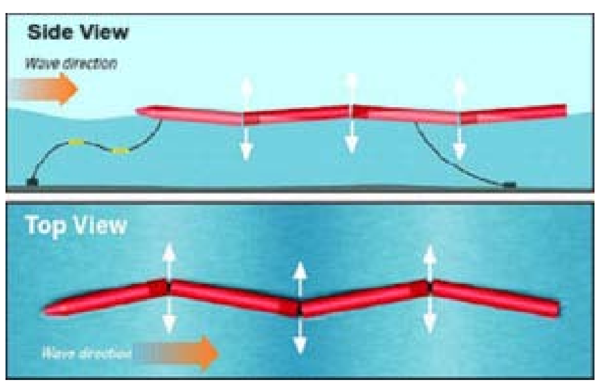


Figure 2-3. An attenuator wave energy converter.
(Source: EPRI, 2007. Used with permission)

- *Overtopping Device:* A floating reservoir, in effect, is formed as waves break over the walls of the device. The reservoir creates a head of water—a water level higher than that of the surrounding ocean surface—which generates the pressure necessary to turn a hydro turbine as the water flows out the bottom of the device, back into the sea.

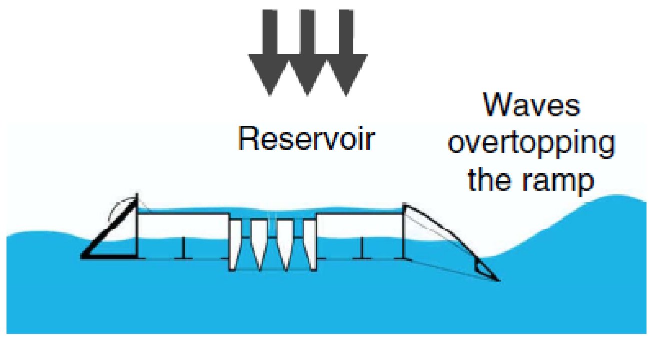


Figure 2-4. An overtopping wave energy converter
(Source: EPRI, 2007. Used with permission)

Beside the design, the WECs could be classified according to their location in the water body. Devices can be located near the shore; however positions will have their pros and cons, related to wave energy availability, installation and maintenances cost and the environmental impact.

> *Devices typically are optimized for operation within a particular depth range. Both water depth and the energy content of the waves tend to increase with distance from shore. Distance from shore also affects accessibility (for deployment, retrieval, operation, and maintenance) and visual impact; at any given site the distance from shore will also determine what aspects of the marine resource may be affected. Another characteristic distinguishing different types of wave energy conversion devices is the method of fixing the device to the site. Bottom-mounted devices are fixed to the seabed by a static member* (Bedard R, 2006).

Rotating Devices capture the kinetic energy of a flow of water, such as a tidal stream, ocean current or river, as it passes across a rotor. The rotor turns with the current, creating rotational energy that is converted into electricity by a generator. Some rotational device designs, like most wind turbines, rotate around a horizontal axis (Figure 2-5), while other, more theoretical concepts are oriented around a vertical axis (Figure 2-6) (Union of Concern Scientists, 2009).

- *Horizontal axis:* This model is like a wind turbine in design, with rotor blades rotating in a plane perpendicular to the axis, which is oriented into the direction of the flow or tidal current.

- *Vertical Axis*: Vertical axis turbines have their blades oriented in line with the axis rather than perpendicular to it.

Typical subsystems include rotor blades which convert the energy in the water to rotational motion, a drive train, usually including a gear box and a generator that convert the rotational shaft motion to electrical energy, and a structure that supports the rotor and the drive train. Other ways to grouping these devices include:

- Support structure. Devices may be either gravity base bottom mounted, attached to a monopole foundation or anchored and moored and allowed to "fly" in the tidal stream.
- Open versus shrouded rotors.
- Fixed versus variable pitch blades.
- Yaw control versus fixed yaw angle.
- Drag versus lift water foil (vertical axis only).

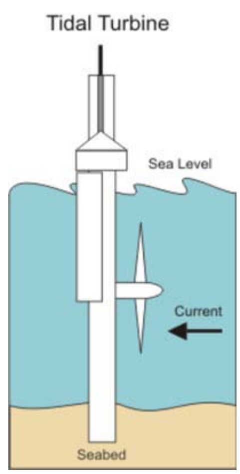


Figure 2-5. Horizontal axis hydrokinetic rotating device
(Source: Bedard et al., 2006. Used with permission)

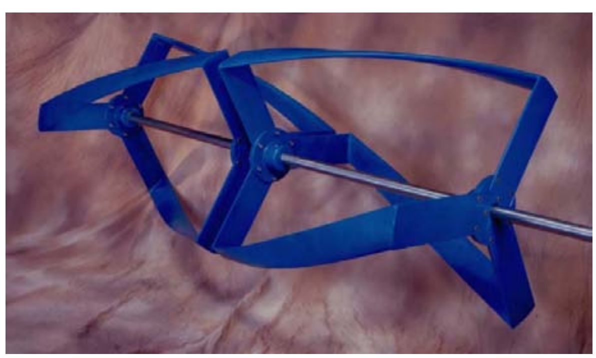


Figure 2-6. Vertical Axis Turbines.
(Source: Bedard et al., 2006. Used with permission)

2.4 Hydrokinetic Technologies Used in U.S. Waterways

> *While the hydrokinetic technology has been tested, the implementation has taken on a variety of forms which all seek to increase the wattage output and efficiency in various types of flow. Factors affecting these parameters include the kinetic pressure head and the turbulence. Also, slow, deeper flows up to 100 feet must be handled differently than fast shallow flows of less than 10 feet. The array of physical implementations has created an equally large variety of solutions. Sizes of power harnessing units for example, range from several meters to 30 meters or more in diameter. Accordingly, the weight of the units can range from a few hundred pounds to many tons. While different systems and applications are being investigated, a common denominator is the fact that the power output is directly related to the velocity of the flow* (Thermal Systems, 2009).

The following companies are among those developing the hydrokinetic technology in the U.S.:

- Free Flow Power (FFP) Corporation (www.free-flow-power.com) based in Gloucester, Massachusetts is proposing projects on the Mississippi, the Ohio and the Missouri Rivers.
- HydroGreen Energy (www.hgenergy.com), a Houston based company, has proposed projects on the Mississippi River in Louisiana and Mississippi, and on the Yukon, Eagle and other rivers in Alaska.
- Verdant Power (www.verdantpower.com) has proposed projects on the Niagara River and on the East River in New York.

The Electric Power Institute (EPRI) characterized eight TISEC devices with the objective of determining technology maturity and any critical issues relating to technological readiness for pilot plan demonstration.

> *For the study, EPRI advisors selected three TISEC devices for the design phases of the study: Lunar Energy, Marine Current Turbines (MTC) and Verdant Power. Although considering the large numbers of devices and different types of devices being developed, they conclude, that the technology is much too young for anyone to be able to know which of these technologies will turn out to be the most cost-effective in the future* (Bedard et al., 2006).

Figures 2-7 and 2-8 summarize the technologies proposed by three major companies developing hydrokinetic technology and include some of the technologies considered in the 2005 EPRI study (Bedard et al., 2006).

Power Turbine Proposed by Verdant Power
(Source: Bedard et al., 2006)

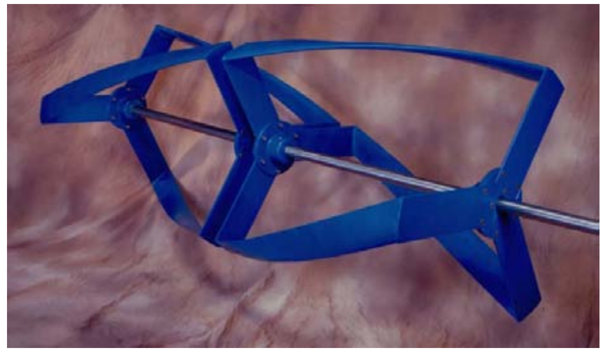
Verdant Power Conceptual Model
(Source: Bedard et al., 2006)

Concept Diagram for a Free Flow
(Hydropower Reform Coalition, 2008)

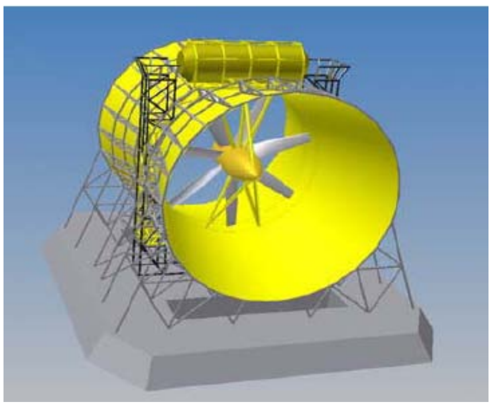
HydroGreen Energy Technology in Mississippi River
(Courtesy: Hydro Green Energy)

Figure 2-7. TISEC devices proposed by the three major companies developing hydrokinetic technology
(Photos used with permission)

Open Hydro Rim Drive Turbine

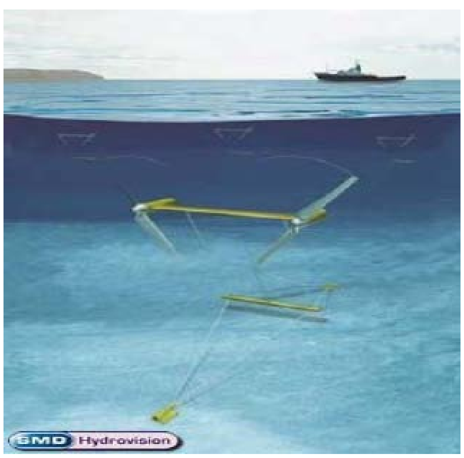


Gorlov Helical Turbine

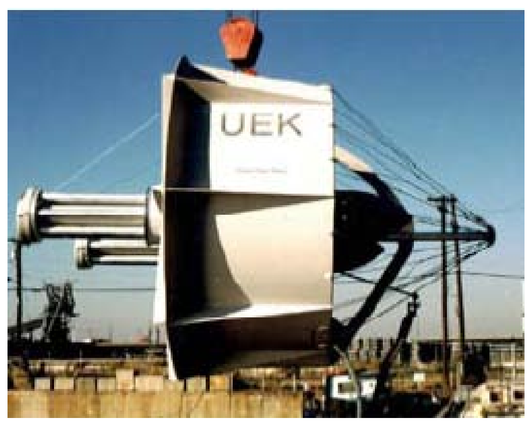


Lunar Energy RTT Turbine

MCT Experimental SeaFlow



SMD Hydrovision



UEK Shrouded Turbine

Figure 2-8. TISEC devices studied by EPRI (Source: Bedard et al., 2006. Used with permission)

2.5 Hydrokinetic Installations in the U.S.

Hastings - Minnesota. The Hastings hydrokinetic turbine is located behind the turbine of the existing conventional hydropower plant on the Army Corps of Engineers' Lock and Dam No. 2. The power is generated by two hydrokinetic units, and will be placed on the electric power grid through Hastings' existing electrical infrastructure.

> *At the design point, the coefficient of performance (COP or water to wire efficiency) for the Hasting hydrokinetic unit is 0.62, the highest in the hydrokinetic power industry at this point in time. Using 83% CF at nameplate capacity (100 kW per unit at 3.5 m/s), the Hastings hydrokinetic power station will produce a maximum of 1,454 Mwh of electricity annually* (Neville, 2009).
>
> *Because the Hastings conventional hydropower facility operates as a run-of-river facility, there is a high CF (over 80%), which the hydrokinetic power station takes advantage of. This also means that the power generated from the hydrokinetic turbines is baseload and predictable. Furthermore, from an operations standpoint, because the hydrokinetic power station is located downstream from an existing hydropower plant, all of the water passing through its turbine already has debris filtered out. Additionally, the hydrokinetic power station's location eliminates river traffic directly in front of the dam, which increases the safety of the installation* (Neville, 2009).

This system was developed by Hydro Green Energy, and they call this type of project a Hydro+ project, considering that they are generating clean energy twice from the same water resources at a specific location.

Alaska. At this time, a number of companies are actively involved in designing pilot projects in Alaska, considering their potential on this new technology. Some of the projects are briefly described below, based on information in reference (Polagye et al., 2006).

- ***The Yukon River at the Community of Ruby - Alaska.*** The Yukon River Inter-Tribal Watershed Council installed a 5 kW New Energy Encurrent turbine in the Yukon River at the community of Ruby for one month in 2008. Ruby was selected as a test case partly because diesel-generated power there is so expensive, and also satisfied some technical requirements.

  A 100-kW turbine about 20 times larger than Ruby's is scheduled to be installed Upper Yukon River village of Eagle, where it's expected to power all the homes in town from breakup to freeze up. That could eventually provide a fuel-free alternative to Eagle's present practice of burning about 80,000 gallons of increasingly costly diesel fuel each year to generate electricity.

- ***Igiugig – Alaska.*** This project is located at the headwaters of the Kvichak River. At this location EPRI has considered a hypothetical 40 kW project mounted on a 30 ft pontoon boat anchored to the riverbed. The pontoon was designed to serve as a platform from which four turbine rotors (4.5 ft in diameter), could be suspended in the water column. A protective 'trash-rack' was mounted in front of the rotors and generator to minimize debris impacts. Three of these pontoons, with a total of twelve devices, were considered for this case study. The 40 kW size of the project was based on village energy consumption (low) and resource availability (high) during summer months. The village currently has three diesel generators ranging in size from 60kW to 100 kW. Historic loads are 40 kW (summer) to 95 kW (December-February).

- ***Cairn Point at Knik Arm.*** Cairn Point is potentially a good location for in-stream tidal power generation, as strong tidal currents occur four times a day, and it is adjacent to significant electrical infrastructure. Cairn Point is located about two miles north of Anchorage in Knik Arm, in upper Cook Inlet. At Cairn Point, water depths exceed 150 ft, and the flow through Knik Arm is constricted. The constricted flows, along with Cook Inlet's large twice-daily tidal range, combine to produce high water velocities. Tidal currents average 2.0 knots (3.4 fps) with peaks of up to 7.5 knots (12.7 fps).

  The EPRI system feasibility study considered two types of in-stream energy generation devices, the Lunar (RTT) and the Marine Current Turbine (MCT), which installed in arrays would produced an average of 17 MW of power with little environmental impact. 17 MW is the equivalent power used by about 12,000 homes, each using 1.3 kW.

Roosevelt Island Tidal Energy (RITE) project. Since 2002, the RITE Project has been operated by Verdant Power Company in the East River of New York City. In three phases, the RITE Project seeks to develop, demonstrate and commercially deliver electricity generated from the tides of the East River using Verdant Power's Free Flow System.

In November 2008, Verdant Power completed a two-year demonstration of its newly developed free-flow tidal turbine system. During the two years, six 5m diameter (35 kW) turbines installed in New York's East River supplied a total of 80 megawatt hours of energy, powering a supermarket and parking garage on nearby Roosevelt Island. The planned project will consist of approximately 200 turbines located in the East River both along the east shore of Roosevelt Island and near the United Nations, generating up to 10 MW of distributed electricity.

Mississippi River between St. Louis, MO and New Orleans, LA. Free Flow Power Corp proposes to install hydrokinetic turbines at up to 55 sites along the Mississippi River. The turbines would have a diameter of 10 feet and be installed below navigation depth. Each turbine can generate roughly 1,600 MW of power which would then be transmitted ashore to the power grid or to industry sites.

2.6 Hydrokinetic Power Potential and Extraction

Capturing the energy contained in near and off-shore waves is thought to have the greatest energy production potential amongst hydrokinetic options (Union of Concern Scientists. 2009), but is not considered here since wave capture devices need not be near navigation facilities.

According to DOE/EIA existing hydropower capacity in 2006 was about 96,000 MW (about 75,000 MW of conventional capacity and 21,000 MW of pumped storage capacity). Hydropower accounted for about 9% of the country's total electric generating capacity and over 75 percent of the U.S renewable energy generation (Bahleda et al., 2007).

Several studies have assessed some of hydropower's future potential including that which could be tapped at existing plants and by developing potential resources with new technologies. These studies have included waterpower technologies as show in Table 2-1, with hydrokinetic power offering a potential 12,800 MW, or about 13 percent of the present hydropower capacity from all sources. Tidal In-stream Energy Conversions (TISEC) potential was examined in a series of EPRI studies for five states (Alaska, Washington, Oregon, Maine, and Massachusetts) and several sites in Canada. The total resource potential for these locations was estimated at approximately 300 MW (Bahleda et al., 2007).

As shown in Table 2-1, the total potential of natural river in-stream conversion without impoundments has been estimated by New York University as 12,500 MW average powers in examined rivers with discharge rates of 113 m^3/s and velocities of 1.3 m/s (Bahleda et al., 2007). In contrast, an assessment by the Idaho National Laboratory stated that nearly 30,000 MW of hydropower exist within the United States without construction of any additional dams (Thermal Systems. 2009).

EPRI initiated the Tidal In-Stream Energy Conversion (TISEC) project in 2005. To date, 17 feasibility reports on wave, tidal, and wind energy have been developed and are published on EPRI's website: http://oceanenergy.epri.com/streamenergy.html (EPRI, 2009].

Table 2-1. Waterpower Existing and Estimated Potential Capacity (MW) (Source: Bahleda et al., 2007. Used with permission)

Waterpower Technology	2006 MW	Potential MW
Conventional Hydro		
Large Hydro (>30 MW)	66,535	(3,100)[1]
Capacity gains at existing large and small hydro	~100[2]	4,300[3]
New Small hydro (> 1 MW <30)	8,023	36,000[4]
New Low power hydro (<1MW[5])	313	22,000[6]
New hydro at existing dams	--	(16,700)[7]
Total conventional hydro	74,871	62,300
Hydrokinetic		
Tidal in-stream	Demos	300[8]
In-stream and constructed waterway	--	12,500[9]
Total hydrokinetic potential	--	12,800
Ocean Energy		
Ocean Wave	Demos	10,000 – 20,000[10]
Ocean Current	--	
Pumped Storage	21,000	Resource not assessed
Total Existing and Potential Waterpower	95,971	85,100 – 95,100

1. Estimated equivalent capacity addition at existing facilities due to generation efficiency gains based on industry expectation of 4 percent improvement. This value is included in the subsequent row for large and small hydro and is, therefore, excluded from the total.
2. Based on estimates for gains being considered by FERC as certified for PTCs.
3. 1998 estimate by DOE (Conner et al. 1998) includes capacity gains from adding new units in existing bays or larger turbines.
4. Corresponds to 18,000 MWa (mean annual power) estimated by DOE (Hall et al. 2004; DOE 2003) and assumes a 50 percent plant factor.
5. Included potential defined as conventional, unconventional and microhydro power by DOE (2003).
6. Corresponds to 11,000 MWa (mean annual power) estimated by DOE (Hall et al. 2004; DOE 2003) and assumes a 50 percent plant factor.
7. This 1998 figure corresponds to the potential at 2,500 of the more than 79,000 dams in the U.S. and therefore should be considered an ultra-conservative estimate (Conner et al. 1998). It is likely to be included in the 2006 estimates of potential noted above and therefore is excluded from the totals.
8. EPRI (2005b) examined the tidal in-stream potential for only 5 states.
9. A study of U.S. in-stream potential was made in 1986 (Miller et al. 1986). It did not include an assessment of constructed waterways. It is unclear whether this estimate is MW or MWa and is shown as the smaller figure.
10. As estimated by EPRI (2005a); the potential could be significantly higher because EPRI (2005a) assumed that only 15 percent of the potential energy could be extracted.

In 2005, the Electric Power Research Institute (EPRI) evaluated the techno-economic feasibility of tidal in-stream energy conversion (TISEC) in North America. Seven states and provinces in North America participated in the collaborative feasibility study: Alaska, Washington, California, Massachusetts, Maine, New Brunswick, and Nova Scotia (Bedard et al., 2006). Complementary studies evaluated specific sites (EPRI, 2009).

The energy available for capture at a site is function of the stream power, which varies with the cube of velocity, so small velocity variations have a large impact. The power flux or power per unit time and area, of a current is given by;

$$P=\frac{1}{2}\rho V^3$$

Where P is the power flux (kW/m^2), ρ is the density of water (about 1000 kg/m^3), and V is the current velocity (m/s), which varies with time and location in the channel. However, the extractable energy is limited. In the extreme case, if all the energy were extracted, the stream would cease to flow. However, practical energy extraction limits will be reached long before that point. Practical limitations include channel geometry (the entire cross-section cannot be filled with circular rotors), reduction in energy extraction efficiency, and environmental considerations (circulation patterns, average flow speed, energy for sediment transport, water quality, etc.). EPRI uses the following considerations to determine the percent of energy that can be extracted for a specific site (Hagerman et al., 2006):

a) *The useable cross-sectional area of a channel is reduced at the top and the bottom of the channel. At the top, navigation clearance requirements will eliminate the upper 15-20 m of water in channels maintained for oceangoing vessels. Elsewhere a 5-m clearance will be required to enable shallow-draft vessels such as commercial fishing boats and deep-keel sailboats to safely travel over the device. At the bottom, the turbine must be above the low-speed benthic boundary layer, which is typically 1/10 of the mean lower low water (MLLW) depth. The maximum energy that can be extracted is calculated as the mean annual power density multiplied by the useable cross-sectional area between the top and bottom limits described above.*

b) *UK researchers have variously estimated that to minimize the turbine's effect on downstream and upstream environments, the mean annual power extracted should be no more than 10% to 20% of the naturally available physical energy flux. With this consideration, EPRI has used 15% as the environmental extraction limit.*

Whichever of the above two considerations is smaller determines the maximum extractable tidal stream energy resource at a given location. For typical commercial-scale tidal projects at most sites, the 15% environmental extraction constraint will be the limiting factor. Using data from a feasibility study developed by Polagye et al., 2006, we can consider the following example of power density determination and computation of number of TISEC that can be installed:

The following example of a design for Cairn Point, Alaska, taken from Polagye et al., 2006, illustrates how a hydrokinetic installation can be configured. The channel at Cairn Point has a substantial average cross-section (73,200 m^2), yielding an average flow power of 114 MW. Table 2-2 and Figures 2-8 and 2-9 illustrate the site's characteristics.

Table 2-2. Relevant Site Design Parameters (Source: Polagye et al., 2006. Used with permission)

Site Characteristic	Value
Channel Width	2,490 m
Average Depth (from MLLW)	29 m
Deepest Point	59 m
Maximum Tidal Range	12 m
Seabed Type	Dense, Silty Sand

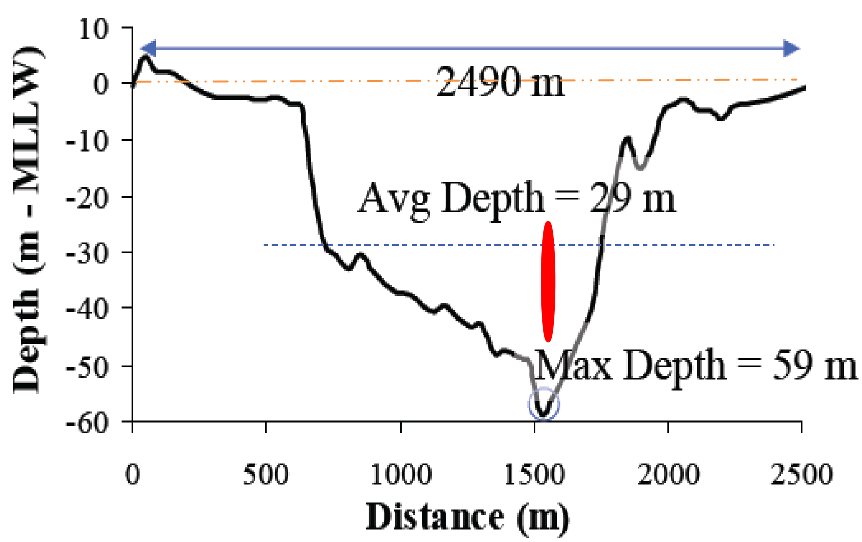


Figure 2-8. Cross section at Cairn Point with one design rotor depicted as red oval and MLLW highlighted as an orange dot-dash line (Adapted from: Polagye et al., 2006).

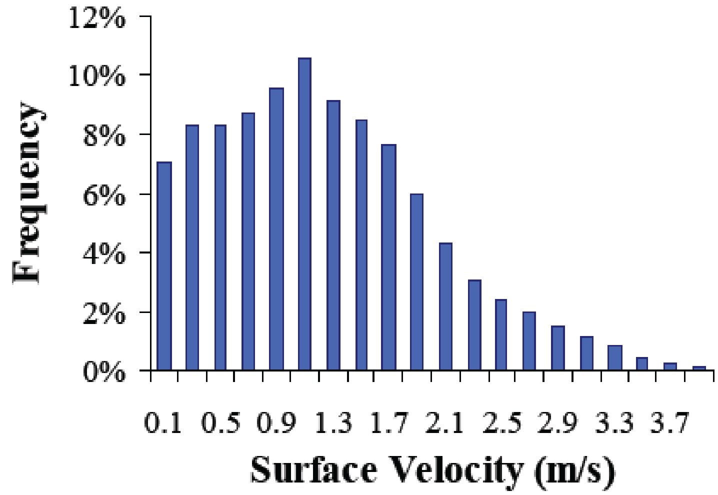


Figure 2-9. Tidal Current Histogram for Cairn Point
(Source: Polagye et al., 2006. Used with permission)

Using the above power equation, and considering the velocity with 50 percent frequency (according to Figure 2-9), the power density at Cairn Point is 1.6 kW/m^2. The average power available is equal to power density (kW/m^2) multiplied by channel cross-section (m^2). The average power available at Cairn Point is 114 MW, considering an area of 72210 m^2 (channel width multiplied by the average depth - MLLW).

The average power extractable is 17 MW. According with the studies developed by EPRI (Polagye et al., 2006), and with the characteristics of the site, a Lunar Energy TISEC was choose as the best option for Cairn Point, considering the ice and sedimentation condition in this site.

The Lunar Energy TISEC device, known as the Rotech tidal turbine (RTT) (Figure 2-8), which is a horizontal axial turbine located in a symmetrical duct. The commercial unit of this kind, the RTT 2000, is designed to produce 2MW from a 7.2 knot tidal stream. Table 2-3 shows details and specifications of the RTT – 2000.

EPRI estimated device performance for the RTT-2000 at the Cairn Point (Polagye et al., 2006), based on the product of rotor efficiency, gearbox and generator efficiency. Based on this efficiency chain and the exposed duct inlet area the device performance at Cairn Point was calculated as shown in Table 2-4. For a commercial array, the mean installation depth for an RTT-2000 would be 48 m.

The following definitions are used in Table 2-3:

- Flow velocity is depth adjusted using a 1/10 power law and represent the bin midpoint of the fluid speed at hub-height of the TISEC device.
- Percentage cases represent the percentage of time the flow at the site is at the flow velocity.
- Percentage load represent the electrical output as a percentage of rated output of the device.
- Power flux shows the incident power per square meter at the referenced velocity.
- Flow power is the power passing through the cross sectional area of the device.
- Extracted power shows the amount of power extracted by the device.
- PTO efficiency shows the efficiency of the power take-off (generator, hydraulics).

Considering Table 2-4 and the velocity (1.47 m/s) used to calculate the power density at Cairn Point, the RTT-2000 shows a PTO efficiency of 61.5 percent and extracted power of 273 kW.

If the extracted power by the RTT-2000 is 273 kW and the average power extractable is 17000 kW (calculated before), we can say that the maximum number of devices to be installed at the Cairn Point will be 63 RTT-2000, in order to fall below the 15 percent extraction limit. (Figures 2-10 and 2-11).

Table 2-3. RTT-2000 specifications Optimized for Cairn Point Size (Source: Polagye et al., 2006. Used with permission)

Generic Device Specifications	**Description**
Power Conversion	Hydraulic
Electrical Output	Synchronized with Grid
Foundation	Gravity Base
Dimensions	
Duct Inlet Diameter	21 m
Duct Length	27 m
Duct Clearance to Seafloor	10 m
Duct Inlet Area	346 m^2
Hub Height above Seafloor	20.5 m
Weight Breakdown	
Structural Steel	780 tons.
Ballast	934 tons.
Total Installed dry-Weight	1,714 tons.
Power	
Cut in Speed	1.0 m/s
Rated Speed	2.55 m/s
Rated Power	1,082 kW
Capacity Factor	15%
Availability	95 %
Transmission Losses	2%

Table 2-4. RTT-2000 Device Performance at Cairn Point (Source: Polagye et al., 2006. Used with permission)

Flow Velocity (m/s)	% Cases	% Load	Power Flux (kW/m^2)	Flow Power (kW)	Extracted Power (kW)	PTO Efficiency	Electric Power (kW)
0.09	7.07%	0.0%	0.00	0	0	0%	0
0.28	8.28%	0.1%	0.01	4	0	1%	0
0.46	8.28%	0.6%	0.05	17	0	3%	0
0.64	8.74%	1.6%	0.14	47	0	8%	0
0.83	9.58%	3.4%	0.29	100	0	17%	0
1.01	10.54%	6.2%	0.53	183	0	29%	0
1.19	9.17%	10.3%	0.87	302	140	44%	62
1.38	8.51%	15.8%	1.34	464	221	57%	127
1.56	7.64%	23.0%	1.95	676	325	66%	216
1.75	6.01%	32.1%	2.72	943	455	71%	323
1.93	4.27%	43.3%	3.68	1274	615	73%	450
2.11	3.09%	56.9%	4.83	1673	809	74%	600
2.30	2.42%	73.0%	6.20	2149	1039	75%	780
2.48	1.98%	92.0%	7.82	2707	1310	76%	996
2.66	1.53%	100.0%	9.68	3354	1424	76%	1082
2.85	1.11%	100.0%	11.83	4097	1424	76%	1082
3.03	0.87%	100.0%	14.27	4942	1424	76%	1082
3.22	0.46%	100.0%	17.02	5896	1424	76%	1082
3.40	0.30%	100.0%	20.11	6966	1424	76%	1082
3.58	0.11%	100.0%	23.55	8158	1424	76%	1082
Average 1.14			1.79	620	249		176

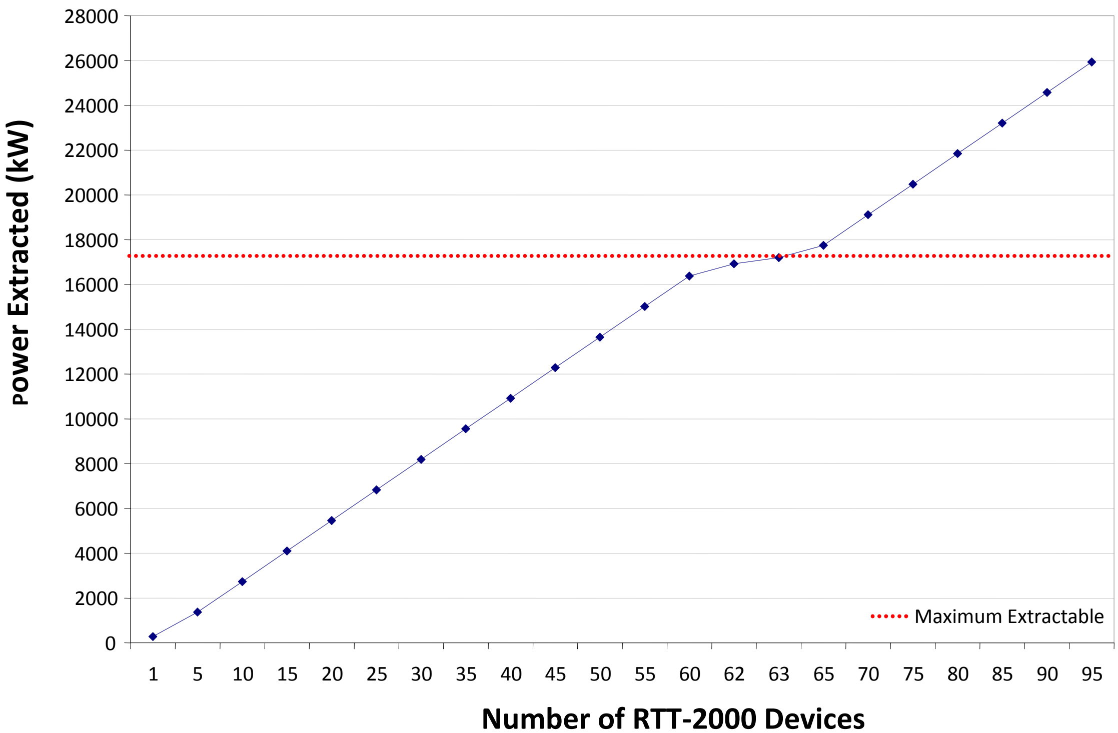


Figure 2-10. Power Available and Extractable at Cairn Point (Adapted from: Polagye et al., 2006)

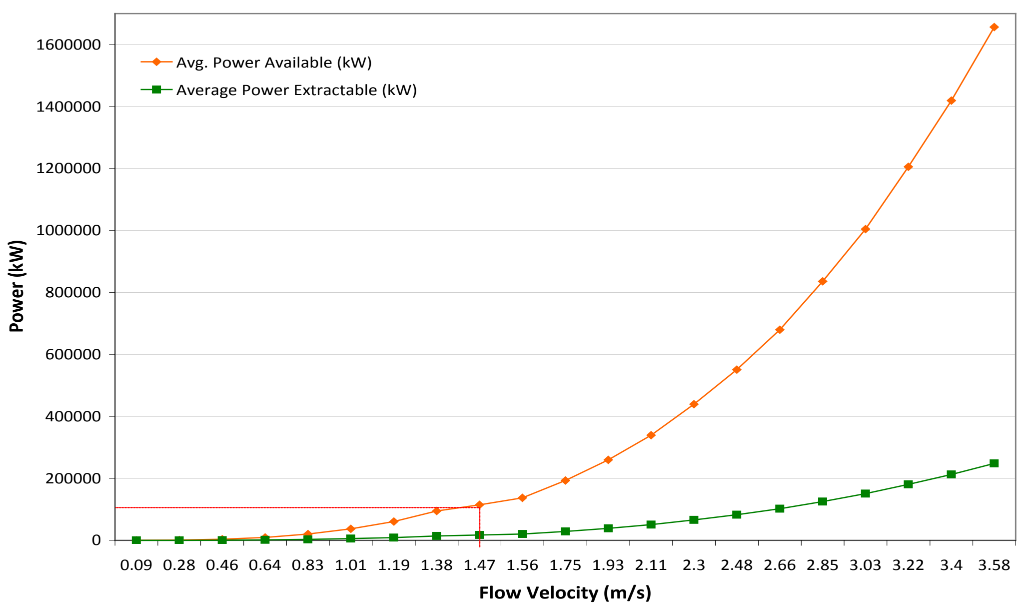


Figure 2-11. Number of RTT-2000 that can be installed at Cairn Point (Adapted from: Polagye et al., 2006) (Computations based on the velocity at 50% of frequency in the histogram)

3. HYDROKINETIC POWER EFFECTS

Advocates of hydrokinetic power correctly point out that it does not release greenhouse gases during operation, does not require construction of new dams, and does not present the aesthetic challenges of wind turbines. Like other renewable energy sources, it is promoted and subsidized in anticipation of providing environmental benefits at competitive prices. The Department of Energy has performed an excellent overall review of potential environmental effects from hydrokinetic power development (DOE, 2009) and only selected highlights of that report and specific concerns will be given here.

3.1 Legal and Economic Considerations

State and Federal policymakers in the U.S. have initiated efforts to promote hydrokinetic energy. For example, ocean energy is eligible for credit under renewable electricity standards in sixteen states, and for federal tax credits, expanded in the Energy Policy Act of 2005. Further, hydrokinetic energy development was proposed for increased research funding in the 2007 Energy Independence and Security Act (Union of Concern Scientists. 2009).

The U.S. Energy Policy Act of 2005 encourages the production of renewable energy from both hydroelectric power and ocean energy (tidal, wave, current, and thermal), and set requirements for the federal government to purchase not less than 7.5% of its electricity from renewable sources by 2013 (Cada et al., 2007).

The cost of hydrokinetic electricity will be a function of the power density of the flow (kW/m^2), distance the electricity must be transmitted, ease of access to a site for maintenance and monitoring, and availability of tax incentives. Fundamentally, sites with manageably stronger currents, all else being equal, will provide the lowest cost hydrokinetic electricity.

The siting of in-stream hydrokinetic projects require review by federal, state, and tribal agencies for effect on water rights, water quality, fish and wildlife (including threatened and endangered), cultural sites, recreation and public safety. In-stream hydrokinetic projects must be either licensed or exempted from licensing by the Federal Energy Regulatory Commission (FERC). FERC's licensing procedure is the framework within which all other environmental approvals must be obtained (Oram and O’Connell, 2008). Environmental protection laws may limit or prohibit hydrokinetic development in certain locations, such as waterways protected under the Wild and Scenic Rivers Act or those serving as habitat for threatened and endangered species.

3.2 Environmental Impacts

Table 3-1 lists potential environmental impacts of hydrokinetic energy identified by the U.S. Department of Energy (Cada et al., 2007).

Table 3-1. Aquatic environmental issues related to hydrokinetic energy (Source: Cada et al., 2007. Used with permission.)

Environmental Issue	Description of the Issue
Alteration of river/ocean bottom habitats	• Bottom habitats will be altered by securing the device to the bottom and running power cables to the shoreline. • Moving parts (rotors) and mooring systems could affect bottom habitat during operation. • Device may create structural habitat in open waters. • Structures may obstruct movements/migrations of aquatic animals.
Suspension of sediments and contaminants	• Deployment and operation may disrupt sediments and buried contaminants and increase turbidity. • Erosion and scour may occur around anchors, cables, and other structures.
Alteration of hydraulics and hydrologic regimes	• Movement of the devices will cause localized shear stresses and turbulence that may be damaging to aquatic organisms. • On larger scales, extraction of energy from the currents may reduce the ability of streams to transport sediment and debris, cause deposition of suspended sediments and thereby alter bottom habitats.
Strike	• Fish and other aquatic organisms, diving birds, and mammals may be struck by moving parts of the devices (e.g., rotors). • Large mobile animals may become entangled in submerged cables.
Impingement on screens	• Screens used to protect the machine or to reduce strike could themselves injure aquatic animals.
Effects of electromagnetic fields	• Electromagnetic fields associated with all of these devices may attract, deter, or injure aquatic animals.
Toxicity of paints and other chemicals	• Paints, cleaners, hydraulic fluids and chemicals used to control befouling may be toxic to aquatic plants and animals.
Noise	• Noise during construction and operations may attract, or injure aquatic animals.
Effects of multiple units	• Effects on hydrologic regimes, sediment dynamics, and strike determined for single machines may be very different than a full deployment of dozens or hundreds of machines.

In the specific case of streams the following parameters were identified as stream ecology concerns by conventional hydropower projects, and may be factors in hydrokinetic installations (Cada et al., 2007; Cada and Meyer, 2005):

- *Hydraulic factors. Shear stress and turbulence will be created near rotors that may injure aquatic organisms or scour nearby sediments. On a large scale, dozens or hundreds of rotating machines or wave energy converters may alter the hydrologic regime and cause large areas of sediment scour or deposition.*
- *Sediments. Disruption of the sediments during installation will alter the bottom habitat and may increase turbidity or release buried contaminants. Sediment disruption may be a temporary event associated with installation, or may continue during operation owing to movements of the rotors or of unsecured power and mooring cables. The "Extraction of kinetic energy" affects the ability of water body to transport sediment; indicating a possible impact on transport and suspension of bed load. Also, sediment size and composition are very important for the organisms that live there, as well as how uniform that sediment is. Some organisms need cobble and gravel to carry on their life cycle.*
- *Habitat. Natural streams provide habitat for resident fish, plants and other types of organisms. Some organisms require cobble stream beds to spawn, whereas silt is the preferred habitat for other species. Is important to consider any change in the habitat, because its affects the life cycle of the organisms that depend on that habitat. Rivers also serve as highways for upstream and downstream movements of organisms. This includes constant, passive drift of aquatic invertebrates and seasonal drift of fish eggs and larvae, these passive drifters are weak swimmers, so they don't have much ability to avoid an obstruction. Other organisms that may be affected by the presence of hydrokinetic turbines in the river include reptiles, diving birds, and mammals. They may be struck by the rapidly turning rotor and suffer injury or mortality. Screens used to exclude aquatic animals from the machine will reduce power productions and may they cause injury if the organism is impinged against the screen.*

Other uses of natural streams which might be affected by hydrokinetic power include:
- Commercial navigation (considered in the following section)
- Recreational navigation
- Swimming, skiing, etc.
- Commercial and recreational fishing
- Municipal, industrial, and agricultural discharges and withdrawals
- Effects of electromagnetic fields
- Noise during construction
- Toxicity of paints

These effects will depend on the design, size, and numbers of turbines and the site-specific characteristics of their locations and their relative significance compared with the impacts of vessel traffic, water withdrawals and discharges, and existing structures.

Power extraction limits of 10 to 20 percent are often cited in examples of hydrokinetic power units as the maximum amount that can be removed without substantial environmental effects. This range is largely based on work reported by Bryden and others (e.g., Bryden, et al. 2004, Bryden and Couch 2006) who examined the average change in water level and flow velocity of power extraction from schematic tidal waterways and found that extracting 10 percent reduced the average current speed by 3 percent and extracting 20 percent reduced average current speed by 6 percent.

We performed a simple backwater calculation using the standard step method (e.g., Mays 2005) to solve the one-dimensional, steady, gradually varying conservation of mass and energy equations, respectively, for flow in a rectangular channel:

$$Q = Vhb = \text{constant} \qquad 3\text{-}1$$

$$\frac{d\left(h+z\right)}{dx} + \frac{d}{dx}\left(\alpha \frac{V^2}{2g}\right) + S_f + S_E = 0 \qquad 3\text{-}2$$

Where Q = discharge, V = flow speed, h = water depth, b = channel width, x = distance along the channel (positive downstream), z = elevation of the bed, α = kinetic energy cross-sectional average coefficient, S_f = friction losses from boundary friction, and S_E = energy loss from extraction, expressed as a slope. Velocity and depth are functions of distance x and the friction slope is calculated by the Manning Equation (for SI units):

$$S_f = \left(\frac{Vn}{R^{2/3}}\right)^2 \qquad 3\text{-}3$$

Where n = roughness coefficient and R = hydraulic radius, or cross-sectional area divided by wetted perimeter. The energy loss from extraction was calculated as a percent of kinetic energy averaged over a reach.

$$S_E = \beta \frac{V^2}{2g} \qquad 3\text{-}4$$

Where β = fractional reduction in kinetic energy. This will be greater than the actual power delivered to the hydrokinetic generator, since the structure and generator housing will offer form resistance to the flow that does not contribute to the electric power generated. We have not estimated the ratio between power depleted from the stream and generated power, but

Polagye (2009) calculated it to be about 1.5, i.e., to get one unit of generational capacity will require 1.5 units of energy be extracted from the stream.

Equations 3-1 through 3-4 are highly simplified in order to enable rapid calculations over long channel reaches. They lack dynamic effects of time variation and nonlinear, three-dimensional processes typical of rivers; however they are useful for identifying the problems which might arise and require closer, more careful examination. Polagye (2009) has modeled these processes in a 1-dimensional unsteady model for tidal flows.

Table 3-2 shows the values used in the calculations, which are typical of a large river where a hydrokinetic generator might be installed. Results of the calculations with no energy extraction, i.e., β = 0, are shown in Figure 3-1. Distances are shown as negative, upstream from the specified tailwater elevation, such as when the reach ends in a reservoir that is large compared to the river. Total energy (expressed as total head (m) for consistency) declines from about 3.6 m to 3.1 m in the downstream direction as friction dissipates it. Water depth falls also; and since discharge remains constant in this example, velocity increases in the downstream direction. It should be noted that we have not calculated channel choke conditions, since that would be an overwhelmingly adverse effect and unlikely to be permitted at any scale.

Table 3-2. Values used in example calculation of energy extraction hydrodynamic effects.

Variable	Value
Discharge, *Q*	10,000 m^3/sec
Roughness Coefficient, *n*	0.025
Length of Channel, *L*	2,000 m
Bottom Slope $S_o = \frac{z_{upstream} - z_{downstream}}{L}$	0.0001
KE Coefficient, *α*	1
Channel Width, *B*	2,000 m
Acceleration of Gravity, *g*	9.81 m/sec^2
Tailwater Depth, $y_{downstream}$	3 m
Extraction Loss Fraction, β	0 to 30 %

Number of Cross-sections	8

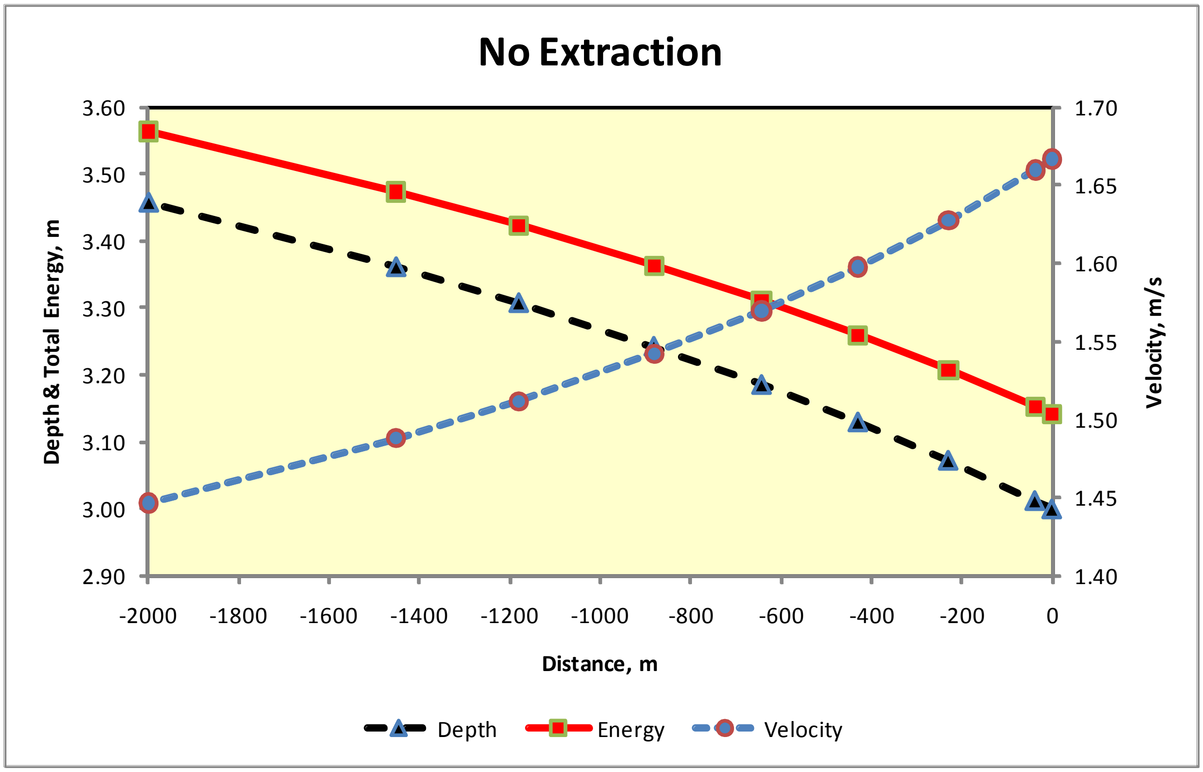


Figure 3-1. Solution of Mass and Energy Conservation for Representative River Channel with Only Friction Losses.

The solution shown in Figure 3-1 can be used as the base condition for examining some hydrodynamic effects of hydrokinetic energy extraction. Figures 3-2 a, b, and c illustrate the effect of a 10 percent extraction rate in one cross-section at about 650 m upstream from the tailwater. Depth and total energy at the upstream end of the reach increase over the no-extraction case by about 0.3 and 0.2 percent, respectively, and speed decreases by about 0.3 percent. This somewhat non-intuitive result can be explained by noting that with a fixed discharge; more upstream head is required to push the specified discharge through the reach if we extract some of the kinetic energy artificially. These results are qualitatively similar to those of Bryden and Couch (2006) but not identical, since that study assumed a constant headwater as well as tailwater elevation and used a 40-m-deep, 4000-m-long channel.

The relatively modest changes in flow depth and speed in the above calculations is due to the characteristics of the case. Of the total energy in the flow, only about 3 percent is contributed by kinetic energy; whereas 97 percent is contributed by water elevation, or potential energy. Thus 10 percent of 3 percent is extracted by the generator, an effect that reduces the impact of the extraction but also reduces the fruitful power generation of the installation. Shallower water moving faster would show a large effect on total stream energy.

Since it sometimes suggested that lining large stretches of river with hydrokinetic generators will be needed to make a significant contribution to U.S. power needs (e.g., DOE, 2009), we repeated the above analysis to demonstrate the effect of a series of hydrokinetic generators over the entire 2000 m length of the representative river reach, i.e., one in each of the 8 computational reaches or about every 250 m. Those results are shown in Figures 3-3, a to c.

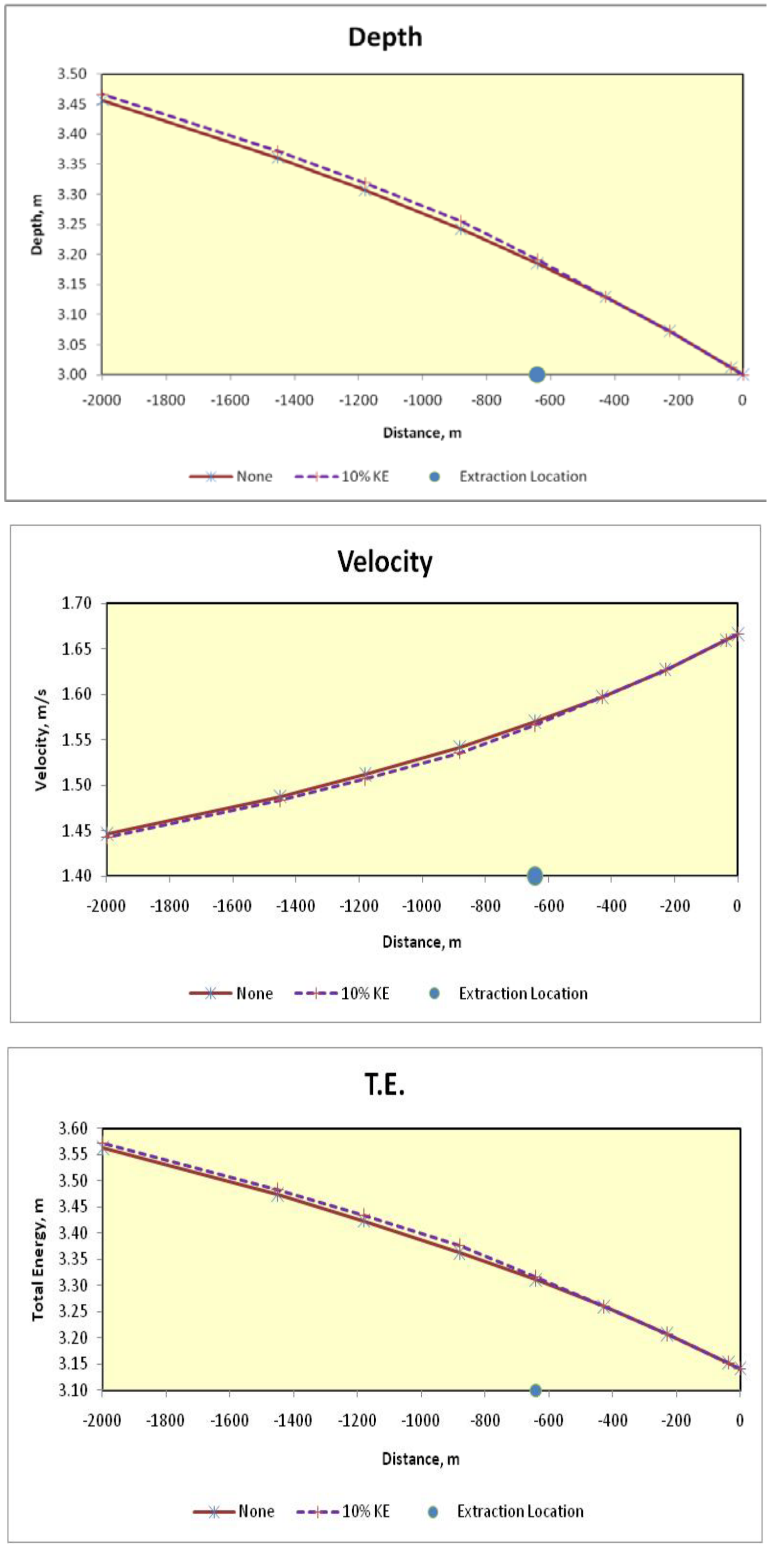
Serial energy extraction at a rate of 10 percent of the kinetic energy produces 2 to 3 percent changes in the total energy, depth, and velocity over the 2000-m-long reach of this case.

We examined the effect of serial energy removal rates up to 30 percent, and Figure 3-4 illustrates the results. Total energy is changed linearly at the rate of about 0.2 percent for each 1 percent kinetic energy extracted. Kinetic energy is reduced at a higher, but nonlinear rate of up to about 0.5 percent per 1 percent extracted.

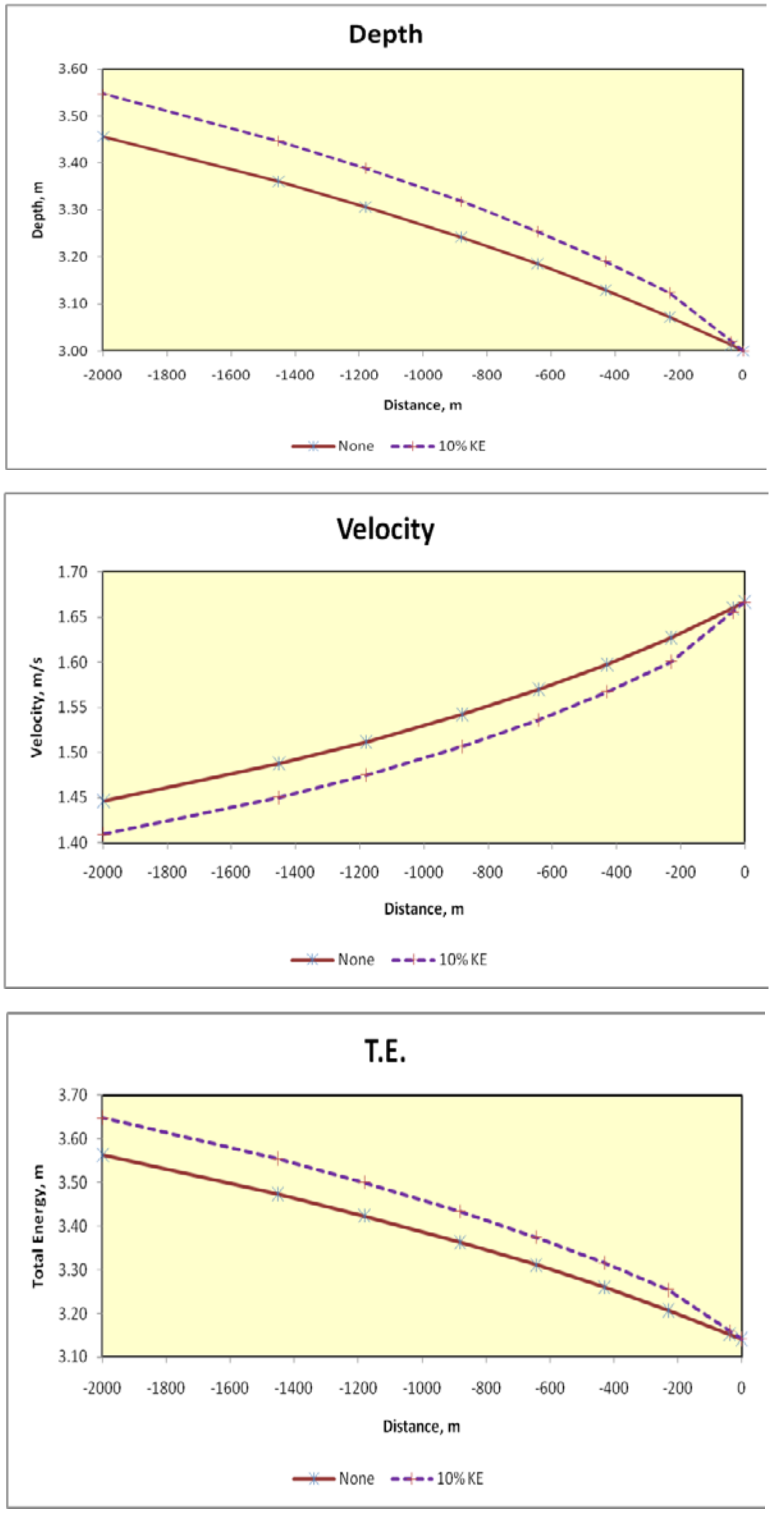
The results of this section show that extracting kinetic energy from streams, either tidal or non-tidal, can be expected to have a small, but not insignificant effect on flow depths, velocities, and energy available for other purposes donstream, upstream, or both. They also show that cumulative effects of multiple units can be substantial.

Biotic and abiotic materials transported by tidal or non-tidal flows will be affected by changes in flow depth and speed in a manner that depends on their size, mass and buoyancy. For example, materials in solution, such as nutrients and salts, will travel at the local speed (in three-dimensional space and time) of the water. Materials with negative or positive buoyancy, such as fish larvae and sediment grains, will move at or near the local velocity plus an incremental speed in the vertical that depends on their buoyancy. Sediment grains that settle to the bottom of the channel may stop moving for a time or move as bedload with a speed dependent on both the local flow speed and the shear stress exerted on the grains by the flow. The latter can be most easily expressed by the product of the kinetic energy and flow speed, changes in which are illustrated in Figure 3-5.

From Figure 3-6 we can see that a 20 percent rate of kinetic energy extraction produces approximately 5 percent reduction in flow speed, which would slow the transport of soluble and neutrally buoyant particles by that amount. Transport power, proportional to velocity cubed, is reduced by about 14 percent. These changes are contrasted to those from a single cross-section extraction of 20 percent in Table 3-3.



Figures 3-2. Effect of 10% energy extraction in one section on flow depth, speed, and total energy



Figures 3-3. Effect of 10% energy extraction in 8 sections on flow depth, speed, and total energy

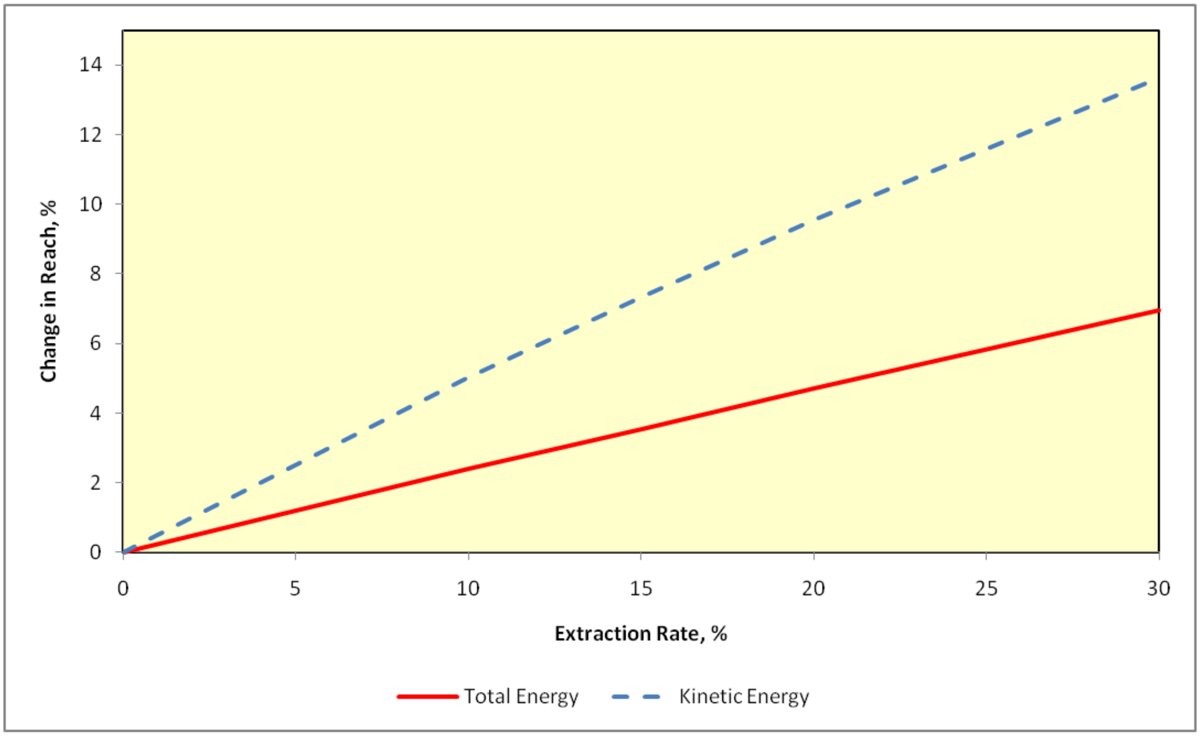


Figure 3-4. Effect of serial extraction rate over a 2000 m length of channel on energy change at the end of the reach.

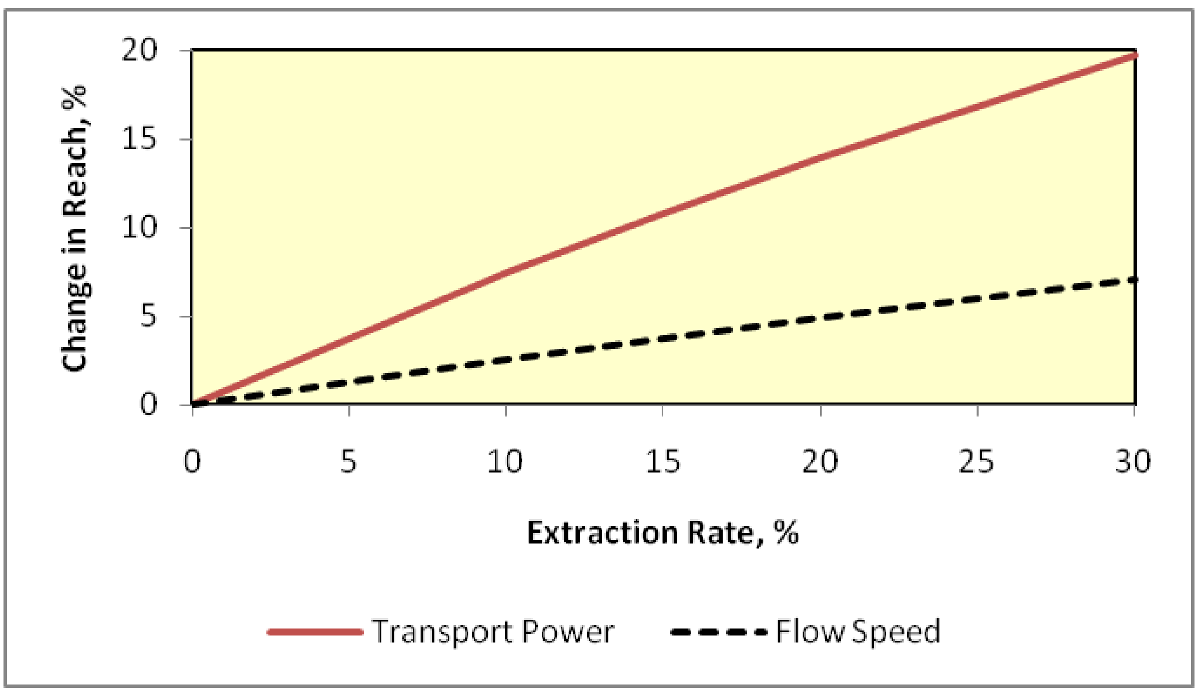


Figure 3-5. Effect of serial extraction rate over a 2000 m length of channel on transport power and flow speed at the end of the reach.

Table 3-3. Change of Single and Serial 20% Energy Extraction Rates on Flow and Transport Power in the Example 2000 m River Reach.

Parameter	Change (%)	
	Single Section Extraction	Serial (8 cross-sections) Extraction
Depth	+0.5	+5
Speed	-0.5	-5
Boundary Shear Stress	-1.0	-10
Transport Power	-1.6	-14

Both the reach example used here and its solution are highly simplified; however, the quantitative results are indicative of the relative impacts. A single hydrokinetic generator reducing the river's kinetic energy at one section by 20 percent will have a very small effect on transport within the reach – less than 2 percent – but it will be systematic, always reducing the transport capacity and extending that effect upstream and downstream to the next control point (e.g., a dam). A series of generators extracting 20 percent in each section will reduce the transport by 5 to 14 percent.

An increase in water depth and decrease in flow speed will also decrease the reaeration rate at the water surface, reducing oxygenation of the water column and affecting water quality. If deeper, slower flows alter the water temperature, biotic kinetics can be changed, by as much as seven-fold in some processes.

For the situation of a live active bed of sand-sized sediment and wash load of silt and clay size particles, these results indicate that increased sediment deposition within the reach is a certainty. For the single section extraction the increase won't be noticeable, but for the multiple extraction points deposition will increase by at least 10 to 14 percent, and if the shear stress is near a tipping point for deposition of fine sediment, i.e., near the critical shear stress for deposition, it could be higher.

Sediment and salt transport in tidal waters may be affected more subtly than these results suggest. Increased turbulence behind the generators can cause increased floculation of fine, cohesive sediment and increased downstream deposition (the "snow fence" effect). Deposition of fine sediment can be a channel maintenance problem or a habitat problem if deposition changes the substrate from suitable habitat such as oyster reef to mud bottom.

Salinity intrusion in estuaries is a process of largely nonlinear interactions between the buoyancy of fresh water and the mixing power of turbulent flows, with the end result sometimes seeming contrary to common sense. Depending on the site and its hydraulic characteristics, salinity at a given location may either increase or decrease with a change in mixing energy. Increases may endanger fresh water supplies and habitat, and decreases may also endanger habitat. A semi-quantitative consideration of salinity intrusion effects can be constructed by considering the Simmons Number, the non-dimensional ratio of the freshwater inflow to an estuary during a tidal cycle to the volume of water flowing in from the sea during that tidal cycle. High Simmons Number values are characteristic of highly stratified estuaries (with large intrusion lengths) and low values are characteristic of well-mixed estuaries (with smaller intrusion lengths) (USACE 1990). We can simplify the Simmons Number with the aproximation:

$$S = \frac{U_f}{U_T} \tag{3-5}$$

Where U_f = average freshwater discharge velocity and U_T = average tidal flow velocity. Sicne the above analyses have shown that kinetic energy extraction causes flow velocity to decrease, we can infer that upstream energy extraction will cause S to decrease, indicating more mixing (and thus reduced salinity instrusion); whereas downstream tidal energy extraction will cause S to increase, indicating less mixing (and thus increased salinity intrusion).

Precise resolution of the magnitude of these effects must be addressed by more sophisticated computations in multi-dimensional numerical models applied on a site-specific basis. However, from these results we anticipate that installation of hydrokinetic generators in tidal and non-tidal rivers can cause:

- Decreased flow speeds
- Altered water levels (positive or negative changes)
- Increased sediment deposition in the vicinity[1]
- Altered salinity intrusion (positive or negative changes) in estuaries
- Altered water quality
- Altered transport patterns and habitats

[1] Scour around the hydrokinetic structures themselves can be expected and treated in the design phase.

The degree, direction, and cumulative effects of these changes plus site conditions will dictate whether a specific site or region is suitable for hydrokinetic electricity generation or not.

While increased water levels, as are possible with energy extraction, are unlikely to be a problem for navigation, they could exacerbate flooding and should be addressed in site-specific evaluations.

4. EFFECTS ON WATERBORNE TRANSPORTATION

In addition to the environmental issues considered, there is concern that this technology could cause navigation problems, as evidenced in a June 2009 article in the Journal of Commerce. According to the journal one of the doubts about the new technology is: "What would happen if low water conditions forced barges into the deep water river bends where the turbines may be installed". In response, the Director of product development at Free Flow noted that turbines in the deep river bends below Baton Rouge will be below the 45 to 55 ft draft of the largest deepwater vessels and will also be out of the way of Corps dredging (The Journal of Commerce, 2009).

In another communication dated July 2009 (AWO, 2009), The American Waterways Operators (AWO) commented on FERC integrated licensing of Free Flow Power Cooperation's (FFP) seven proposed lead projects at Greenville Bend, Scotlandville Bend, Kempe Bend, Ashley Point, Hope Field Point, Flora Creek Light and McKinley Crossing. Some of the suggestions and comments in this document are:

- *In order to ensure that proposed alternative energy projects do not pose risks to vessels, it is absolutely critical that FERC set up a formal process to coordinate with experts on navigation, safety and the environment from industry, the U.S. Coast Guard, and the U.S. Army Corps of Engineers (Corps) when projects are proposed for review. At this time, it is not clear whether FERC or FFP have reached out to the navigation specialists in the Corps, a step essential for this process, as is outreach and coordination with the Coast Guard and the maritime industry.*
- *Before a company is licensed to install alternative energy projects on or near the river, FERC should require the company to submit a detailed plan for how it will build and maintain the structures without interfering with the safety or movement of commercial vessels. In addition, the process must allow ample time for the public review of, and comment on, each site once the schematics are available.*
- *Before a license is issued, FFP or any future license holder should fully describe how maintenance of projects will be handled to avoid navigation delays or closures.*
- *The approval process should also require that turbines and associated equipment be sited in areas below the Low Water Reference Plane (LWRP) or 200-yr low river level, whichever is lowest, with a minimum 15-ft clearance between equipment and towboats and barges. The Corps is directed by Congress to maintain a channel depth of 45-ft south of Baton Rouge, and a 9-ft channel north of Baton Rouge for navigation.*
- *Project approval should require the marking of all sites with an electronic Automatic Identification System (AIS) signature which can be read on an electronic navigation chart. Working with the Coast Guard and industry to establish this requirement will greatly enhance the ability of vessels to safely navigate around turbines and other structures in the river.*

- *Since the river is ever changing, all studies should be site-specific and cumulative. The analysis should review the shifting of the navigation channel and bank to bank changes from year to year and throughout each year and assess the impact the turbines and associated equipment would have on the integrity of structures, including revetments, that maintain the navigation channel and protect against flooding. It should also include an evaluation of resultant scouring and silting in the channel and potential damage to all engineering structures and navigation, dredging, dredge of material disposal, bank erosion and sediment transport.*
- *Each site should be required to produce of an individual Environmental Impact Statement (EIS).*
- *The studies should verify that electrical current that the projects will create in the river is not potentially harmful to vessel personnel and cargo. AWO suggests that FERC review carefully the man overboard studies done on the electric fish barrier on the Illinois Waterway that clearly state that, given certain circumstances, a very small electrical current in the water can cause injury or death.*
- *AWO urges FERC to require FFP to examine the operational realities of the barge industry and take them into consideration during the review of each proposed project. Each site may be impacted by the location of fleeting areas, rapid currents or velocity changes influenced by bridges or other naturally occurring or manmade structures and narrow bends and a variety of other unique river challenges, for this reason seven proposed lead sites can not be considered representative sample for its other 48 proposed sites.*

AWO also raised specific concerns related to some of the proposed sites (AWO, 2009).

Consider the schematic navigation channel shown in Figure 4-1, with a vessel traveling through a straight, uniform channel. In the end view the areas available for a hydrokinetic installation are shown as shaded – either within the design channel width but below the design depth (vessel draft plus underkeel clearance) as shown by the cross-hatched area or outside the design channel prism to either side as shown by solid shading. The possibility of a vessel striking the hydrokinetic generator must be considered in two cases – a "vertical strike" in which a vessel strikes a generator placed in the channel below normal maximum draft, and a "lateral strike" in which a vessel strikes a generator beyond the sides of the design channel.

The water level for design depth in tidal waters is commonly specified as a mean low tide elevation, typically either mean low tide or mean lower low tide. Neither is the minimum water level that a channel will experience during a year, since maximum spring tides with lower levels contribute to the "mean" value used. In non-tidal waterways the design water level is often taken as the lowest 15-day running average of mean water level during the navigation season. Again, lower levels can be expected to occur, such as during droughts.

Variations in the water level datum for a channel plus vessel motion effects (squat, trim, etc.) are accommodated by a design underkeel clearance, comparable to a safety factor. Channel underkeel clearance may be based on the probable consequences of a vessel making contact with the bottom, e.g., dependent on how hard the bottom is (rock beds will damage a vessel more than mud beds) and consequences of a spill or grounding. Generalities are very difficult, since every channel is designed specifically for local conditions, but we can say that underkeel clearances will have to be re-evaluated for any channel with hydrokinetic generators within the cross-hatched area of Figure 4-1, since vessel contact with a hardened rotor is likely to be catastrophic for the generator and possibly expensive for the vessel.

Vessels which stay within the channel alignment at all times will not be in danger of lateral strikes on hydrokinetic installations in the solid shaded areas of Figure 4-1 – side areas. If currents are relatively weak and parallel with the channel axis and wind is not a factor then a vessel will have little difficulty maintaining its position within the channel. However, wind and/or cross currents require the pilot to compensate with vessel steering to cause a crab angle, which is the difference between the vessel heading and the direction of motion. This "crabbing" effectively makes the vessel use more of the channel width at a specific cross-section. Similarly, moving through channel bends requires more width than straight channels. In either case, vessels may stray from the channel limits on occasion, putting them at risk for collision with off-channel hydrokinetic installations.

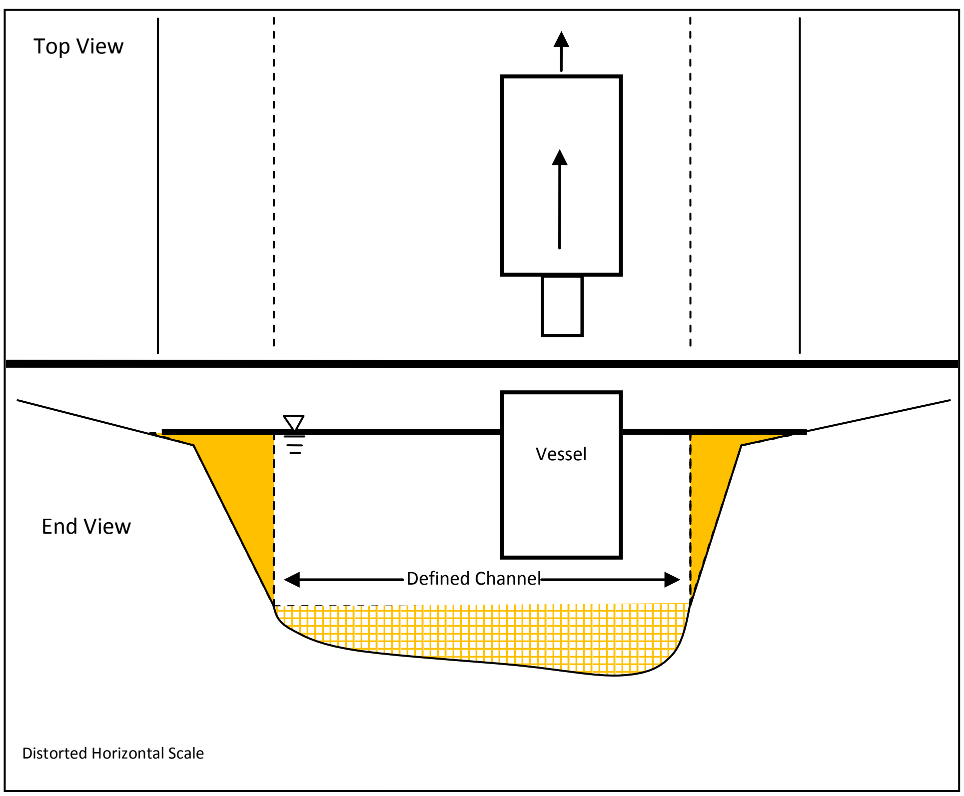


Figure 4-1. Schematic of channel with vessel in transit. Shaded areas outside the prism lines represent potential hydrokinetic generator location sites.

As an example of vessel traffic passing outside channel limits, consider Figures 4-2 and 4-3. The vessel (a tow in this case) is outside the nominal channel before and after making the turn. In this case the intrusions are fairly small, but under adverse conditions they may become large and put any structure outside the channel at risk, including hydrokinetic installations.

Figure 4-2 - Tow path through channel turn (Courtesy of US Army Corps of Engineers Research and Development Center)

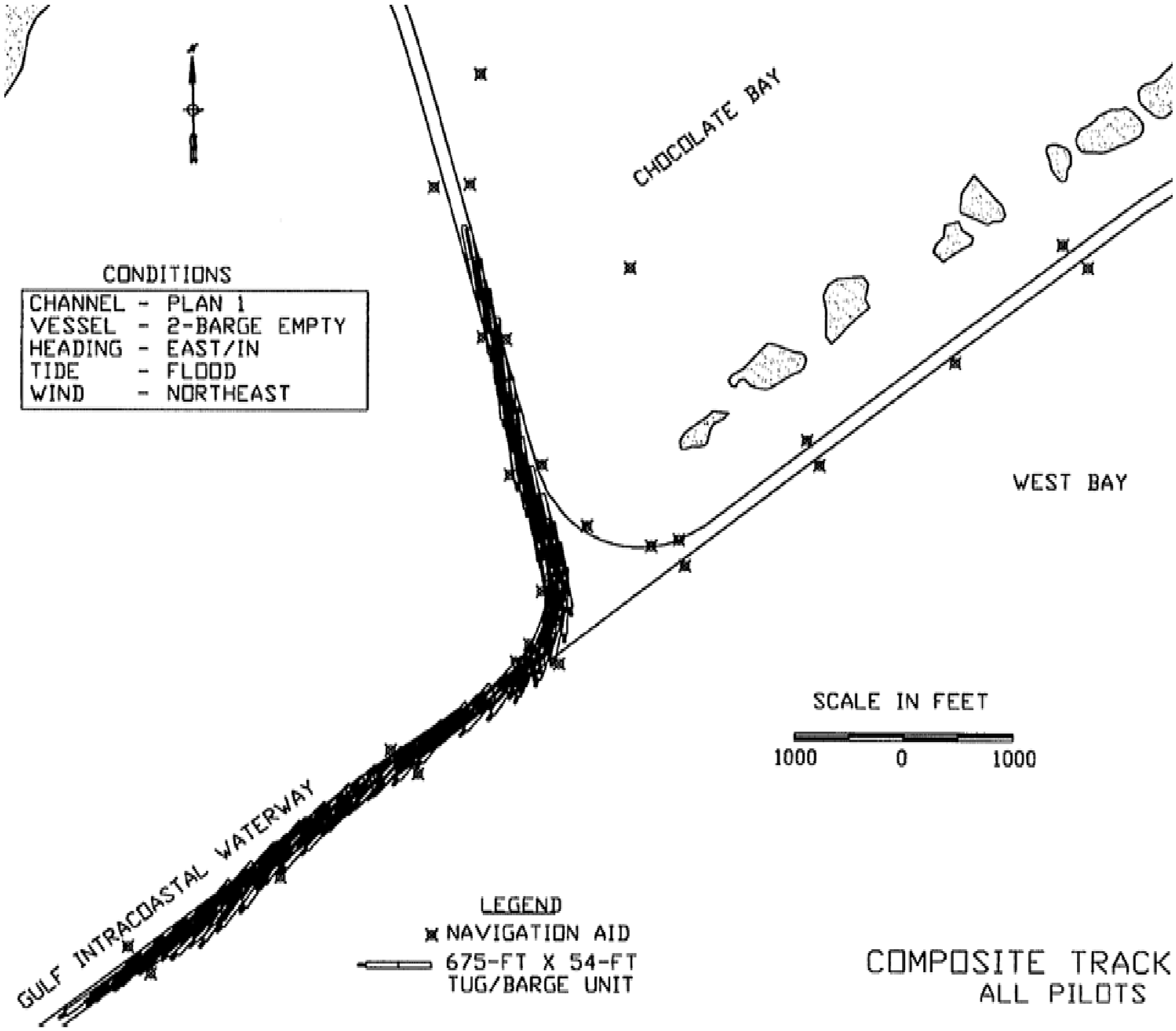


Figure 4-3. Composite of multiple passes through a navigation turn. (Courtesy of US Army Corps of Engineers Research and Development Center)

Rigorous estimates for the probability of vessel collisions with hydrokinetic structures is beyond the scope of this paper. However, an instructive example can be found in an analysis by Le Blanc and Rucks (1996) for a sample of 936 vessel accidents occurring in the Lower Mississippi River between 1979 and 1987. The channel length with reported accidents is approximately 250 miles. This information may be used to create a rough estimate of vessel accidents, as in:.

$$Rate = \frac{936 \;\; Accidents}{250 \;\; Miles \cdot 9.0 \;\; Years} = 0.42 \frac{accidents}{year \cdot mile}$$

These previous data includes all accidents, of which 207 were collisions, 422 rammings, 297 groundings and 10 unknown. Ramming is the contact of a vessel with a fixed object, while grounding is contact with the river bottom, nearly always occurring outside the lateral channel boundaries. If we assume that both ramming and groundings are caused by the vessels leaving the marked navigation channel, as shown in Figure 4-4, the calculation may be made again with 719 accidents instead of 936. The rate of out-of-channel lateral strike accidents would then become 0.32 per year-mile.

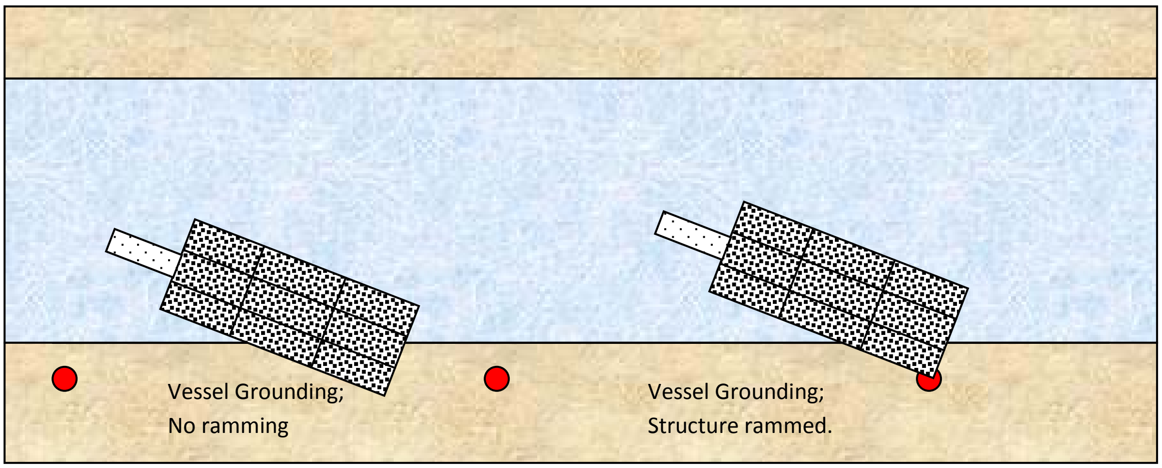


Figure 4-4 - Plan View of Possible Vessel Grounding and Lateral Strike

Applying a rate of 0.32 out-of-channel accidents per year-mile and roughly 2000 miles of channel in the Mississippi River, we might expect about 640 out-of-channel accidents reported per year. We cannot apply this number directly to predicting strikes of hydrokinetic installations. It may be too high, since the installations will not form a solid wall along the river, or it may be too low, since many (or more likely, most) excursions outside the channel limits do not cause accidents and are thus not reported.

This type of analysis does not include a potential increase in accident rate from vessels attempting to avoid striking a well-marked hydrokinetic installation near, but not in the channel. If such installations are proposed, navigation simulations can provide insight into the likelihood of other collisions and/or the need for channel modifications.

A rigorous approach to calculating lateral strike probabilities is to develop a probability distribution curve for vessel location in various types of channels – straight, sharp and smooth bends – under various environmental conditions – aligned with current and wind, cross-current and wind – etc. either by observations or vessel simulator, then apply the appropriate distribution function to a specific reach for which a hydrokinetic installation is planned. The probability of excursion to the installation location times the number of annual vessel transits will provide an estimate of the lateral strike probability. Figure 4-5 illustrates how the probability distribution might look for a Gaussian path distribution, but the actual distribution may well be non-Gaussian.

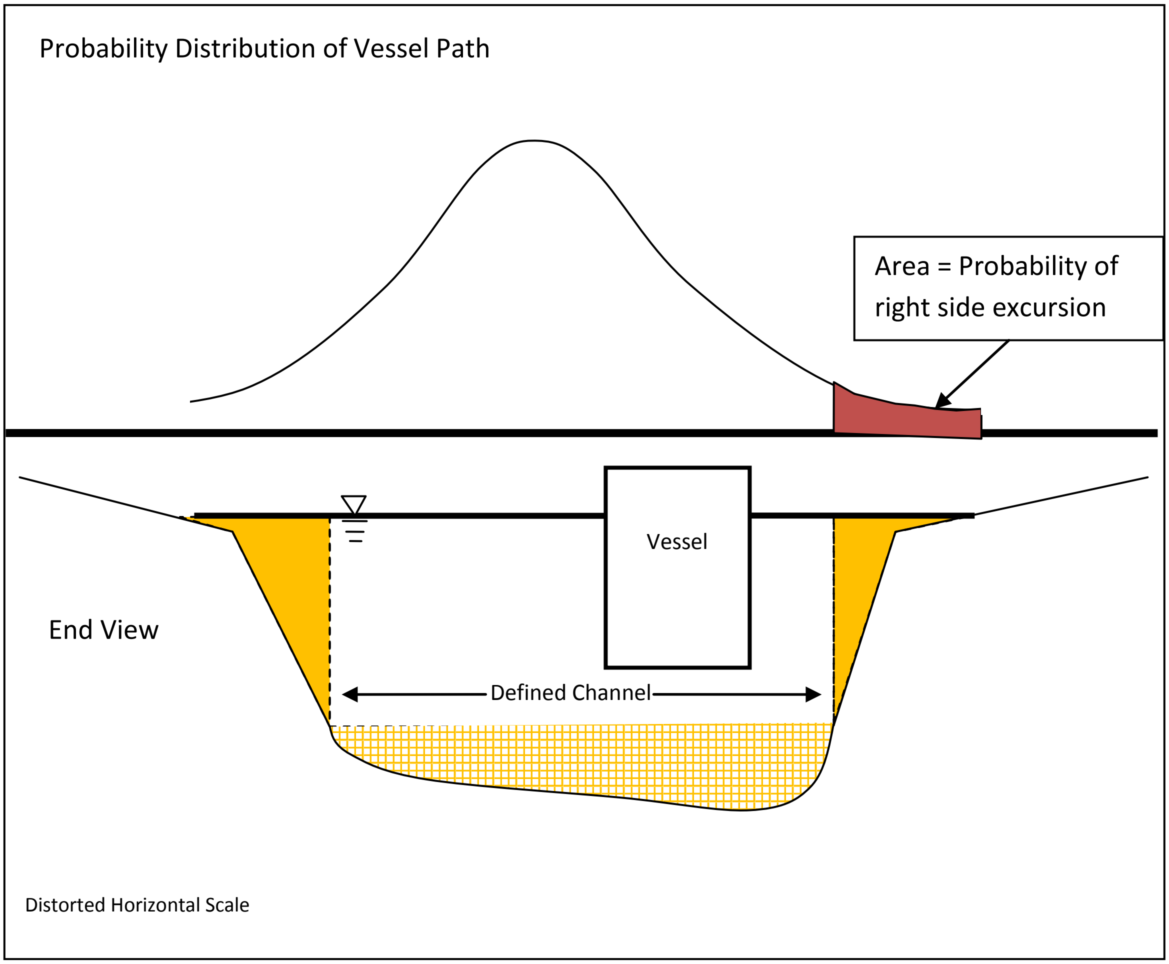


Figure 4-5. Application of Path Probability to Calculate Excursion Probability

The previous chapter estimated changes to flow depth and speed under various scenarios of hydrokinetic energy extraction. In general, the changes can be characterized as deepening and slowing the flows by small amounts, although cumulative effects of hydrokinetic extraction over considerable channel lengths could be significant. Decreased flow speed could be either a plus or a minus for navigation interests, depending on the direction of travel; however, deeper channels will always be better for navigation.

5. CONCLUSIONS AND RECOMMENDATIONS

This report reviews hydrokinetic power – generators capturing some of the kinetic energy of natural water flow – in the context of its potential effects on navigation projects of the U.S. Army Corps of Engineers.

Hydrokinetic power generation offers the potential to make a significant contribution to U.S. electricity needs by adding as much as 20,000 to 30,000 MW to the present 75,000 MW of hydroelectric power generation capacity. About a third of that potential occurs as in-stream generation in tidal and non-tidal rivers and in estuaries. Among its attractive features, hydrokinetic operations do not contribute to greenhouse gas emissions or other air pollution and because the installations are underwater, they have less visual aesthetic impact than wind turbines.

The Corps of Engineers mission to provide safe, sustainable, and effective Federal navigation projects requires a careful examination of hydrokinetic installation effects on navigation. Possible effects include increased risk of waterborne vessel accidents, including collisions with hydrokinetic structures, and environmental effects that impinge on navigation projects' safety, sustainability, and effectiveness.

Potential effects of hydrokinetic installations on navigation include:

- Decreased flow speeds
- Altered water levels
- Localized bed scour around the installation (near field)
- Increased sediment deposition in the vicinity (far field)
- Altered salinity intrusion in estuaries
- Altered water quality
- Altered transport patterns
- Altered habitats
- Increased vessel accidents

The degree, direction, and cumulative effects of these changes plus site conditions will dictate whether a specific site is suitable for hydrokinetic electricity generation or not.

The likelihood of a vessel striking a hydrokinetic installation depends on the configuration and site conditions. For installations shallower than vessel draft lying outside lateral channel limits, a rate of 0.32 rammings per year per mile of channel is a reasonable estimate for the Mississippi River until more rigorous studies can be made. For installations below channel design depth a risk-based study of the combined probability of low water conditions and vessel motion will be required to estimate the number of accidents.

We recommended that the Corps of Engineers review applications for hydrokinetic installations based on:

- Ratio of total energy loss to energy generation for various hydrokinetic installations defined by large scale lab experiments
- Site-specific 3-dimensional numerical model study of each proposed installation with energy extraction based on equipment performance and above extraction ratio
- Consideration of individual and cumulative environmental effects on water level, flow speed, sedimentation, salinity intrusion, water quality, and habitat
- Site-specific probabilities of vessels striking the installation or suffering another accident in trying to avoid the installation.

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