Literature Review, Synthesis and Proposed Guidelines Related to the Biological Evaluation of "Fish Friendly" Very Low Head Turbine Technology in Canada

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Abstract

Cooke, S.J., Hatry, C., Hasler, C.T., and Smokorowski, K.E. 2010. Literature review, synthesis and proposed guidelines related to the biological evaluation of "fish friendly" very low head turbine technology in Canada. Can. Tech. Rep. Fish. Aquat. Sci. 2931: v + 33 p.

Very Low Head (VLH) turbine technology is a unique, cost-effective hydropower technology developed to address a hydraulic head of less than 3 meters and up to 500 kW of generation capacity. Natural Resources Canada is supporting the first North American demonstration of this technology at two sites in Canada, to optimize and adapt the VLH technology to North American conditions. Here we report on the findings of a literature review and synthesis intended to provide information and guidance for the field biological evaluation of VLH turbine technology in Canada. The objectives of this review were twofold: 1) to provide a summary of the various ways in which VLH turbine technology has and/or can be evaluated for its biological impacts on fish; 2) to propose scientifically-defensible guidelines to test the effectiveness of the VLH turbine in minimizing biological impacts on fish in Canada. We propose a suite of endpoints that should be examined which incorporate relevant metrics that have the potential to influence long-term survival, health, condition, and fitness. We also propose approaches that combine simple methods, such as full net recovery, with more natural studies where fish are passed downstream and their survival and behaviour is monitored for long (weeks to months) time periods.

Resumé

Cooke, S.J., Hatry, C., Hasler, C.T., and Smokorowski, K.E. 2010. Literature review, synthesis and proposed guidelines related to the biological evaluation of "fish friendly" very low head turbine technology in Canada. Can. Tech. Rep. Fish. Aquat. Sci. 2931: v + 33 p.

La turbine à très faible teneur de charge (TFTC) constitue une technologie de production d'hydroélectricité unique et économique conçue pour remédier aux charges hydrauliques de moins de 3 m et générant un maximum de 500 kW d'électricité. Ressources naturelles Canada appuie la première mise à l'essai en Amérique du Nord de cette technologie à deux endroits au Canada en vue de l'optimiser et de l'adapter aux conditions du continent. Le présent rapport présente les conclusions tirées d'un examen de la documentation et des synthèses dont le but est de fournir des renseignements et des conseils pour l'évaluation biologique sur le terrain de la

technologie de turbine à très faible teneur de charge au Canada. Les objectifs de cet examen étaient les suivants : 1) fournir un résumé des diverses façons dont les effets biologiques de la technologie de turbine à très faible teneur de charge sur les poissons ont été ou peuvent être évalués; et 2) proposer des lignes directrices défendables d'un point de vue scientifique pour mettre à l'essai l'efficacité de la turbine à très faible teneur de charge pour minimiser les effets biologiques sur les poissons au Canada. Nous proposons une série de résultats finals qui devraient être étudiés et qui incorporent des mesures pertinentes ayant le potentiel d'influencer la survie et la santé à long terme des poissons. Nous proposons également des démarches qui combinent des méthodes simples, comme la capture au filet, et des méthodes d'étude plus naturelles où les poissons sont déplacés vers l'aval et leur survie ainsi que leur comportement sont étudiés pendant de longues périodes (de semaines à des mois).

Background

Very Low Head (VLH) turbine technology is a unique, cost-effective hydropower technology developed to address a hydraulic head of less than 3 meters and up to 500 kW of generation capacity (Figure 1; Figure 2). VLH technology allows for significant cost savings related to civil works due to its modularity concept, making the development of very low head hydro resources economically feasible. Natural Resources Canada is supporting the first North American demonstration of this technology at two sites in Canada. The main goal is to optimize and adapt the VLH technology to North American conditions through cold climate engineering studies and on-site demonstration to show the economic viability, excellent energy efficiency and fish friendliness of the VLH turbine technology. At present, however, there is no set of guidelines for testing the effects of this turbine technology on fish despite the fact that a need for such studies on fish friendly turbines has been recognized for a number of years (Brookshier et al. 1995).

There are a number of mechanisms by which fish can become injured or killed as a result of passage through turbines as summarized by Čada (2001) and listed here:

- rapid and extreme pressure changes (water pressures within the turbine may increase to several times atmospheric pressure, then drop to subatmospheric pressure, all in a matter of seconds),

- cavitation (extremely low water pressures cause the formation of vapor bubbles which subsequently collapse violently),

- shear stress (forces applied parallel to the fish's surface resulting from the incidence of two bodies of water of different velocities),

- turbulence (irregular motions of the water, which can cause localized injuries or, at larger scales, disorientation),

- strike (collision with structures including runner blades, stay vanes, wicket gates, and draft tube piers), and

- grinding (squeezing through narrow gaps between fixed and moving structures).

In recognition of these mechanisms, the US Environmental Protection Agency has defined a set of five engineering-based criteria that should be present if a fish turbine has the potential to be considered as "fish friendly" (USEPA 2000). The five criteria are:

- Peripheral Speed = < 12 m/s

- Minimum Pressure = 69 kPa

- Rate of Change of Pressure = < 550 kPa/s

- Shear Stress Indicator = < 180 m/s/m

- Blade to discharge ring gap < 2.0 mm

Such criteria can be measured in a laboratory using scale models, via computer simulations, or with Computational Fluid Dynamics (CFD) modeling. However, these approaches do not involve any "hands-on" biological research or monitoring which means that the responses of fish to these injury mechanisms are frequently missing (Ventikos et al. 1997). In addition, although these criteria have a biological basis (e.g., Lucas 1981), they are not necessarily universal as it is inconceivable that one could use an "average" fish (which is essentially what was done by the author of the US EPA report) and then derive a single value that would be relevant to all species. For example, fish occur in a wide range of sizes as a result of interspecific differences in growth potential and intraspecifically as a result of ontogenetic development. Fish also have extensive variation in body shapes, ranging from laterally compressed to elongate. Even differences in fish scales and epidermis/dermis may influence how fish will respond to different aspects of the criteria listed above. Moreover, fish swimming capacity varies extensively among species and across life stages/sizes and is strongly mediated by water temperature. Different species and life-stages also have different sensitivity to changes in pressure. Quite simply, there is much inter- and intra-specific diversity in fish morphology, anatomy, behaviour and physiology that will influence the extent to which the various criteria listed above are truly applicable.

The first demonstration site of the VLH technology has been in successful operation in France since March 2007. Natural Resources Canada is supporting the first North American demonstration of this technology in Canada. This VLH turbine exceeds all of the "fish friendly" criteria that are noted above. In addition, Lagarrigue et al. (2008) has conducted a biological field study in France with a focus on Atlantic salmon smolts and documented reasonably low levels of mortality (approx. 3%). Additional research is planned for the turbine in France with a focus on other species (silver eels) but with a continued emphasis on injury and mortality as endpoints.

To that end, for the purpose of this paper it is necessary to define a biological objective that has ecological relevance for field studies that would determine whether or not a turbine is indeed "fish friendly". From the outset, it is important to recognize that it is unlikely that any turbine could yield zero mortality. Moreover, the level of mortality that one observes is context specific and must be considered relative to the ecology of a given species and local population characteristics. For example, for a population of threatened fish or species with life-history characteristics such as late age at sexual maturity and low fecundity, even low levels of mortality (e.g., < 5%) may be sufficient that in the long term the population would be unlikely to persist. It is also important to recognize that mortality, although easy to define and measure, is simply one way to evaluate the biological effectiveness of a turbine. Nonetheless, the majority of studies conducted have focused only on mortality as an endpoint (reviewed in EPRI 1987).

There are a range of sublethal effects that must also be considered when determining if a given turbine technology is friendly to fish. In some cases, sublethal effects can be additive or cumulative and may lead to delayed mortality. Examples of possible sublethal effects include injuries, physiological stress, behavioural alterations, changes in growth or condition, disease, or reduced fitness. One can envision a wide range of outcomes for a fish passing through a turbine such that although a fish may be "clinically" alive upon passage, it may die hours, days or weeks later, or alternatively survive but exhibit a reduction in fitness. Recently, some researchers have also considered the effects of fish interactions with turbines in the context of fish welfare (Huntingford et al. 2006).

Given the above, for the purpose of this document "fish friendly" is a subjective term that is context dependent (based on local fish populations and ecosystem characteristics including human values for different species). A "fish friendly" turbine should result in minimal immediate or delayed mortality, produce little physical injury, and result in minimal negative consequences on fish health, condition, behaviour, physiology, or fitness. Alternatively, if fish do experience significant sublethal disturbances, the recovery should be sufficiently rapid that there are no long-term consequences on fitness. This approach is generally consistent with other fisheries-related fields such as quantifying consequences of recreational and commercial fishing practices on fish that are to be discarded/released. In those fields, there is much effort devoted to not only quantifying mortality, but to also understanding the sublethal consequences of those activities (Cooke and Schramm 2007) as well as impacts on fish welfare (Arlinghaus et al. 2007; Huntingford et al. 2006).

The first objective of this document is to provide a summary of the various ways in which VLH turbine technology has and can be evaluated for its biological impacts on fish. The synthesis will cover a broad range of lethal and sublethal end points, as well as their measurement, that could be used to determine the "fish-friendliness" of the turbine. Using information emanating from this synthesis, the second objective is to propose scientifically-defensible guidelines to test the effectiveness of the VLH turbine in minimizing biological impacts on fish in Canada.

Objective 1 - Assemble a detailed literature review summarizing the various ways in which VLH turbine technology has and can be evaluated to understand its biological impacts on fish.

For the purpose of this objective, we first conducted a literature review to summarize the ways in which the biological effectiveness of VLH turbine technology has been studied. We used Web of Science (1901-2010; via Institute of Scientific Information), Environmental Sciences and Pollution Abstracts (coverage of 1981-2010; via Scholars Portal), Environment Index (1972-2010; via EBSCOHost), Applied Science and Technology (1983-2010; via Wilson Web), the American Fisheries Society Infobase (coverage of 1880-2010; via Fisheries.org) and Google Scholar (search date of March 30, 2010). A variety of Boolean search terms were used including "turbine", "entrainment", "fish friendly", "biolog*", "ecol*", "fish*", and "mortality". We also used the "cited reference" search feature of Web of Science to identify additional articles that cited key papers found during the search. Given that there are relatively few published studies that deal with VLH turbines, we included all turbine types/sizes in the review in order to ensure that we did not "miss" potential study approaches that have been used on larger facilities. That said, not all approaches will be applicable to low head facilities and those aspects are discussed under "objective 2" where a specific suite of guidelines are proposed. For the purposes of this review, we focus on endpoints and within each describe the tools available for their study. Where available, we provide examples of how these endpoints have been used to study the consequences of turbine passage on fish.

Mortality

Fish mortality is the most commonly studied endpoint for biological evaluations of turbines (see Table 1 for summary of studies to date). Mortality has biological relevance in that an individual is removed from a population which reduces population size and could also influence community interactions or ecosystem processes. Mortality is a common metric in the study of other stressors such as catch-and-release fishing, commercial bycatch, cold shock, etc. Studies for all of those fields have identified that mortality alone is not an appropriate endpoint due to the potential for sublethal impacts (e.g., Davis 2002; Arlinghaus et al. 2007; Donaldson et al. 2008a). Mortality can be measured on a variety of time scales. For example, immediate mortality is generally defined as that which occurs within several minutes (less than 1 hr) of exposure to a stressor. Short-term mortality is usually defined as being mortality that occurs between 1 hr and 48 hr post stressor. Long-term mortality is defined as mortality that occurs beyond 48 hrs. Mortality can be estimated in a variety of ways. Each of the main approaches for estimating mortality is presented below including a brief overview of their strengths and limitations.

- Mark recapture/return – Fish are tagged as juveniles before passage through turbines and then estimates of mortality are determined from return rates of adults. This method has limitations as there are many factors that can contribute to mortality in the "normal" life of a fish making it difficult to yield statistically valid findings (Paulik 1961). Such studies require use of appropriate controls and require large sample sizes. Passive integrated transponder (PIT) tags are perhaps the most common means of marking fish for such long-term studies. Evaluation requires several years to complete as one must wait for adult fish to return.

- Partial recovery – Fish are marked or tagged upstream and passed through the turbine. Fish below are recaptured using nets and/or electrofishing but the gear is not configured in a manner where it is possible to collect all fish passing through the turbine (e.g., Schoeneman et al. 1961). This approach tends to be used in large systems where full recovery is not possible (e.g., large dams on the Columbia River). Partial recovery methods require large sample sizes and there are a number of assumptions regarding recovery ratios (of live and dead fish) that must be addressed.

- Full recovery – Fish are marked or tagged upstream and passed through the turbine. Fish below are recaptured using a net that is configured such that it collects all fish passing through the turbine (e.g., Cramer and Donaldson 1964). This approach is not practical for large systems. Sample sizes can be smaller due to the fact that all fish are recovered. Full recovery tends to avoid the statistical problems associated with partial recovery if the technique can be used in a given system.

- Biotelemetry field estimates – Fish are tagged with an electronic device that enables them to be tracked after passage to evaluate behaviour and mortality. One of the challenges is determining if and when a fish is dead. A variety of sensors can be used (e.g., mortality switch, depth sensor) to better identify dead fish (Cooke et al. 2004). Manual tracking and use of fine-scale telemetry arrays is also effective for identifying mortality. This approach can be expensive but provides immense realism (Donaldson et al. 2008b). Appropriate controls to address tagging bias are required.

- Balloon field estimates – Fish are tagged with a balloon device that expands following fish passage through turbines such that it is possible to recover fish for examination. Not all balloons will inflate and there are some assumptions with recapture.

Given that mortality can occur on a variety of time scales and given that not any single approach for estimating mortality can provide reliable data across all time scales (Table 2), it is necessary to combine techniques. Where possible, combining full recovery (to address immediate and short-term mortality) and biotelemetry (to address short-term and long-term mortality) is the most meaningful and robust approach to the biological evaluation of turbines. Generating two estimates of short-term mortality (both of those techniques can do so) provides additional power in that it enables researchers to identify how biotic or abiotic factors beyond turbine passage can interact to alter mortality. For example, it could be possible to generate a mortality estimate for fish passing through turbines using the full recovery approach that is very low for fish held in a net pen or tanks for observation. However, fish that pass through the turbines and are tracked with telemetry could exhibit much higher mortality if it were mediated by factors such as post-passage predation. In other words, using multiple approaches that combine captive holding (confinement in tanks or pens) with field biotelemetry enables the researcher to identify the basis for mortality. This approach has been adopted by those studying bycatch and hooking mortality and has led to the generation of robust mortality estimates and also identified opportunities for reducing mortality (e.g., Cooke and Schramm 2007).

Injury

Physical injury can arise from a number of turbine-related stressors and is regarded as a common and logical endpoint. Perhaps the most obvious are physical strikes that cut the fish into pieces. Such injuries typically result in rapid mortality as a result of excessive bleeding or a direct blow to the head (cerebral region). Injury can also be less obvious and include loss of scales, bruising, or minor cuts which are not immediately lethal. However, even minor injuries can serve as entry points for pathogens that could themselves become lethal. Internal injury can also occur as a result of rapid changes in pressure. Some injuries (e.g., to the eyes or mouth) can affect fish condition by impairing feeding or potentially promote post-passage predation by hindering swimming ability.

Although injury may seem like a simple endpoint to measure there are a number of challenges, not the least of which is that one must recapture fish after turbine passage to quantify injury. Often times the collection techniques used and subsequent research handling can impart some level of injury, so the use of controls is essential. Collecting fish (e.g., via electrofishing or using partial or full recovery nets) enables macroscopic examination such as the scoring of scale loss, cuts, bruises, etc. Scale loss is often characterized as the percent of scale loss (e.g., Kostecki et al. 1987). It is also possible to use radiographs (x-rays) or other imaging technology (e.g., magnetic resonance imaging, ultrasound) to examine potential internal damage. Internal injury can also be evaluated using careful dissections. Some researchers have used macroscopic examinations in an attempt to determine the source of injury. For example, Stokesbury and Dadswell (1991) classified source of injury based on the type of injury observed; 1) pressure - blood under skin on the gill cover, 2) mechanical strike - fish cut by turbine blades, 3) shear stress - head torn off, and 4), internal damage - blood from anus. However, such macroscopic examinations are rather subjective and typically are unable to detect smaller injuries such as slime loss or minor scale loss.

Recent developments in forensic ecology have provided a new suite of tools for identifying and quantifying fish injury. A recent review (i.e., Colotelo et al. 2009) provided a summary of the various forensic tools available for potentially quantifying injury. The premise for most of the tools is that a chemical is applied to the fish skin which reacts with the haem group (from blood) which generates a reaction that can be quantified. Researchers have used a combination of fluorescein bath and ultra-violet light exposure to assess tissue damage (Noga and Udomkusonsri 2002). Other chemical enhancers including Hemastix®, HemidentTM, Phenolphthalein and Bluestar© may offer alternatives to fluorescein for detecting fish skin abrasion (Colotelo et al. 2009). The use of chemical enhancers as a common tool in assessing tissue damage in fish is likely a few years away, as much work is still needed to determine if there are any negative effects of the chemicals on the fish and aquatic environments, as well as to determine the extent to which false positives or false negatives may influence conclusions.

To investigate injury potential, several researchers have deployed "fake" fish to serve as surrogates to real fish. For example, Čada et al. (2005) developed an approach where pressure-sensitive film was used to estimate pressures experienced by fish exposed to potentially damaging mechanical and fluid structures during downstream passage at hydroelectric dams. Carlson and Duncan (2003) detailed the development of the "sensor fish" which can be used to document a range of conditions observed during passage. Although neither approach is a direct substitution for direct injury examinations, these creative approaches can be used to identify the hydraulic conditions and injuries that may be anticipated by "real" fish.

Physiological Status

When exposed to stressors, organisms respond with a series of adaptive responses. Biologists routinely measure physiological parameters to understand the extent to which the homeostasis of an organism is altered relative to "normal" conditions (Barton et al. 2002). In most instances, an organism can recover from stressors, however, in some cases fish do not recover and either die or experience other indirect effects. For example, if the physiological status of fish is altered, they may be more susceptible to disease or exhibit behavioural impairments (Schreck et al. 1997). Physiological indicators can be extremely sensitive. Indeed, even the most "fish friendly" turbine design would certainly result in some level of physiological disturbance as a result of passage. As such, it is important to consider the ecological relevance of the various stress parameters. Here, the basic stress response of fish is summarized and potential parameters are identified. We focus on hormones, metabolites, ions, and enzymes but also briefly comment on the utility of physiological genomics. Hasler et al. (2009) should be consulted for additional details regarding the potential use of physiological tools for evaluating fish interactions with hydropower infrastructure.

Stress hormones can be useful for understanding a wide range of stressors including those imparted by hydropower facilities or operations (Adams 1990; Wendelaar Bonga 1997). Stress hormones are endocrine responses to perceived changes in the surrounding environment. The two main types of hormones that are commonly used to measure stress are catecholamines and corticosteroids (Wendelaar Bonga 1997; Barton 2002). Plasma catecholamines are released rapidly in response to perceived ambient disturbance and are linked to tissue oxygen delivery and fuel mobilization for tissue metabolism. However, because catecholamines are very rapid acting, sampling fish in a manner that would be reflective of concentrations of catecholamines during the stressful event, and sampling control fish without inducing a catecholamine response would be difficult. Cortisol, on the other hand, may be a good indicator of the magnitude and duration of acute stress because there is a time lag between the stressor and the response (Barton 2002; Barton et al. 2002). Indeed, cortisol is regarded as "the" stress indicator in fish and can be measured and interpreted with relative ease. Although, to our knowledge, cortisol has not been measured in the context of turbine passage, cortisol has been used to link hydropower operations to sub-organismal stress (Reviewed in Hasler et al. 2009). Cortisol is of relevance to turbine passage studies because if cortisol becomes elevated for prolonged periods of time, it can lead to impaired immune function. Furthermore, a cortisol response is incompatible with the production of reproductive hormones so may impact fitness. Measuring the magnitude of cortisol response after turbine passage, coupled with recovery time, would be meaningful measures for turbine passage.

With the onset of a hormonal response to stress (described above), numerous secondary effects occur (Wendelaar Bonga 1997). Mainly, metabolites such as glucose, lactate, glycogen, and numerous other reactants and products of metabolism change to meet energetic demands to fuel the stress response (Mazeaud et al. 1977). In field studies, blood samples can be taken rapidly and non-lethally by caudal puncture (and/or gill puncture) and plasma glucose and lactate can be measured using inexpensive portable devices or simple laboratory methods. Increases in either glucose or lactate can indicate a metabolic response to stress. Plasma glucose is an indicator of mobilization of energy reserves, and plasma lactate a by-product of anaerobic respiration. Other, more invasive techniques can be used to measure tissue glycogen or tissue lactate. Tissue glycogen is an indicator of the metabolic reserves stored in the liver and muscle and is a good indicator of muscular activity, but is highly dependent on temperature and when the fish last ate. Similar to the endocrine measures described above, metabolites have not been used in the study of turbine passage. Since glucose, glycogen, and lactate would likely change in hydropower systems in relation to exhaustive exercise, they may be highly relevant for turbine passage studies. For example, one may expect that a fish that passes a turbine may swim vigorously during the entrainment and passage process, potentially exhausting tissue energy stores and accumulating metabolites such as lactate. These measures are ecologically relevant given that if fish are exhausted, they may be unable to avoid predators downstream. Measuring time for tissue energy stores to be replenished and metabolites to be cleared would provide meaningful information relative to turbine passage under different conditions.

Typically in studies aimed to quantify the magnitude or physiological consequences of stress in fish, the concentrations of specific ions (e.g., Na^+, Cl^-, and K^+) or minerals (e.g., total calcium, total magnesium, total phosphorous) are measured to understand the secondary effects of stress (Mazeaud et al. 1977; Wendelaar Bonga 1997); the primary response being the release of stress hormones. Plasma ions are often used to understand the ability of an organism to deal with stress responses, such as acidosis, a secondary response that is the result of lactic acid build-up caused by anaerobic respiration (e.g., Wood 1991). Following exhaustive exercise, ion concentrations may be disturbed over a period of 4 – 24 h before returning to baseline levels. In some cases, severe ion imbalances can lead to mortality (Wood 1991). Methods to determine ion concentration are not difficult or expensive; some can even be done using handheld instruments. Currently, few studies have applied measurements of plasma ion concentrations to assess fish dealing with hydropower infrastructure and operations, despite the fact that it can be used in a manner similar to the metabolites discussed above.

Measuring the rates of enzymatic reactions involves the quantification of a particular rate limiting enzyme or reagent. With the development of commercial assay kits and spectrophotometers, enzyme activities can be measured with relative ease, though some can be costly. Some disadvantages of using enzymatic activities are that typically a variety of enzymatic activities need to be measured to fully understand the processes being measured, and results may be influenced by a number of endogenous and exogenous factors. Activities of a number of enzymes have been used to measure tissue damage, energetics, growth, smoltification, and the effects of various pollutants. The enzymes of most revelance to turbine passage are those that deal with tissue damage. When cells are damaged or die, the intracellular enzymes are released into the blood. By measuring the levels of alanine aminotransferase (ALT), aspartate aminotransferase (AST), creatine kinase (CK), and lactate dehydrogenase (LDH) in the blood, inferences to the magnitude and type of tissue damage can be made (Grizzle et al. 1992; Wagner and Congleton 2004).

Despite this large body of tools that are available to study physiological endpoints of fish, relatively few of them have been applied to hydropower (Murchie et al. 2008; Hasler et al. 2009) and even fewer have been used to study the sublethal consequences of turbine passage. Physiological tools can help to identify the specific mechanisms that could lead to behavioural impairments or even death and thus are important in determining whether a given turbine design is "fish friendly". One of the only examples of using physiological tools was a study by Maule and Mesa (1994) where they evaluated plasma cortisol concentrations of juvenile Chinook salmon that passed through turbines at hydroelectric dams on the Columbia River. The authors emphasized the importance of using appropriate controls to be able to account for handling effects.

Reflex Impairment

Recent experimental laboratory research has shown that measuring the presence of reflex actions in fishes can provide an integrative measure of organismal condition and also predict survival (Davis 2007). Some of these reflexes include checking for a fish's ability to right itself if turned upside down in water (righting reflex), a fish's reaction to burst-swim away when a handler attempts to grab its tail (evasion reflex), and for whether a fish's eyes roll within its body when it is rotated about a length-wise axis out of water and is able to track the handler and remain level (vestibular-ocular response; Davis 2010). These reflexes are neurological measures that respond to increasingly severe stress treatments by becoming impaired whereby a greater proportion of an individual fish's reflexes become impaired (i.e., absent) following increasingly severe treatments (Davis 2010). By assessing presence or absence of a group of reflexes, a reflex impairment index value is calculated for each individual that serves as an indicator of relative condition (i.e., vigour) which, hopefully, correlates with post-release survival (Davis 2010). As a simple and rapid measure of condition and a predictor of survival, RAMP (Reflex Action Mortality Predictors) holds promise for field applications and could be used to determine condition of fish in the context of turbine passage. Although the RAMP approach was formally developed for use in bycatch research, those that study turbine impacts on fish do routinely evaluate disorientation. If fish are disoriented and unable to maintain equilibrium after turbine passage, they may be susceptible to predation in the tailwaters below the dam (Čada 2001).

Condition and Growth

Condition-based indicators encompass length-weight relationships, organosomatic indices, and necropsy-based assessments. These assessments range from being relatively non-invasive to lethal. Also included are basic measures of fish growth. Length-weight relationships are typically very easy to measure, as fish only need to be handled briefly, and they are appropriate indicators of general health. Organosomatic indices involve the comparison of a particular organ to body weight ratio (e.g., hepatosomatic index [liver:body weight, HSI], gonadosomatic index [gonads:body weight, GSI], viscerosomatic index [entire viscera:body weight, VSI], and splenosomatic index [spleen:body weight, SSI], see Barton et al. 2002). These indices can be used to measure stress, as values that are lower or higher than normal indicate that energy allotment to organ maintenance and growth is altered. Another condition-based indicator is necropsy-based. This method involves necropsies of sacrificed fish as well as linking the condition of internal organs to stress based on published guidelines as to the condition of normal organs (Barton et al. 2002; also known as the health assessment index). It is difficult to relate condition-based assessments to stress, as results could be influenced by a variety of variables (i.e., disease, pollution, genetics, etc.), thus caution should be used. Nonetheless, condition and growth have much ecological relevance and have potential for use in understanding the long-term consequences of turbine passage. These metrics could be used by either recapturing fish after passage (weeks to months later) or holding fish in captivity and comparing condition over time (between fish that passed turbines versus control fish). To date, there are no examples in the literature that we are aware of where these metrics have been used in the context of turbine passage effects.

Swimming Performance

Swimming requires the integrated function of many different body systems (Schreck 1990), and thus alterations in locomotory activity (i.e., depressed activity, hyperactivity) can serve as sensitive indicators of stress (Schreck et al. 1997). Swimming is essential for food acquisition and avoiding predators and, when performance is impaired, one or both of these essential activities may be affected. Swimming performance can be readily studied using devices such as swim flumes. Fish exposed to different treatments (e.g., turbine passage vs non-passage) can be quantitatively compared with respect to their maximum aerobic swimming capacity (also known as U-crit or critical swimming speed) where fish are exposed to a series of stepwise velocity increments until they become exhausted (Beamish 1978). It is also possible to compare burst swimming capacity using flumes with high speed video. Swimming performance is commonly used to study if fish exposed to different stressors (e.g., starvation, cold shock, air exposure) vary in swimming performance. Such studies can be done in the laboratory although there are also swimming flumes that have been developed which can be used in the field (e.g., on the river bank; Farrell et al. 2004). To date, swimming performance has not been used as an endpoint for evaluating turbine passage despite its ecological relevance.

Behaviour

Behavioural measures of stress have proven to be sensitive indicators of the complex biochemical and physiological changes that occur in response to stress (Schreck 1990). Changes in behaviour may be adaptive and increase the probability of survival, or may reflect deleterious changes in how an animal senses and responds to its environment. Significant departures from behavioural norms may indicate altered success of food acquisition, predator avoidance, orientation, migration and reproduction and, may therefore be suggestive of a decreased probability of survival (Schreck et al. 1997). In the context of turbine passage, behavioural alterations such as territorial, agonistic, schooling and reproductive behaviours have rarely been addressed. One of the few studies to do so in the context of turbine passage reported that delayed mortality was caused by sublethal impacts to fish sensory systems, which increased vulnerability to predation in the tailrace (Ferguson et al. 2006). There are now a suite of tools available that enable researchers to study fish behaviour relative to turbine passage such as biotelemetry (including passive integrated transponder technology and accelerometers) which can incorporate sensors that measure fine-scale activity (e.g., Cooke et al. 2004). Studies of Pacific salmon smolt downstream migration routinely use telemetric tools to evaluate behaviour of fish between different dams. Not all fish will be passed through turbines, but telemetry enables one to determine which fish take which path through a dam and what their subsequent behaviour and survival is in other downstream reaches.

Fitness

Fitness metrics are the ultimate expression of whether or not a given stressor will affect future populations (Rosenberg, 1978; Beatty, 1992). Fitness is difficult to define and even more difficult to measure. For the purpose of this review, fitness is defined to mean any endpoint specifically related to reproduction and the production of offspring. Given that so few studies measure true fitness (i.e., how offspring fare), we focus on metrics that are measurable and have ecological relevance. For example, reproductive investment, gamete quality, and reproductive behaviours (e.g., migration, finding mate, spawning, parental care, etc.) are all relevant and measureable endpoints. Quite simply, no examples of fitness metrics were located for fish in the context of turbine passage. This clearly represents an opportunity and should be pursued as fitness metrics have direct relevance to population biology.

Summary

Although the majority of studies that have examined fish passage through turbines have addressed simple metrics related to injury or immediate/short-term survival, there are a suite of tools available that collectively are robust means of evaluating the biological efficiency of VLH turbines. To that effect, it is recommended that studies of fish friendly turbines incorporate a range of metrics that span the different levels of biological organization, including physiological status, reflex impairment, condition, growth, swimming performance, behaviour and fitness. Such studies are not easy as they require use of a variety of specialized tools and techniques. However, if regulatory agencies are going to encourage industry to use fish friendly turbine designs, it is essential to determine which turbines actually have the potential to achieve such a goal. To be a fish friendly turbine it is important that a given design is exposed to true biological validation even if the design meets engineering-based criteria. Indeed, it is likely impossible to develop a single value for each of the hydraulic design criteria that will ensure that a given design is fish friendly. Only a combination of laboratory evaluations, simulations and field-based biological evaluations using a range of endpoints (such as those described in the report) can ensure that a turbine is worthy of the moniker of “fish friendly turbine”. It is important to recognize that much of the existing literature is inadequate and fails to incorporate contemporary techniques or knowledge. Relying on the conventional “tried and true” techniques doesn't capture the potentially substantial deleterious effects on individuals and populations resulting from the sublethal consequences of turbine passage.

Objective 2 – Generate a proposed suite of guidelines spanning lethal and sublethal approaches for fish testing of the VLH turbine in Canada

Guiding Principles

There are a number of guiding experimental design principles that should be considered when developing approaches for studying fish responses to VLH turbines. To date, most turbine evaluations have been flawed or limited in their scope of inference given serious study limitations. If a turbine is to be deemed to be "fish friendly" by regulators then studies evaluating turbine designs should consider the following principles. It is worth noting that although these were developed in the context of the VLH turbine testing in Canada, the general principles should be of relevance beyond Canada and to other turbine studies.

- **Study must extend across multiple seasons including the winter** – Most of the previous studies have limited their assessment of turbine impacts on fish to a single season. In some cases, such timing is dictated by the downstream migration of key fish species (e.g., Pacific salmon smolts). However, this approach fails to recognize the mobility of the entire fish community. In Canada, winter is a period that is often forgotten when considering fish biology (Cunjak 1996). Given that water temperature is the "master factor" in the lives of fish, affecting all enzymatic processes, swimming ability, behaviour and physiology, it is necessary to study how fish respond to turbine passage in all seasons including winter. Failure to study the "fish friendliness" of turbines in winter would make it difficult to know whether such a moniker is appropriate. Given that one of the goals of Natural Resources Canada is to optimize and adapt the VLH turbine technology to North American conditions through cold climate engineering studies, field studies related to biological impacts must encompass the winter period.

- **Study must encompass a range of life-history stages –** For a turbine to be fish friendly it should be able to pass a variety life-history stages that are relevant in a given system spanning juveniles to adults.

- **Study must include several species that represent a diversity of behaviours, size and morphology –** It is necessary to use multiple species that represent a diversity of characteristics that span the key guilds and morphotypes present in a system. Using a single model species is problematic given the impressive level of diversity in freshwater ichthyofauna.

- **Study must incorporate a combination of lethal and sublethal metrics –** Mortality is reasonably simple to study but there is a need to also consider sublethal consequences given that there is a broad spectrum of fish condition when fish are simply categorized as being "alive". For example, fish may have injuries that may impede their ability to swim and forage which could affect growth and fitness. Physiological disturbances may influence susceptibility to disease. There are a broad range of sublethal metrics (summarized above), some of which are particularly relevant to the study of fish turbine interactions.

- **Study must extend beyond immediate effects to consider long-term consequences of passage –** Studies of immediate or short-term (48 hrs or less) mortality fail to consider that fish can succumb to injuries or stress in the longer term. As such, it is recommended that a subset of fish be monitored for survival for one week or more.

- **Need to incorporate field realism in experiments –** Although it is often easier to bring fish into a laboratory or hold them in net pens to monitor survival, it is recommended that at least a portion of mortality studies be conducted in the wild on free swimming fish (e.g., using telemetry techniques) given that some of the mortality (e.g., post-passage predation) would not be detected in fish that were only held in a laboratory or net pen. Čada (1997) acknowledged that most of the studies related to hydraulic conditions for determining the "friendliness" of a turbine for fish are based on studies in laboratories where a single hydraulic parameter is evaluated. Given the potential for cumulative or interactive effects, it is necessary to include field experiments in the evaluation process.

- **Study must incorporate appropriate controls –** Simply documenting mortality in fish that are passed through the turbine is inappropriate without using appropriate controls. Indeed, sometimes the techniques used to study mortality (or other endpoints) can themselves cause stress, injury and mortality. It is therefore essential to use appropriate controls to enable the determination of mortality (or other endpoints) that is (or are) directly attributable to turbine passage.

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Table 1. Summary of mortality studies associated with fish turbine passage with a focus on endpoints, method of study, and context.

Endpoint	Method	Context	Comments	Reference
Immediate mortality	Full recovery approach using net	Juvenile rainbow trout experimentally passed through a Francis turbine at a dam on the Hinemaiaia River, New Zealand	Used fin clips to mark fish; Included control group	Dedual 2007
Immediate mortality	Balloon tagging	Pacific salmon smolts in the Columbia River Basin	Paper was actually a meta-analysis of several years of balloon tagging experiments from consulting reports but also included data from other Kaplan turbines in other systems and for other species	Skalski et al. 2002
Immediate and delayed mortality	Full recovery approach using net	Juvenile American shad and striped bass experimentally passed through Ossberger crossflow turbines at a small-scale hydro dam on the Susquehanna River in New York	48 hr was the extent of the delayed mortality monitoring; Included control group and corrected for mortality observed in controls	Dubois and Gloss 1993
Community entrainment patterns and immediate mortality	Downstream net monitoring	Four low head dam turbines in Michigan	Comprehensive study with a focus on warm and cool water fish assemblages; Included diel and seasonal evaluation	Navarro et al. 1996
Immediate and short-term (48 hr) mortality	Full recovery approach using net	Pacific salmon smolts at facilities in the Columbia Basin	Developed the net recovery approach; Used tattoos to differentiate treatments	Cramer and Oligher 1964
Immediate and long-term mortality (weeks)	PIT tags, radio tags and balloon tags	Pacific salmon smolts at facilities in the Columbia Basin	Determined that delayed mortality comprised from 46% to 70% of total estimated mortality; Used a telemetry array that extended 40+ Km	Ferguson et al. 2006

			downstream from dam	
Immediate and long-term mortality	Full recovery approach using net	Studied Ossberger crossflow turbines to quantify mortality of juvenile steelhead, rainbow trout and Atlantic salmon at a small-scale hydro dam on the Susquehanna River in New York	Used hatchery fish to introduce into penstocks	Gloss and Wahl 1983
Immediate mortality	Balloon tagging	Evaluated immediate (1-h) turbine-related mortality of juvenile American shad at the Hadley Falls Hydro Station on the Connecticut River, Massachusetts		Mathur et al. 1994
Immediate mortality	Styrofoam float tagging	Developed a method using a fish hook with line attached to small Styrofoam floats to document fish mortality	Technique has not been widely adopted	Johnson 1970
Immediate mortality	Partial recovery approach using passive nets	Studied mortality of juvenile American shad and blueback herring experimentally passed through a low-head Kaplan turbine on the Connecticut River, Massachusetts	Used dye marking; Not all fish were recaptured because nets were not placed directly on the outflow	Taylor and Kynard 1985
Immediate and short-term mortality and behaviour	Radio telemetry	Studied mortality and behaviour of adult American shad passed through a low-head Kaplan turbine on the Connecticut River,	Tagged dead fish to understand how they would "behave" downstream; Used manual tracking; Fish tracked for a minimum of 5 hr	Bell and Kynard 1985

		Massachusetts		
Immediate and short-term mortality and behaviour	Radio telemetry	Studied mortality and behaviour of Atlantic salmon smolts passed through a low-head Kaplan turbine on the Connecticut River, Massachusetts		Stier and Kynard 1986
Community entrainment patterns and immediate mortality	Downstream net monitoring	Studied mortality of juvenile and adult warmwater fish at a hydro facility in Oklahoma		Sorenson et al. 1998
Immediate and short-term mortality	Partial recovery using nets	Studied mortality of Pacific salmon smolts at McNary Dam in the Columbia River Basin	Invested significant effort in validating assumptions of tag and recapture approach	Schoeneman et al. 1960
Immediate mortality	Full recovery approach using nets	Developed and validated approach using nets for full recovery of fish	Good methods study	Cramer and Donaldson 1964

Table 2. Summary of techniques for estimating mortality relative to their potential use across a variety of time scales. Methods were characterized as being "possible" if they had the potential to provide a mortality estimate at a given time scale if such studies had been previously conducted and yielded data without serious limitations. Methods were characterized as "not possible" if there were unable to generate a robust mortality estimate for a given time period.

Mortality Estimate Technique	Immediate Mortality	Short-term Mortality	Long-term Mortality
Mark-recapture/return	Not Possible	Not Possible	Possible
Partial recovery	Possible	Possible	Not Possible
Full recovery	Possible	Possible	Not Possible
Biotelemetry	Not Possible	Possible	Possible
Balloon	Possible	Not Possible	Not Possible

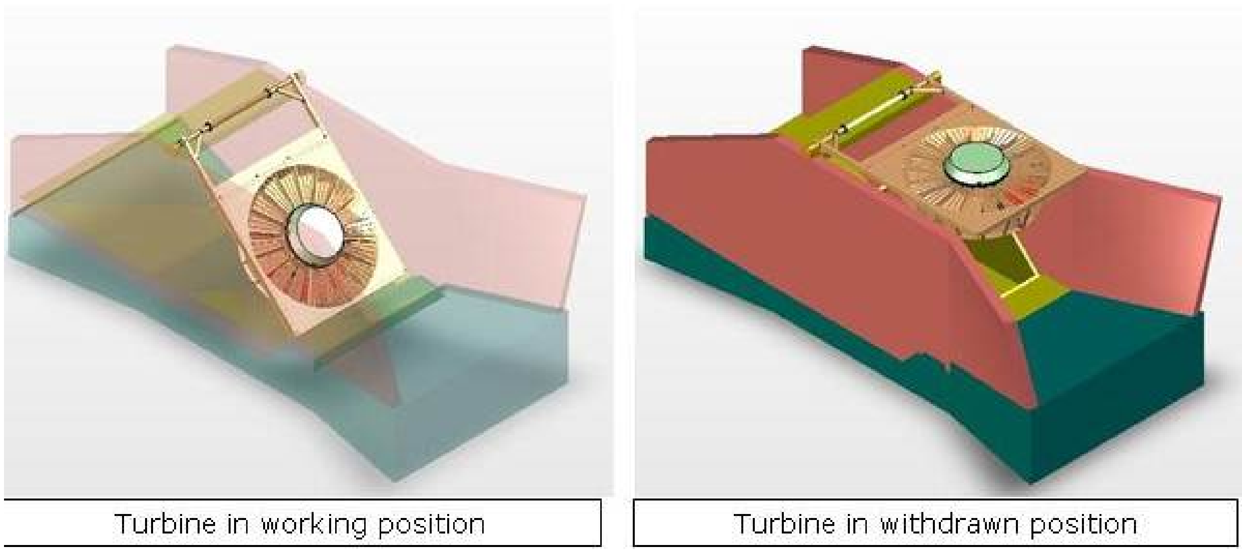

Figure 1. Potential configurations of a very low head turbine in working position, as well as in a withdrawn position (Photo: Leclerc, 2007).

Figure 2. Image of a very low head turbine in working position, without water flowing through sluiceway (Photo: Leclerc, 2007).