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REVIEWS

Ecology of fishes in a high-latitude, turbid river with implications for the impacts of hydrokinetic devices

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Abstract Hydrokinetic devices generate electricity by capturing kinetic energy from flowing water as it moves across or through a rotor, without impounding or diverting the water source. The Tanana River in Alaska, a turbid glacial system, has been selected as a pilot location to evaluate the effects of such a device on fish communities that are highly valued by subsistence, sport, and commercial users. The basic ecology and habitat use of fishes in turbid glacial systems are poorly understood; therefore it is necessary to study the species composition of the fish community and the spatial and temporal patterns of mainstem river use by these fishes to evaluate impacts of a hydrokinetic device. In this document, we provide an overview of existing knowledge of fish ecology in the Tanana River and impacts of hydrokinetic devices on fishes in other river systems. Seventeen fish species are known to inhabit the Tanana River and several may utilize the deepest and fastest section of the channel, the probable deployment location for the hydrokinetic device, as a seasonal migration corridor. Previous studies in clearwater river systems indicate that mortality and injury rates from turbine passage are low. However, the results from these studies may not apply to the Tanana River because of its distinctive physical properties. To rectify this shortcoming, a conceptual framework for a comprehensive fish ecology study is recommended to determine the impacts of hydrokinetic devices on fishes in turbid, glacial rivers.

Keywords Hydrokinetics · Tanana river · Turbine · Glacial river · Salmonid · Smolts

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Introduction

In-stream hydrokinetic devices generate electricity by capturing kinetic energy from flowing water as it moves across or through a rotor, without impounding or diverting the water source (Cada et al. 2007). These devices may aid in alleviating the high cost (>US$1 per kW h) of diesel-generated electricity in remote communities near large rivers. For example, Alaska has many villages located along large, turbid glacial rivers and most of them are not connected to the main electrical grid supplying power to the state's large cities. Hydrokinetic turbine projects are either being developed or considered for many of these rural communities. Development projects are actively under construction at Eagle and Ruby, both on the Yukon River, while feasibility studies are being conducted for the communities of Whitestone and Nenana on the Tanana River and Igiugig on the Kvichak River (Previsic et al. 2008). Other communities that have been considered for hydrokinetic projects are Manley Hot Springs on the Tanana River, Pilot Station on the Yukon River and Juneau near the Taku River (Previsic and Bedard 2008) (Fig. 1). All of these rivers are large, glacially fed systems with high turbidity, fast current and heavy siltation.

To guide the development of hydrokinetic resources in these rivers, Nenana, Alaska, on the Tanana River, has been chosen as a site for developing a conceptual framework for deployment of in-stream hydrokinetic devices throughout the state. Part of this framework is understanding the fishery resources at each potential deployment site and how hydrokinetic devices may impact them.

Hydrokinetic devices can impact fishes directly, such as when the fish and the turbine use the same part of the river at the same time, or indirectly, such as when the installation or operation of the device causes changes to the river environment (Cada et al. 2007). Examples of direct impacts include blade strikes and pressure differentials encountered by fish actually passing by or through the device while examples of indirect impacts may include chemical or electromagnetic changes to the water or alteration of river hydraulics resulting in increased sedimentation (Table 1).

To evaluate the potential impact of hydrokinetic units on fishes, it is necessary to understand the species composition of the fish community, the temporal and spatial patterns of river channel use by the fish community, the overlap in time and space between the hydrokinetic device and the fish community, and how fishes may potentially interact with hydrokinetic devices.

Fisheries scientists have an incomplete understanding of how fishes use river channels in large, glacially influenced systems and how they may interact with a hydrokinetic device. Therefore, the objectives of this review are to: (1) compile information about the species composition and mainstem river use of the fish community in a large, turbid glacial river, the Tanana River, (2) review prior research on interactions between fishes in other environmental systems and hydrokinetic devices, (3) identify critical knowledge gaps that need to be filled in order to assess impacts of a hydrokinetic device on fishes in the Tanana River, and (4) propose a transferable conceptual framework to assess impacts of hydrokinetic devices in turbid rivers. To accomplish these objectives, we reviewed all available literature, including peer-reviewed journal articles and agency and consultant reports.

Overview

Hydrokinetic devices

All of the hydrokinetic projects currently under consideration in the state are small in scope, employing single turbines of low power output and

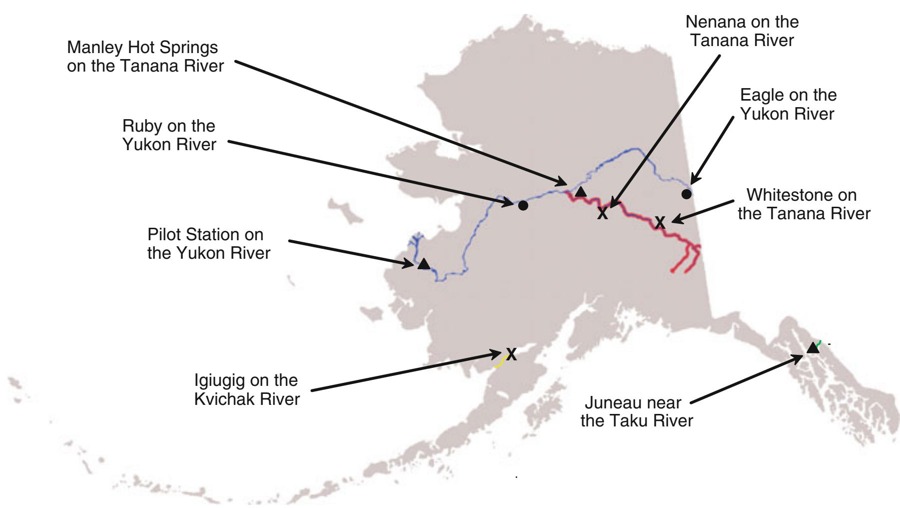


Fig. 1 Rural communities located along turbid, glacial rivers in Alaska that are sites of active development projects (*circles*), conceptual deployment framework studies (×), or projects under consideration for in-stream hydrokinetic devices (*triangles*)

Table 1 Potential environmental issues associated with the deployment of hydrokinetic devices in riverine habitats (identified by Cada et al. 2007)

Environmental issue	Brief description of the issue
Strike	Fish and other aquatic organisms may be struck by moving parts of the devices (e.g. rotors)
Impingement on screens	Screens used to protect the machine or to reduce strike could themselves injure aquatic animals
Alteration of river bottom habitat	Bottom habitats will be altered by securing the device to the bottom and running power cables to the shoreline. Moving parts could affect bottom habitat during operation
Suspension of sediments	Deployment and operation may disrupt sediments. Erosion and scour may occur around anchors, cables, and other structures
Alteration of hydraulics and hydrological regimes	Movement of the devices will cause localized shear stress and turbulence that may be damaging to aquatic organisms. On larger scales, extraction of energy from the water may reduce the ability of streams to transport sediment and debris, and thus cause deposition of suspended sediments and thereby alter bottom habitats
Effects of electromagnetic fields	Electromagnetic fields associated with these devices may attract, deter, or injure aquatic animals
Toxicity of paints and other chemicals	Paints, cleaners, hydraulic fluids and chemicals used to control biofouling may be toxic to aquatic plants and animals
Noise	Noise during construction and operations may attract, deter, 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 of machines

limited to summer-only operation. The long term goals of the projects however, are to evolve to multiple device arrays that can operate year round to economically generate electricity in the winter, when electrical demand is highest. Because river characteristics and operating conditions are drastically different from summer to winter, a variety of turbine designs are being appraised. Each design has unique features and properties that can be tailored to the demands of the project and the characteristics of the deployment site.

The designs being considered for Alaska can be classified by the orientation of their rotational axes as horizontal turbines, vertical turbines or crossflow turbines. Horizontal turbines (Fig. 2) have axes parallel to the water flow or inclined into it and usually have propeller-type rotors, similar to wind turbine designs. They can be anchored to the riverbed or inverted and suspended from a floating platform. Vertical turbines, also known as "egg beaters," have vertical axes perpendicular to the water flow and the water surface. Current hydrokinetic projects under development in Ruby and Eagle utilize vertical turbines with an H-Darrieus rotor configuration (Fig. 3). Crossflow turbines (Fig. 4) have axes parallel to the water surface but orthogonal to the flow. The rotor of this design resembles a waterwheel or a helical structure. In-stream applications of crossflow turbines usually have a lower profile in the water column and are suitable for use in shallower rivers. These turbines are usually submerged. The Nenana hydrokinetic project is being developed to employ crossflow turbines.

In addition to the design of the turbine, there are a number of placement options for hydrokinetic devices (Fig. 5). Turbines can be anchored to the riverbed in a bottom structure mounting, suspended from a barge in a floating structure mounting or attached to a shore-based structure that positions the rotor closer to the surface in a Near-surface Structure Mounting (Khan et al. 2009). Each of these mounting configurations positions the device in a different portion of the river channel and therefore can be selected to match the characteristics of the river in which it is located.

Study site

The Tanana River in Alaska is the largest tributary of the Yukon River, with a drainage of 115,250 km^2 extending over 1,000 km from its headwaters to its confluence with the Yukon River (Fig. 1). The village of Nenana is located on the Tanana River approximately 260 km upstream of its mouth. Glacial-melt runoff and associated sediment loads dominate the river's hydrology and channel morphology (Durst

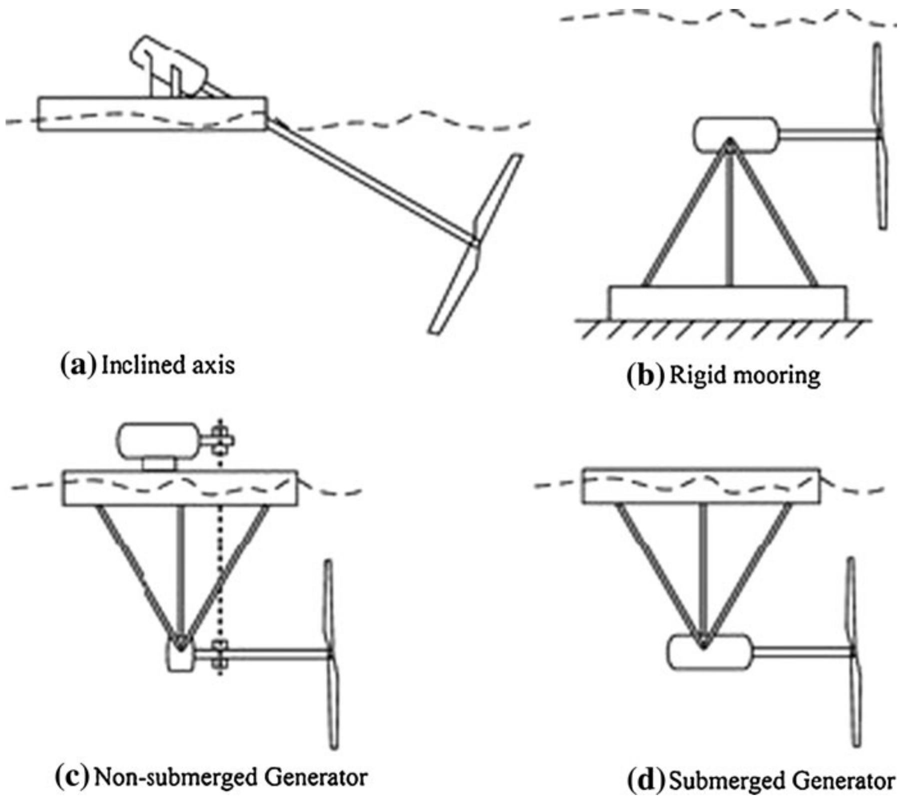


Fig. 2 Examples of horizontal axis turbines that are suspended from a floating structure or anchored to the riverbed with submerged or non-submerged generators (reprinted with permission from Khan et al. 2009)

2001). Like other subarctic, glacial rivers, the Tanana River has a dynamic, but predictable, flow regime. During the ice-free period (May through mid-October), the Tanana River is a high-energy, braided, silted river, with shifting bed load and a variable discharge (Fig. 6). When frozen (November through mid-April), it is a moderate-energy, split channel, clear-water river, with stable bed load and discharge (Durst 2001).

Fish community

Seventeen known fish species, both anadromous and resident, use the Tanana River drainage. They display a variety of life history strategies and habitat preferences. The life history patterns and habitat selection of fishes in the Tanana River are not fully understood, particularly for sub-adult fishes. This is due, in part, to the system's size, complexity, high turbidity and large woody debris during the majority of the ice-free season, which limits research and observation. In the following sections, the ecology of fishes in the Tanana River is reviewed, with particular emphasis placed on aspects of each fish species' habitat use which may result in interaction with a hydrokinetic device. The fishes are categorized into groups based on their life history types: resident non-migratory, resident migratory, and anadromous (Table 2). Information for some fishes is not available for the Tanana River and therefore these are not reviewed. In some cases, behavior and habitat use is inferred from studies conducted on the same species in similar river systems.

Habitat use by Tanana river fishes

Resident, non-migratory

Lake chub (*Cousius plumbeus)*, longnose sucker (*Catostomus catostomus)*, and slimy sculpin (*Cottus cognatus)* are widely abundant resident species in the Tanana River (Table 3). They are of no commercial, sport or subsistence value, but represent important forage species for other fishes, as well as birds and mammals. River margin sampling studies have

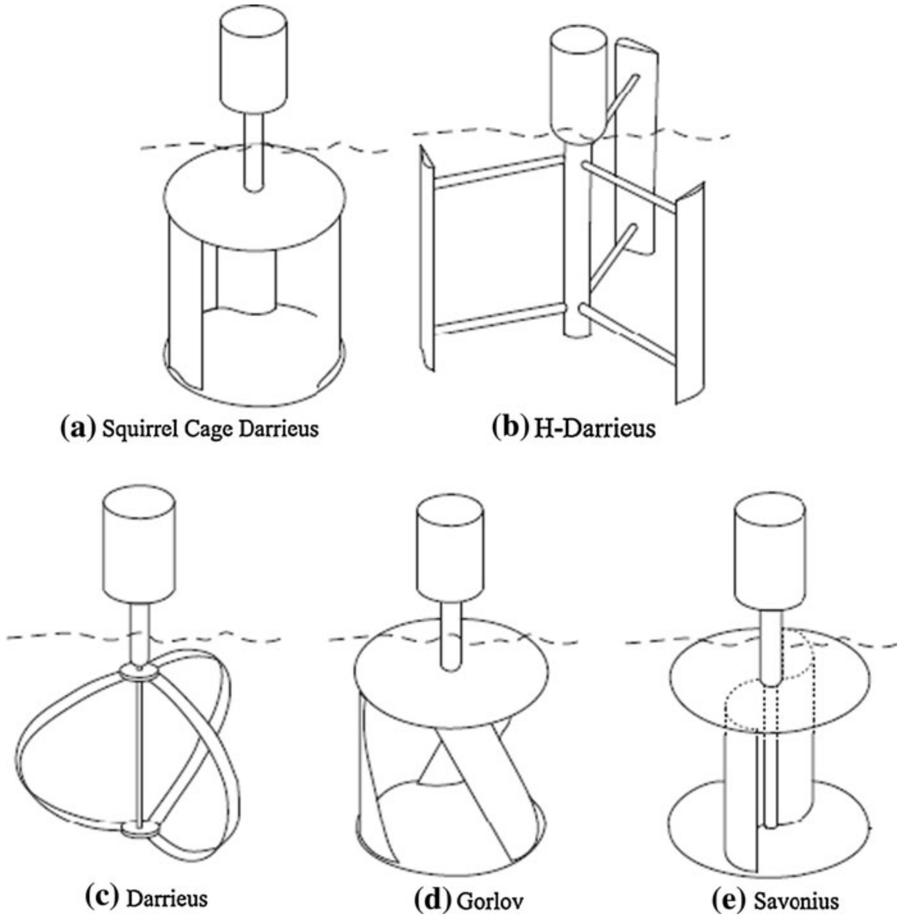


Fig. 3 Examples of vertical axis turbines (reprinted with permission from Khan et al. 2009)

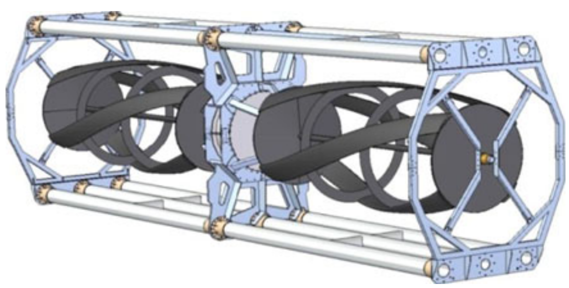


Fig. 4 Example of a crossflow turbine with the axis orthogonal to the river current as in this design proposed for the Nenana, Alaska hydrokinetic project (image courtesy of Ocean Renewable Power Company)

consistently found these three species to be the most common fishes found in the Tanana River drainage (Chen 1968; Mecum 1984; Ott et al. 1998).

Lake chub are commonly found in the margins of the Tanana River mainstem (Durst 2001; Hemming and Morris 1999), but it is unknown whether they utilize the swifter, deeper portions as well. Bottom dwellers that feed on aquatic insects, algae and small fishes, lake chub are frequently captured in clearwater sloughs and tributaries (Hemming and Morris 1999). Young-of-the-year inhabit shallow backwaters over silt and sand substrates in water velocities of less than 30 cm s^{-1}, while adults are generally found in deeper water over gravel and rubble-cobble substrates where velocities exceed 30 cm s^{-1} (Mecum 1984). Little is known about lake chub spawning behavior in the Tanana River. In lakes they often migrate into streams to spawn in shallow water over rocky substrates and gravel, but they have also been observed spawning over silt and leaves (Brown et al. 1970; Roberge et al. 2002).

Longnose suckers are abundant throughout the Tanana River drainage. Younger fish are usually found in shallow backwaters over fine substrates and older fish are found in deeper water with larger particle size substrates (Roberge et al. 2002; Ott et al. 1998). Young-of-the-year spend most of the ice-free season in

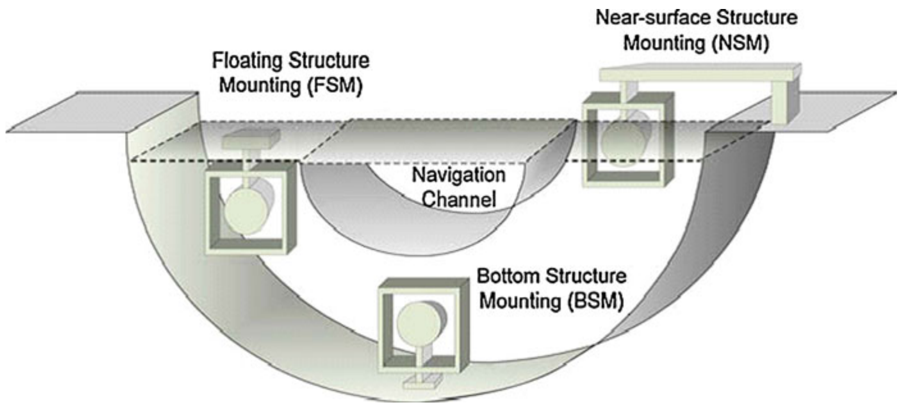


Fig. 5 Examples of mounting configurations for a hydrokinetic device in a river channel (reprinted with permission from Khan et al. 2009)

Fig. 6 The braided and turbid Tanana River with Fairbanks, AK, USA in the background (photo courtesy of US Army Corps of Engineers)

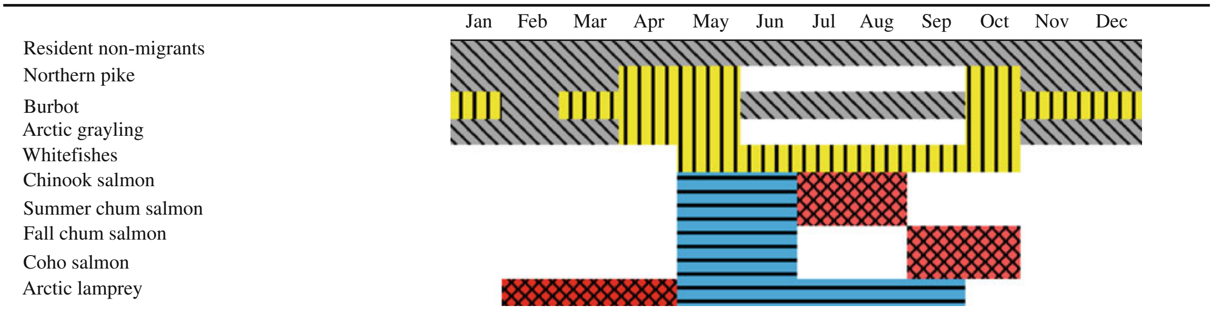
shallow water habitats (up to 9 cm) in very low water velocities (less than 9 cm s^{-1}) with aquatic emergent vegetation and sand and silt substrate (Mecum 1984). Juveniles and adults tend to occupy greater depths with higher velocities and substrates of larger particle size (Mecum 1984; Scott and Crossman 1973; Ott et al. 1998). In most of their range in North America, longnose suckers' primary habitat is in clear, cold-water lakes (Roberge et al. 2002), but they are also common in rivers and tributary streams and are found in both glacial and brackish waters (Scott and Crossman 1973). In early summer, they migrate into tributary streams to spawn over gravel and cobble substrates in 10–60 cm of water with velocities of 30–45 cm s^{-1} (Geen et al. 1966; Scott and Crossman 1973). Adults tend to return to lakes immediately after spawning (Morrow 1980) while young-of-the-year and juveniles can be found in tributary streams and mainstem river margins until freeze up. It is not known whether they utilize the swifter center portions of the Tanana River for migration or overwintering.

Table 2 Fishes of the Tanana river categorized by life history types

Resident non-migratory	Resident migratory	Anadromous
Lake chub (*Couesius plumbeus)*	Arctic grayling (*Thymallus arcticus)*	Chum salmon (*Oncorhynchus keta)*
Longnose sucker (*Catostomus catostomus)*	Humpback whitefish (*Coregonus pidschian)*	Coho salmon (*Oncorhynchus kisutch)*
Slimy sculpin (*Cottus cognatus)*	Least cisco[a] (*Coregonus sardinella)*	Chinook salmon (*Oncorhynchus tshawytscha)*
Nine spine stickleback[a] (*Pungitius pungitius)*	Broad whitefish[a] (*Coregonus nasus)*	Arctic lamprey (*Lampetra japonica)*
	Round whitefish[a] (*Prosopium cylindraceum)*	
	Sheefish or inconnu (*Stenodus leucichthys)*	
	Northern pike (*Esox lucius)*	
	Burbot (*Lota lota)*	
	Dolly varden char[a] (*Salvelinus malma)*	

[a] Species not reviewed due to lack of literature available

Table 3 Approximate timing of movement of selected fishes in the Tanana river



Gray represents residency with limited movement; yellow represents movement of resident fishes; red indicates upstream movement of anadromous adults to spawning areas; blue represents downstream movement of anadromous juveniles to rearing areas. Resident non-migrant species include lake chub, longnose sucker, and slimy sculpin. Whitefishes include humpback whitefish, round whitefish, least cisco, broad whitefish and inconnu

Slimy sculpin are occasionally captured in the margins of the Tanana River mainstem, though they are common residents of clear headwater tributaries and lakes throughout the Tanana River watershed (Mecum 1984). They prefer moderate depths with gravel and rocky substrates. In one study, densities were highest in depths ranging from 20 to 30 cm at water velocities of 40–49 cm s^{-1} over medium-sized gravel substrates (Mecum 1984). Slimy sculpin are sedentary, benthic fish that exhibit limited movement except when they migrate into shallow waters to spawn (Birtwell et al. 2005; Morrow 1980). Spawning occurs in May, typically in the shallows of rocky streams or the stony shores of lakes (Roberge et al. 2002). The sculpin's sticky eggs are deposited on the underside of large rocks, tree roots, submerged logs, and other debris. The males are guarders that fiercely defend the nest from spawning to hatch (McPhail and Lindsey 1970; Morrow 1980). It is not known whether they utilize the swifter center portions of the Tanana River during any stage of their life history.

Resident, migratory

Arctic grayling (*Thymallus arcticus)* are popular sport fish found in many of the Tanana River tributaries. They are sight-feeding fish that require low-turbidity waters; therefore it is believed that they do not reside for long periods of time in the mainstem of the Tanana River during the summer months (Table 3; Tack 1980). However, they are believed to overwinter in deep sections of the river adjacent to the main current (Clark and Ridder 1988) and have been observed in large schools in December (Durst 2001).

Arctic grayling maintain a complex cycle of migratory behavior that puts them in the mainstem at different times of the year (Clark and Ridder 1988). Soon after the ice melts in early May, they undertake an upstream migration to spawning locations in unsilted, rapid-runoff tributary streams. Arctic grayling show fidelity to natal streams and juveniles follow adults to the spawning sites, which probably provides a mechanism for imprinting future migration patterns (Tack 1980), though the homing mechanisms used by this species have not been studied. After spawning, which usually occurs at the mouths of tributaries in riffled areas over gravel and rocky substrates (Birtwell et al. 2005), adults return to the mainstem to migrate downriver to clearwater tributaries to feed (Tack 1980). Juveniles follow adults to the feeding sites and it appears that Arctic grayling show considerable fidelity to feeding, as well as spawning, streams (Birtwell et al. 2005; Tack 1980).

For most of the summer, Arctic grayling reside in these feeding tributaries, where larger adults tend to occupy the headwaters and smaller fish are distributed downstream (Hughes 1998, 1999). Food variety for Arctic grayling is quite broad. While their primary diet is aquatic insects, they also feed on terrestrial insects, small fish, fish eggs and crustaceans. They are heavily dependent on consistent current velocities for drift feeding (Birtwell et al. 2005). Occasionally, sub-adults use glacial mainstem waters for cover while feeding in clearwater/glacial mixing zones and for feeding on chum salmon (*Oncorhynchus keta*) eggs in autumn (Durst 2001).

In advance of ice formation in autumn, all age classes of Arctic grayling migrate in a downstream direction to the mainstem of the Tanana River and other deep tributaries for overwintering (Tack 1980). Overwintering is probably the most critical period for Arctic grayling (Birtwell et al. 2005), yet winter habitat requirements are poorly understood. Once a suitable winter refuge is established, entire populations of grayling will migrate upstream and downstream to exploit it (Birtwell et al. 2005).

Burbot (*Lota lota)* are cold water, piscivorous, bottom-dwelling fish that prefer turbid water and are abundant throughout the Tanana River drainage (Table 3). They are popular as sport fish and important to subsistence users. Burbot feed, migrate and spawn primarily in the mainstem of the Tanana River (Mecum 1984; Breeser et al. 1988; Evenson 1993). During the summer, they feed on a variety of food sources, including other migratory fish species, and occasionally move into clearwater tributaries to feed in late summer (Breeser et al. 1988). They are largely sedentary, ambush predators (Roberge et al. 2002) but can have a relatively large range during feeding. There is evidence from other river systems that burbot actively move laterally in the river channel from bank to bank and vertically in the water column in their pursuit of prey that exhibit diel migration (Slavík et al. 2005), but this behavior has not been confirmed in the Tanana River.

In addition to lateral movements, they are known to travel, upstream and downstream, up to 225 km year^{-1} with greatest movements associated with river freeze-up and river ice-out (Evenson 1993). These migrations are likely associated with movement between feeding areas and spawning sites (Slavík and Bartos 2002) that burbot occupy in February in the main channels of the Tanana River (Breeser et al. 1988). Spawning activity is poorly understood due to the difficulty of sampling and monitoring spawning locations beneath the ice, but they appear to be orgiastic spawners; assembling in large aggregations to spawn with no apparent pairing of males and females (Evenson 1993).

Five coregonine (whitefish) species have been documented in the Lower Tanana River: humpback whitefish (*Coregonus pidschian),* round whitefish (*Prosopium cylindraceum),* least cisco (*Coregonus sardinella),* broad whitefish (*Coregonus nasus),* and inconnu *(Stenodus leucichthys).* All are locally important to subsistence users for human and canine consumption, and the largest, inconnu (sheefish), supports a local sport fishery as well. All age classes have been found in the Tanana River margins (Table 3), but lateral and vertical distribution within the channel is largely unknown. All of these species are capable of anadromy (Reist and Bond 1988), but the exact proportion of anadromy is unknown, as is whether anadromous and potamodromous fish use the river corridor differently. For the purpose of this review, whitefish will be considered as resident species, as they are in local management plans.

Of the whitefish species found in the Tanana River, humpback whitefish is the most studied. Adult humpback whitefish migrate from their overwintering locations in the mainstem of the river or in deep lake habitats into clearwater lake systems in the Tanana River valley each spring and early summer to feed (Alt 1979). During mid to late summer, they move into clearwater river habitat, where they are believed to feed exclusively (Bradford et al. 2008), and disperse widely throughout the Tanana River watershed (Brown et al. 2002).

By late fall, whitefish concentrate in lakes and in discrete regions along the Tanana River mainstem which are believed to be major spawning areas (Brown et al. 2002; Dupuis 2010). During spawning, eggs are broadcast over relatively deep riffles, where they incubate in the gravel through the winter and hatch in the spring. The emergent fry are carried downstream to a wide variety of rearing habitats, including river backwaters, off-channel lakes, and estuary regions at river mouths. Juvenile whitefish typically remain in downstream rearing areas until reaching sexual maturity, at which point they migrate back upstream to spawning areas in the fall. Migration behavior is poorly understood, but it appears that whitefish cease feeding during migration as individuals sampled from large, turbid rivers have had little or no food in their stomachs (Brown et al. 2002).

Local populations of inconnu (sheefish) reside in tributary streams of the Tanana River. The winter movements of these fish are poorly understood, but they probably overwinter in the Tanana River because of anoxic winter conditions in their clearwater feeding sites (Alt 1987). Inconnu appear to begin migrating back to feeding areas under the ice in small numbers in late April. Major movements of inconnu to these waters occur within 2 weeks after breakup (Alt 1987). Spawning occurs in late September and early October in fast-flowing, clearwater tributaries over gravel substrates in depths of 120–250 cm and it is thought that inconnu exhibit fidelity to natal sites (Roberge et al. 2002). Pre-spawning and immature fish are usually present in the Tanana River by mid-May (Alt 1987). Post-spawning migrations commence immediately after spawning (Alt 1987).

In addition to its value as a subsistence fishery, Northern pike (*Esox lucius*) is one of the most esteemed indigenous sport fish species in interior Alaska. Up to 90% of the state's annual northern pike harvest comes from the Tanana River drainage (Burkholder and Bernard 1994). Pike are slow-water, predatory fish that spawn, rear and mature in shallow areas of lakes, marshes, backwater sloughs and sometimes slow rivers (Roberge et al. 2002). They are common in many of the lakes, sloughs and tributaries of the Tanana River (Doxey 2007). Northern pike only move into the Tanana River mainstem in the fall (Table 3), as a refuge from the anoxic and/or ice conditions found in the winter in their preferred shallow habitat. Migrations in the mainstem of the Tanana River to and from overwintering areas are typically short (Doxey 2007) and a radio telemetry study of northern pike that overwinter in the Tanana River indicated no movement or dispersal of the fish within the river other than migration to and from winter refugia (Burkholder and Bernard 1994).

Anadromous

Of all the fish species that inhabit the Tanana River, the most important to local fisheries are anadromous populations of Chinook (*Oncorhynchus tshawytscha),* chum (*O. keta)* and coho (*O. kisutch)* salmon (Bradford et al. 2008; Table 3). All three species support subsistence, commercial and personal use fisheries in the Tanana River and its tributaries. Subsistence fisheries take an average of 1,700 Chinook salmon, 4,200 summer chum salmon, 18,500 fall chum salmon and 12,000 coho salmon (Hayes et al. 2008). Chum salmon harvests have dominated the historic catches and have been as high as 100,000 fish for the summer and fall chum salmon runs combined. Recent harvest averages are much lower and chum salmon was designated a stock of concern by the Alaska Board of Fisheries (Bue et al. 2004). Recovery was noted in 2007 and this designation has now been lifted.

Adult salmon use the main channel of the river as a migratory corridor when traveling to upstream spawning grounds during two time periods. The summer season (July to mid-August) is dominated by runs of Chinook and summer chum salmon that spawn in runoff tributaries. The fall season (mid-August to October) includes runs of genetically distinct fall chum and coho salmon (Borba 2007; Cappiello and Bromaghin 1997). Fall chums spawn from mid-October through November in several upper mainstem and tributary areas, while the coho's spawning distribution is limited to only clearwater tributaries (Ott et al. 1998). The peak of the coho run occurs in Nenana in mid-September (Borba 2007). Mainstem chum spawning sites are located in deeper portions of the channel, where groundwater upwelling through the gravel substrate helps to stabilize incubation temperatures and maintain levels of dissolved oxygen during the frigid winter (Cappiello and Bromaghin 1997). In large, swift rivers, up-migrating chum and coho salmon conserve energy by swimming close to shore and low in the water column where water velocities are slowest (Ransom et al. 1998; Daum and Osborne 1998). Chinooks, being generally larger and stronger fish, follow the same migration routes, but farther from shore in faster currents (D. Helmer, personal communication, 2010). The main channel of the Tanana River also serves as the smolt out-migration corridor for all three salmon species.

Age zero chum smolts begin their downriver migration soon after emergence from the river bed during ice breakup and their density in the mainstem of the Tanana River is greatest during the months of May and June (Hemming and Morris 1999; Durst 2001). In clearwater rivers, chum smolts travel at night and in large schools to avoid predation (Koenig 2002), but the long migrations of Tanana River chum salmon may require daytime travel as well. There is evidence that smolt predation is reduced by the turbidity of glacial waters (Gregory and Levings 1998) and this may provide enough protection from visual predators to allow the smolts to travel during daylight hours (Koenig 2002, Gregory and Levings 1998). Migrating chum salmon smolts must feed during their long migration (Durst 2001) but, as small, young-of-the-year fish, their ability to maneuver in the fast currents of the river mainstem is not well-understood. The chum smolts are abundant in the river margins during their migration (Ott et al. 1998), but it is not known if they use this portion of the river channel exclusively for feeding, or traveling as well.

Both Chinook and coho salmon rear in freshwater, where they feed and grow for one to several years before migrating to the ocean. Therefore, as larger fish, their ability to maneuver laterally and vertically throughout the mainstem river channel is probably better than the maneuverability of the chum salmon smolts. Juvenile coho salmon are found in the river margins in significant numbers during their outmigration (Ott et al. 1998) with peak abundance occurring in mid-May (Hemming and Morris 1999). In contrast, sampling with minnow traps and shallow water seines has been unsuccessful at capturing juvenile Chinooks in the margins of the Tanana River (Mecum 1984; Ott et al. 1998). It has been speculated that this is a sampling artifact resulting from the possibility that out-migrating Chinook salmon use higher velocity and deeper water in the center part of the channel, which is difficult to sample with traditional methods (Ott et al. 1998).

Juvenile Arctic lampreys (*Lampetra japonica)* are relatively common throughout the Tanana River drainage, but their ecology is poorly understood. They are benthic inhabitants when in freshwater and, have only been captured close to the bottom in the margins of the river mainstem (Mecum 1984; Bradford et al. 2008). Two forms of the Arctic lamprey spawn and rear in turbid glacial rivers; an anadromous type and a brook type (McPhail and Lindsey 1970) that is possibly a separate species (*Lampetra alaskensis*). Both forms spawn in the mainstem of the Tanana River, in medium water velocities over gravel substrate, between late May and early July (Roberge et al. 2002). Eggs hatch in a few weeks and larvae move immediately to river margins where they burrow into soft mud or sand substrate. The larval form, called ammocoetes, remain in the substrate for up to 4 years, feeding on drift detritus and decomposing post-spawn salmon carcasses (Kucheryavyi et al. 2007). Metamorphosis to the adult form occurs in the fall after they emerge from the gravel and they begin their migration to the sea or to downstream lakes (Roberge et al. 2002). Because so little is known about the complex life histories of Arctic lampreys, their migration behavior and river channel usage is unknown.

Impacts of hydrokinetic devices

There are well over 100 conceptual designs for hydrokinetic energy conversion and most of them have not been developed as full scale operational prototypes that can be tested in the field (USDOE 2009). Although most of the studies of these designs are predictive in nature and have not been verified (USDOE 2009), there have been a few operational studies undertaken and they can be useful in identifying common environmental risks associated with hydrokinetic technologies that can be applied to glacial rivers like the Tanana River and the fish that inhabit them.

Potential environmental impacts include: alteration of substrates and changes in sediment transport and deposition, emission of electromagnetic fields, blade strikes by turbine rotors, and changes in the hydrodynamics of the river (USDOE 2009; Cada et al. 2007).

Alteration of substrates and sedimentation

Because these devices extract energy from moving water, they alter local hydraulics by reducing downstream current velocities, which usually results in a higher deposition of sediment in the shadow of the device (Michel et al. 2007). Sedimentation disruption may change bottom habitats, especially during the installation process, and may also increase turbidity. During the ice-free season, this effect is likely to be inconsequential in glacial rivers due to their high natural turbidity, but it may impact fishes during the winter months when turbidity decreases. Excessive sedimentation of fine sand and silt over fall chum salmon redds can impede upwelling in areas with low vertical hydraulic gradients and may also act as a barrier to emergent fry (Burril et al. 2010).

Generation of electromagnetic fields (EMF)

A crucial component of any in-stream hydrokinetic project is a way to deliver the electricity to the onshore power grid, which is usually accomplished with a submerged cable. Current passing through a cable includes both an electric field and an induced magnetic field. The electric field can be completely contained by sealed insulative sheathing, but the magnetic field cannot be contained. Even burying the cable in sand or sediment will not reduce the strength of the magnetic field, which dissipates with distance from the cable (CMACS 2003).

A number of fish species, both freshwater and marine, can sense subtle changes in the Earth's magnetic field and appear to use this sensitivity for navigation or spatial orientation. At least four species of Pacific salmon belong to this group of fishes (Mann et al. 1988). While it is generally accepted that they use olfactory cues to navigate in freshwater (Dittman and Quinn 1996; Stewart et al. 2004) and would therefore be unlikely to be impacted by EMF, very little is known about the role of other homing mechanisms (Odling-Smee and Braithwaite 2003) and EMF may potentially disrupt the fishes' ability to navigate.

Strikes by rotor blades or other moving parts

The main direct impact of a turbine on fishes is a blade strike. The consequences of a blade strike vary in severity, ranging from non-lethal injury to mortality, which are directly related to fish characteristics, including size and orientation at the time of the strike, and turbine design, including angular velocity and shape of the blade (Deng et al. 2005; Cada 1997). Studies of direct impacts by hydrokinetic devices on various fish taxa have been conducted in other river systems and can be helpful in identifying potential risks to fishes and useful methodologies that can be adapted to Alaskan environments. A survival and injury study of fishes that passed through an in-stream hydrokinetic device was performed in 2008 on the Mississippi River near the city of Hastings, Minnesota. The project features a Floating Structure Mounted, horizontal turbine. The unit's rotor is 12 feet in diameter and its three blades spin at 21 RPM, making it the slowest spinning hydrokinetic turbine in the industry (Normandeau 2009).

In this study, adult bluegill (*Lepomis macrochirus*), yellow perch (*Perca flavescens*), freshwater buffalo (*Ictiobus niger and I. bubalus*) and channel catfish (*Ictalurus punctatus*) were marked with balloon tags and forced through the turbine. After passage through the device, the balloon tags were inflated and the fish floated to the surface of the water. The marked fish were recaptured and held for 48 h to evaluate the effects of turbine-passage, including blade-strike injuries, and immediate and latent mortality. For fishes that passed through the device, no turbine blade injuries were observed and the immediate survival rate was 99% while the 48 h survival rate was 100%, after adjusting for control group mortality (Normandeau 2009).

Several studies of fish entrainment in traditional dam turbines demonstrate that fish injury and mortality rates are positively correlated to the number of blades and the rotation speed of the turbine (Franke et al. 1997; Headrick 1998; Winchell et al. 2000). If this concept is transferred to hydrokinetic devices, the low injury and mortality rates observed in the Hastings study may possibly be attributed to the slow rotational speed and low number of blades in the device.

Exposure to altered water pressures

In addition to blade strikes, fish passing through a river turbine are exposed to a number of sudden pressure changes. To test the effect of these pressure changes, a series of studies simulated various turbine-passage pressure regimes in a hyperbaric chamber and evaluated the effects on three species of Columbia River fishes (rainbow trout (*Oncorhynchus mykiss*), Chinook salmon *(O. tshawytscha)*, and bluegill sunfish (*Lepomis macrochirus*) (Abernethy et al. 2001, 2002, 2003).

Pressure regimes were selected for two different dam turbine designs; a vertical axis Kaplan turbine, designed to be used in high-head applications (Abernethy et al. 2001; 2002) and a horizontal axis bulb-type turbine, often installed in low-head applications (Abernethy et al. 2003). Prior to each test, the fish were acclimated to different pre-test pressures; a low pressure to simulate surface oriented travel, and a higher pressure to simulate fish travel at depth. The fish were then exposed to various time/pressure scenarios and evaluated for immediate and latent (48 h) injuries and mortality.

The bluegills were found to be more susceptible to injury than either of the two salmonid species. Furthermore, the severity of their injuries increased when the fish were acclimated at greater pre-test pressures and then exposed to extreme pressure changes. It was also noted that the pressure regime a fish experiences in a vertical turbine is relatively uniform throughout the device and the potential for injury does not depend on the fish's trajectory through it. In contrast, in a horizontal turbine, the pressure changes to which the fish is exposed are highly dependent on where the fish enters and exits the turbine. Furthermore, the turbulence behind a horizontal turbine is directed upward and is more likely to move the fish vertically through different depths instead of horizontally in the water column, as it would be in a vertical turbine (Abernethy et al. 2003). Rapid pressure decreases are more harmful to fish than pressure increases (Cada 1997), thus the implication from these results is that fish passing through the horizontal turbine from depth are more likely to sustain injury than those entering from the surface.

All of the impacts outlined above have implications for in-stream hydrokinetic devices placed in the Tanana River. Changes in sedimentation can affect the habitat quality of the project area for benthic species like burbot and other species that may have specific substrate requirements for spawning or overwintering. Strong electromagnetic fields potentially may interfere with the navigation of migratory species, particularly those species whose migratory process is not well-understood, like whitefishes and Arctic grayling. Direct impacts, like blade strike and pressure differentials, can occur if there is overlap in spatial and temporal distribution between the fish and the turbine. In most cases, to maximize energy extraction from the river, the hydrokinetic device will be placed in the middle of the water column in the deepest and swiftest portion of the river channel. Therefore, it is necessary to consider the use of this habitat by fishes. Predicting potential direct impacts in this portion of the river channel is problematic due to critical knowledge gaps in the horizontal and vertical distribution of fishes in the Tanana River, particularly sub-adults.

Knowledge gaps

The most conspicuous knowledge gap for Tanana River fishes is the lack of information available about the spatial and temporal distribution of each species in the river channel. Lack of research in this area is understandable, as the fast currents and high debris load of this river during the summer make mid-channel sampling difficult and dangerous and the use of optical or acoustical technologies is limited by the woody debris and high turbidity of the water. Thick winter ice cover and destructive spring ice movements complicate research during the periods when the river water is clear. Findings from previous research on the same fish species in clearwater river systems may not be transferable to Tanana River fishes because of this river's glacial characteristics. For example, studies indicate that salmonid smolts in clearwater systems do not merely act passively in heterogeneous flows, but exhibit active swimming, maneuvering and avoidance of changes in water velocity and hydrostatic pressure (Kemp et al. 2005; Svendsen et al. 2007). However, it is not known if salmon smolts are capable of these evasive actions in highly turbid, fast-current rivers.

Also absent from nearly all existing literature about the ecology of fishes in turbid glacial rivers is data related to overwintering behavior. This is in spite of the fact that understanding winter habitat use is now recognized as critical to the management of many species. This knowledge gap is not new and was reported 75 years ago in a plea for more winter research of high latitude freshwater fishes (Hubbs and Trautman 1935). Reasons that the authors cited for the dearth of winter studies included: the inherent challenges of sampling ice-covered habitat; the lack of funding available for winter research; the shortage of qualified research personnel during the months that universities are in session; and, not surprisingly, the reluctance on the part of researchers to leave the comfort of their warm office responsibilities for the misery of winter fieldwork in high latitudes (Hubbs and Trautman 1935). These reasons are as evident today as they were 75 years ago, and many of the questions raised by Hubbs and Trautman (1935) remain unanswered: Where do fish overwinter and what do they eat? What are the habitat requirements of overwintering fish? What parts of the river do they use and what is their range of movement? These questions will become more important as in-stream hydrokinetic technology advances and more projects evolve to include winter operations when the demand for electrical conversion is greatest.

These inherent sampling challenges limit the body of information about habitat use by fishes in large, glacial rivers. As a result, fisheries scientists have a poor understanding of how fish, particularly juveniles, distribute themselves in large, glacial river channels such as the Tanana River, for residence and migration. This scarcity of information makes it difficult to predict the potential impacts of a hydrokinetic device placed in a particular part of a river channel.

Recommendations

Understanding the impacts of a hydrokinetic device on fishes in the Tanana River is essential to assuring sustainable development of alternative power sources without sacrificing historically important fisheries resources. We recommend conducting an in situ study that assesses potential and realized impacts of an in-stream hydrokinetic turbine on the fish community.

To assess potential impacts, it will be necessary to determine three dimensional spatial distributions of all life history stages of fishes in the river channel, both before and after deployment of a turbine. To accomplish this, we recommend fixed and mobile deployments of split-beam echo sounders to characterize fish abundance, size, horizontal and vertical distribution, and direction of travel through the turbine deployment area (Mueller et al. 2006).

To verify acoustic targets and capture larval fishes that may not be detected by an echo sounder, a variety of methods should be used to capture fishes throughout the river channel. Sampling in the middle of the river channel can present many challenges, but small vessels and fixed platforms, such as those from which some turbines are suspended, offer ideal opportunities for sampling this habitat.

To assess realized impacts of a hydrokinetic device on riverine fish communities, it will be necessary to monitor the behavior of fishes near the turbine and the health of fishes that actually pass through it. Because the Tanana River is turbid during the ice-free season, an optical camera cannot be used to observe fish behavior around the hydrokinetic device, therefore an alternative such as an acoustic imaging camera (i.e. DIDSON) will have to be employed. Because many small fish, especially salmonids, have similar appearances, species verification methods must be employed for acoustic imaging camera observations. To assess the health of fish that pass through a hydrokinetic device, it will be necessary to capture fish directly behind the turbine. These fish should be examined for gross external injuries caused by turbine blade strikes or collisions with the turbine attachment system. In addition, some fish should be held to determine latent mortality.

Winter sampling is important for identifying spawning, refuge or migration locations under the ice. Low turbidity of the water during the winter should make optical monitoring possible and capture sampling can be accomplished by deploying gear from stable ice surfaces. Winter sampling will fill critical knowledge gaps in our understanding of the ecology of the fish community and provide valuable baseline biological data in anticipation of future year-round hydrokinetic projects.

Conclusion

In-stream hydrokinetic devices represent a potentially important source of clean, renewable energy, especially in small, rural communities near rivers, such as Nenana, Alaska on the Tanana River. However, fisheries resources are cultural and economic mainstays of these communities, and before deploying a hydrokinetic device in the river, it is critically important to assess its impacts on the local fish species. To accomplish this, spatial and temporal use of the river channel by fishes must be understood. Given the challenges of sampling a fast and turbid glacial river, very little is known about movement patterns and habitat use by fishes in the Tanana River. Most of these fishes use the main river channel to travel between feeding, spawning, and overwintering grounds (Table 3) and may be susceptible to impacts of a hydrokinetic device during periods of movement associated with seasonal and ontogenetic shifts in habitat use.

We hypothesize that adult fish in the Tanana River will have minimal interaction with a turbine because they are relatively large and competent swimmers with well developed sensory systems that will likely sense a spinning device. In contrast, down-migrating juvenile fish are smaller and weaker swimmers and may use the highest velocity area of the river channel to conserve energy during down-migration. Because this is exactly the location where a hydrokinetic device will likely be deployed, it is imperative to study river channel and habitat use by these fishes. If there is overlap between the portions of the channel used by the fish and the turbine, then studies should be conducted to examine the direct impacts of the device on fishes. Evidence suggests that salmon smolts in clearwater rivers may be able to actively avoid direct contact with a hydrokinetic device, however, the horizontal and vertical distribution of down-migrating fishes and their behavior must be studied in order to verify that this is also the case in fast, turbid rivers like the Tanana River.

To determine potential and realized impacts of a hydrokinetic device on fishes in glacial rivers, we recommend the following study framework: To understand potential impacts, it will be necessary to determine temporal and three dimensional spatial distributions of all life history stages of fishes in the river channel using a combination of split-beam echo sounders and capture methods. To understand realized impacts of a hydrokinetic turbine on riverine fish communities, it will be necessary to monitor the behavior of fishes near the hydrokinetic device using an acoustic imaging camera and to monitor the health of fishes that actually pass through the turbine by capturing fish directly behind it. To better understand seasonal use of the river channel by the fish communities, it will be necessary to conduct winter sampling.

We believe that the conceptual framework for the fish study that we propose for the Tanana River is transferable to many other high-latitude, glacially influenced rivers that are being considered for hydrokinetic devices because the fish species diversity is relatively small and remarkably similar among them. Additionally, the river characteristics, particularly those that limit research, are also very much alike.

Conducting the recommended study not only facilitates the opportunity to exploit a previously unused source of clean, renewable energy in northern latitudes, but also serves to expand our knowledge about the ecology of fishes that inhabit large, turbid, glacially influenced river systems, about which we know very little, but which is vital to the culture and economy of Alaska.

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