Literature Review: Fish Mortality Risks and International Regulations Associated with Downstream Passage Through Hydroelectric Facilities

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Analyse documentaire : Risques de mortalité du poisson et règlements internationaux liés au passage du poisson vers l'aval dans les installations hydroélectriques

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ABSTRACT

Crew, A.V., Keatley, B.E. and Phelps, A.M. 2016. Literature review: Fish mortality risks and international regulations associated with downstream passage through hydroelectric facilities. Can. Tech. Rep. Fish. Aquat. Sci. XXXX: iv + 47 p.

The purpose of this report was to document the current knowledge of the mortality risks fish are exposed to when passing downstream through a hydropower facility. Four main mortality risks were identified: 1) turbine mortality 2) screen/rack impingement; 3) behavioural and operational entrainment/impingement risks; and 4) rapid flow alterations. Examining these mortality risks, key messages associated with each risk and the current knowledge gaps were identified. In addition, an examination and evaluation of how four countries regulate fish mortality from downstream passage through hydropower facilities, was conducted. The countries chosen include two countries from the European Union (Sweden and the Netherlands), Norway and the United States. These countries were chosen to examine the differences in the approaches used to regulate fish mortality. The goal of this report is to create a knowledge base to help guide the Canadian government in establishing a national framework for managing mortality of fish undergoing downstream passage through hydropower facilities.

RÉSUMÉ

Crew, A.V., Keatley, B.E. et Phelps, A.M. 2016. Analyse documentaire : Risques de mortalité du poisson et règlements internationaux liés au passage du poisson vers l'aval dans les installations hydroélectriques. Rapp. tech. can. sci. halieut. aquat. XXXX : iv + 47 p

L'objet du présent rapport est de documenter les connaissances actuelles sur les risques de mortalité auxquels les poissons sont exposés lorsqu'ils traversent une installation hydroélectrique vers l'aval. Quatre principaux risques de mortalité ont été décelés : 1) les risques de mortalité liés aux turbines, 2) les risques d'impaction liés aux grillages et aux pièges à débris, 3) les risques liés à la réponse comportementale et opérationnelle à l'impaction ou à l'entraînement et 4) les risques liés aux modifications subites du débit. En examinant ces risques de mortalité, on a pu déterminer des messages clés associés à chacun des risques et définir les lacunes actuelles dans les connaissances. Les auteurs ont également examiné et évalué la méthode utilisée par quatre pays pour réglementer la mortalité du poisson attribuable à son passage vers l'aval dans des installations hydroélectriques. Les quatre pays choisis étaient la Suède et les Pays-Bas (de l'Union européenne), la Norvège et les États-Unis. On a examiné les différences des approches utilisées par ces pays pour réglementer la mortalité du poisson. Le but du présent rapport est de créer une base de connaissances qui aidera le gouvernement canadien à élaborer un cadre national visant à gérer la mortalité du poisson qui traverse les installations hydroélectriques vers l'aval.

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1.0 INTRODUCTION

1.1 NEED FOR THE CURRENT STATE OF SCIENTIFIC KNOWLEDGE ON THE FISH MORTALITY RISKS FROM HYDROELECTRIC FACILITIES

Canada is the third largest producer of hydroelectricity in the world and possesses enormous hydropower potential (World Energy Council 2013). At the end of 2015, the total installed hydroelectric capacity in Canada was 79, 202 MW, whereas the ‘total unexploited technical hydro potential’ is more than double the current capacity (International Hydropower Association 2016). From 2011 to 2030, there is an estimated potential in Canada for 158 hydropower projects totaling 29,060 megawatt of new capacity that could be installed (Desrochers et al. 2011).

While hydropower generation has many environmental advantages, such as lower greenhouse gas emissions, hydropower dams can alter the natural ecology and hydrological conditions of rivers and cause significant ecological impact, especially for the fish that live in or migrate through impounded river systems (Cada 2001).

Hydroelectric dams may also impair biological connectivity of riverine fish populations (Katano et al. 2006; Liermann et al. 2012; Januchowski-Hartley et al. 2013). For fish populations migrating upstream there are many new technologies that can increase the effectiveness of fish passage over these barriers (Schilt 2007; Roscoe and Hinch 2010). Conversely, upon downstream migration, fish species can experience many adverse conditions including: turbine entrainment, screen/rack impingement, and rapid flow alterations. Each one of these conditions has the ability to cause fish injury or mortality.

In Canada, the mortality of fish is regulated under the federal *Fisheries Act*. Section 35(1) of the *Fisheries Act* prohibits any work, undertaking or activity that results in serious harm to fish (defined as death to fish, permanent alteration to, or destruction of fish habitat) that is part of a commercial, recreational or Aboriginal fishery, or to fish that support such a fishery, unless otherwise authorized. Despite this legislation, there are currently no federal guidelines to guide the assessment of authorizations for fish mortality from a given hydropower project.

There is a need for evidence-based guidance to manage fish mortality from hydroelectric facilities in Canada. This is a challenge due to the large geographical area of Canada, which is comprised of a variety of different aquatic ecosystems, fish communities and hydraulic regimes.

1.2 PURPOSE AND SCOPE OF REVIEW

The purpose of this report is to:

1) Review the current state of scientific knowledge on mortality risks fish are exposed to at hydroelectric facilities.
2) Assemble the information available on the current status of fish mortality guidelines used internationally.

To conduct this review, two online resources from DFO’s virtual library were used (Web of Science, Google Scholar) along with supplemental searches using Google. A variety of search terms were used to encompass all studies related towards hydropower, fish mortality and jurisdictional regulations (e.g., fish* turbine mort*, hydro* entrainment fish* mort*, hydro* legislation) where the asterisk (*) is a search wildcard. The search returned a broad array of studies, many of which were related towards the impacts of hydropower on aquatic ecosystems. Each relevant study was summarized by the year of publication, the type of study, study species and the type of injury/mortality. Due to the large body of literature on fish injury and mortality associated with downstream migration through hydroelectric facilities, a large portion of this report depended on existing literature review articles. There was also a greater emphasis put on more recent articles (since 2005) that summarized the current state of scientific knowledge, however older studies cited within these review articles and in the literature that were relevant to the topics of the paper were also cited. The goal of this report is to provide a concise overview of the various mortality risks associated with downstream passage through a hydropower facility. Moreover, we identify and briefly describe the various causes of injury and mortality, the types of injury and mortality as well the magnitude of injury and mortality.

For the jurisdiction review, the report provides a general overview of the differences in regards to how fish mortality and injury are regulated in various international jurisdictions.

2.0 REVIEW OF THE MORTALITY RISKS FOR FISH PASSING DOWNSTREAM THROUGH HYDROELECTRIC FACILITIES

Fish mortality and injuries that can cause delayed mortality have been analyzed in extensive detail in the scientific literature. Research has identified a variety of potential mortality risks attributed to downstream passage through hydroelectric power facilities, which can be categorized into four groups: 1) turbine mortality; 2) screen/rack impingement; 3) behavioural and operational entrainment/impingement risk; and 4) rapid flow alterations. Each of these potential mortality risks vary in the diversity and magnitude of injury/mortality. In this section, we review the scientific literature related to each of these risks individually with the objective of highlighting what is known and the knowledge gaps that exist in regards to their contribution to the mortality risks associated with downstream passage through hydroelectric facilities.

2.1 TURBINE MORTALITY RISKS

The mortality risks associated with downstream turbine passage and the associated biological response of fish have been recently reviewed in a systematic literature review (Pracheil et al. 2016). This review provided insight into which hydropower turbines (Kaplan, Francis, Crossflow, Deriaz etc.) are the most popular in the US (Francis), which are the most studied (Kaplan) and which average the highest turbine entrainment morality (Francis: 28%) (Pracheil et al. 2016). The majority of mortality was identified to occur through three key mechanisms: 1) rapid and extreme pressure changes; 2) shear stress; and 3) blade strike/mechanical wounding (Pracheil et al. 2016). Each of these mechanisms varies in the types of injuries to fish and the factors that affect the severity of such injury. Here, we examine each of these mechanisms to review the extent of mortality associated with each mechanism during turbine entrainment.

Rapid and extreme pressure changes

Table 1: Summary of rapid and extreme pressure changes - Key messages and knowledge gaps

Key Messages	Knowledge Gaps
- All fish are exposed to rapid pressure changes once entrained into hydro facilities - Significant injury can occur as a result of barotrauma - Probability of injury differs significantly among species - Probability of mortal injury is dependent on the ratio of pressure change	- Do different turbine types have an effect on severity of barotrauma? - Future research should focus on appropriate operational guidelines that align with spawning periods for fish species that drift during developmental life stages - The proportion of entrainment mortality that is associated with rapid pressure changes

All fish are exposed to rapid pressure changes once entrained into a hydropower facility (Brown et al. 2014). Thus, a significant amount of research has been dedicated to focusing on the mortality risks associated with pressure changes. When fish become entrained in a hydroelectric facility, they are exposed to a slow compression in the intake followed by a rapid decompression as they pass either side of the runner blades, followed by a return through the draft tube to hydrostatic conditions in the tailrace (Carlson et al. 2008; Richmond et al. 2014). This slow compression and rapid decompression can cause significant injuries (barotrauma) that contribute to mortality (Brown et al. 2012a; Brown et al. 2014). Barotrauma can arise from one of two major pathways, the pathway governed by Boyle's law and the pathway governed by Henry's law.

The first pathway is Boyle's law. This is where barotrauma damage occurs due to the amplification of a pre-existing gas phase within the body of a fish such as that confined in the swim bladder (Pflugrath et al. 2012; Brown et al. 2012b; Brown et al. 2014). This law states that at constant temperature, in a closed system, with increasing pressure the volume of a gas will decrease proportionately (Van Heuvelen 1982). As it relates to fish and hydropower infrastructure, when fish pass through turbines, if the surrounding pressure is decreased by half, the volume of the pre-existing gas in the body doubles (Brown et al. 2014). The expansion of the swim bladder can injure fish in a variety of ways including exophthalmia (eyes popped outwards), swim bladder rupture, and internal hemorrhaging (Rummer and Bennet, 2005; Brown et al., 2009a; Stephenson et al., 2010; Brown et al., 2015).

The second pathway is Henry's law. This is where barotrauma damage occurs due to gas bubble formation (emboli) due to a decompression-induced reduction in solubility (Brown et al. 2012b; Brown et al., 2014). This law states that the amount of gas that can be dissolved in a fluid is directly proportional to the partial pressure to which it is equilibrated. When fish pass through areas of low pressure, such as those exhibited in hydroelectric turbines, and experience decompression, their blood and other bodily fluids may become super saturated resulting in emboli in their blood, organs, gills or fins (Brown et al. 2014). As these gas bubbles continue to develop, they can lead to internal rupturing of vasculature leading to hemorrhaging (Colotelo et al. 2012).

Fish may experience both processes when passing through hydroelectric turbines. However, they may not result in equal magnitude of injury experienced by fish. Most of the current evidence suggests that the more significant cause of injury is swim bladder expansion and rupture associated with Boyle’s law (Brown et al. 2014).

Since fish species contain swim bladders that vary in form and function, the probability of injury may differ considerably among species. There are two general groups that researchers have identified: physostomes and physoclists. Physostomes (e.g., Chinook Salmon, *Oncorhynchus tshawytscha*) are species that have an open swim bladder and are able to swallow air at the surface and force it into their swim bladder whereas physoclists (e.g., Yellow Perch, *Perca flavescens)* have a closed swim bladder and must regulate swim bladder volume and buoyancy (Rummer and Bennett 2005; Brown et al. 2014). For physoclists, the gas within the swim bladder is regulated and adjusted for through diffusion into the blood, a process that can take hours to complete (Cada and Schweizer 2012). Consequently, physoclists have greater potential for injury than physosomes as they cannot quickly release gas as the swim bladder expands during rapid pressure changes under turbine conditions (Brown et al. 2012).

A third group of species that do not contain swim bladders (e.g. American Eel, *Anguilla rostrata*) are less susceptible to Boyle’s law. For example, Colotelo et al. (2012) found that Pacific Lamprey (*Entosphenus tridentatus*) were uninjured after rapid decompression whereas more than 95% of the Chinook Salmon in the study had suffered mortal injuries under the same conditions. In addition, Colotelo et al. (2012) examined the effect of Henry’s law on juvenile Western Brook (*Lampetra richardsoni*) and Pacific Lamprey and held both species under low pressure (13.8 kPa) for an extended period of time (>17 min) and did not document any immediate or delayed mortality. Together, these results suggest that fish without swim bladders may have limited susceptibility to barotrauma.

Life stage of fish is another important aspect to consider with barotrauma and fish passage through hydro turbines. Different life stages may be more vulnerable and have a higher exposure to hydro turbine passage than others and therefore is critical to our understanding of how susceptible different fish species are too rapid and extreme pressure changes. To date, the majority of research focused on barotrauma has been focused on migrating juvenile salmonids (Stephenson et al. 2010; Brown et al. 2012c; Richmond et al. 2014), in particular, Pacific Salmon species. These species are semelparous; where the only life stages that are affected from downstream migration through hydro infrastructure are the juveniles. In Canada, there are also many economically important iteroparous species that may pass through turbines multiple times throughout their lives as they migrate back to the ocean after spawning events (e.g., Atlantic Salmon, *Salmo salar*) and potadromous species which migrate in river system to complete their life cycle (e.g., Walleye, *Sander vitreus* and Lake Sturgeon, *Acipenser fulvescens*). Due to this potential increased exposure to hydro facilities, these fish species may be at higher risk of receiving a mortal injury. Obtaining a greater understanding of the ecology and migration patterns of iteroparous and potadromous species is critically important in improving our understanding of their increased mortality risk associated with barotrauma.

Furthermore, recent research has begun focusing on the effects barotrauma on drifting eggs and larval stages (Brown et al. 2013; Boys et al. 2016). While this area of research is relatively new, it appears that eggs may be less susceptible to barotrauma than larval stages and that larval susceptibility can vary with age; where some larvae may only be susceptible within a certain period or stage of their development (Brown et al. 2013; Boys et al. 2016). Future research should focus on developing appropriate operational guidelines that align with spawning periods for fish species that drift during developmental life stages to best minimize the effect on those fish species.

Some studies have begun to quantify the probability of mortal injury expected from barotrauma for fish exposed to hydro turbine passage. McKinstry et al. (2007) combined the likelihood that Chinook Salmon had one, or a combination of eight injuries present following simulated turbine passage with the likelihood of mortality to establish a mortal injury metric. Building off this, Brown et al. (2012c) determined that the probability Chinook Salmon will be mortally injured is related to the pressure exposure using the following equation:

$$Probability\ of\ mortal\ injury = \frac{e^{-5.56+3.85*LRP}}{1+\ e^{-5.56+3.85*LRP}}$$

Where LRP is the natural log of the ratio of pressure change (acclimation/nadir pressure) to which the fish are exposed. Using this model, Brown et al. (2012c) determined that the probability of barotrauma-related mortal injury increased in sigmoidal fashion in the juvenile Chinook Salmon as the ratio of acclimation pressure to exposure pressure increased. At lower pressure ratios (0-1), probability of mortal injury is low (10-20%), whereas at medium (1-2) and high pressure ratios (2-3), probability of mortal injury is nearly 100% (Brown et al. 2012c). Techniques similar to those used by McKinstry et al. (2007) and Brown et al. (2012c) could in theory be used to develop mortality standards for other species.

Pracheil et al. (2016) reviewed the scientific literature and documented the survival of fish that had been subjected to barotrauma for each injury type. The average survival (±SD) was lowest for species with prolapsed cloaca (26.7%± 24.5), ocular emphysema (30.0 %±22.5) and exophthalmia (32.1%±26.4). The highest survival was found for species with swim bladder distention (73.8%±26.4), membrane emphysema (66.4%±34.3) and stomach eversion (66.3%±30.6). These models still need to address the mortality risks of other fish species, and whether turbine type has an effect on injury severity. Research clearly signifies that barotrauma has a significant effect on the likelihood that fish endure a mortal injury during downstream turbine passage.

Shear stress

Table 2: Summary of shear stress - Key messages and knowledge gaps

Key Messages	Knowledge Gaps
- Injuries that are associated with shear stress include bruising, operculum damage, gill bleeding, isthmus tear, descaling, temporary disorientation or prolonged swimming impairment and loss of equilibrium - For the slow-fish-fast-water scenario, minor, major, and fatal injuries began at velocities of 12.2, 13.7, and 16.8 $m \cdot s^{-1}$ - For the fast-fish-slow-water scenario, injuries began at entrance velocities of 15.2 $m \cdot s^{-1}$for juvenile salmonids - Injuries associated with the operculum were the most common	- Whether different turbine types affect shear injury severity - What proportion of entrainment mortality is associated with shear stress

Less research has been focused on the isolated effects of shear stress on fish species. Shear stress is the interaction that occurs between two masses of water moving in different directions (Cada et al. 2007). If a fish is trapped within the boundary between the two masses of moving water, it be may be forced in opposing directions, known as shear stress. At elevated levels of shear, injury or mortality can occur (Deng et al. 2007). At hydroelectric facilities there are two scenarios that can cause shear stress. A fast-fish-slow-water scenario, where fish are entrained into and carried by the fast-moving water before exposure to slower water, causing turbulent shear (e.g., high-flow outfalls or spillway jets) and a slow-fish-fast-water scenario where fish are exposed to the shear before they can align with the flow (e.g., in a turbine) (Richmond et al. 2009). Research has examined the biological response to each of these scenarios to determine the probability of minor or major injury at different velocities (Johnson et al., 2003; Neitzel et al. 2004; Deng et al. 2005; Richmond et al. 2009; Deng et al. 2010). Injuries that are associated with shear stress exposure include minor injuries such as minor bruising, operculum damage, slight gill bleeding, minor isthmus tear, minor descaling, or temporary disorientation and major injuries of severe bruising, bleeding, tearing, creasing, multiple injuries, prolonged swimming impairment, disorientation, and loss of equilibrium (Deng et al. 2010).

For the slow-fish-fast-water scenario, Neitzel et al. (2004) estimated 10% of the test population of juvenile salmonids (American Shad (*Alosa sapidissima*), Rainbow Trout (*Oncorhynchus mykiss*), Steelhead (anadromous rainbow trout) and Chinook Salmon) sustained minor injuries when exposed to shear zones at a velocity of 9.1 $m \cdot s^{-1}$.

Whereas Deng et al. (2005), determined that the onset of minor, major, and fatal injuries occurred at velocities of 12.2, 13.7, and 16.8 $m \cdot s^{-1}$.

Examining the fast-fish-slow-water scenario, the field and laboratory investigations by Johnson et al. (2003) showed that juvenile Chinook Salmon were not injured by entry velocities as high as 15.2 $m \cdot s^{-1}$. Based on these results, there is some evidence to suggest that a jet entry velocity up to 15.2 $m \cdot s^{-1}$ should allow juvenile Chinook Salmon to pass safely at high-flow outfalls (Johnson et al. 2003).

The velocity thresholds for fish injury under the fast-fish-to-slow-water mechanism were higher than those of fish under the slow-fish-to-fast-water mechanism for both minor and major injuries (Deng et al. 2010). For the fast-fish-to-slow-water scenario, the results of Deng et al. (2010) were consistent with those of Johnson et al. (2003) with jet entry velocities for the onset of injuries occurred at 15.2 $m \cdot s^{-1}$ with head or body bruises being the most common injuries. For the slow-fish-to-fast-water scenario, the results were consistent with those of Deng et al. (2005) where injuries began at a lower jet velocity of 12.2 $m \cdot s^{-1}$. In addition, injuries associated with the operculum were the most common injuries and began to occur at significant levels at 12.2 $m \cdot s^{-1}$ (Deng et al. 2010).

While it is difficult to quantify the direct mortality attributed solely to shear stress, some estimates suggest that shear produces at least 15% of the injuries to fish from passage through Kaplan turbines (Mather et al. 2000). Knowledge gaps exist as to whether different turbine types affect shear injury severity. However, these results provide some insight into what could be considered 'safe' velocity differences between water masses at a hydro turbine intake. With this knowledge, flow field characteristics can theoretically be better managed to help reduce injury and mortality at hydroelectric facilities.

Blade strike/mechanical wounding

Table 3: Summary of blade strike/mechanical wounding - Key messages and knowledge gaps

Key Messages	Knowledge Gaps
- Injuries associated with blade strike/mechanical wounding include bruising, laceration, hemorrhaging, amputation and decapitation - Factors that affect injury severity include fish length (thus, species and age class), discharge, turbine type and project operations - Blade strike mortality is high for adult fish and generally low for juveniles	- How fish morphology influences the probability of mechanical wounding - What proportion of entrainment mortality is associated with mechanical wounding - test these models at various hydroelectric facilities to determine whether they reflect the true entrainment of the species present

Fish that become entrained through a turbine may come in contact with the moving turbine runner blades and a variety of other fixed structures. These fixed structures include the walls of the turbine passage, stay vanes, wicket gates and draft tube piers (Cada 2001). The contact a fish may make can range from a high speed collision with a structure head-on (strike) to low force contacts with a structure that is parallel to the path of the fish (grinding/abrasion) (Cada and Schweizer 2012). Injuries associated with blade-strike include minor and major bruising, laceration, hemorrhaging, amputation and decapitation (Pracheil et al. 2016).

Blade strike has traditionally been thought of as the direct contact between a fish and the leading edge of a turbine blade. When examining blade strike and mechanical wounding as a mechanism for fish mortality, scientific studies have generally depended on blade strike modeling to determine the estimated mean probabilities of mortality (Ferguson et al. 2008; Deng et al. 2011; Richmond and Romero-Gomez 2014). Within these models are variables that can increase or decrease the probability of a blade coming in contact with a fish. These variables include fish length (thus, species and age class), turbine characteristics such as discharge rates, turbine type and project operations (Cada 2001). There is a consensus among studies that the longer a fish is, the slower the flow rate is and more blades that a turbine has, the higher the probability of blade strike (Ferguson et al. 2008; Deng et al. 2011).

Different studies have used blade strike modeling to estimate the probability of mortality, and the results are fairly consistent. For example, Ferguson et al. (2008) modelled the mortality of adult and juvenile Atlantic Salmon and sea-run Brown Trout (*Salmo trutta*) after passing through a Kaplan turbine. Results showed that mean blade strike mortality was higher for adult Atlantic Salmon and sea-run Brown Trout (25.2%–45.3%) than for juveniles (5.3%–9.7%). Deng et al. (2011) examined both deterministic and stochastic blade-strike models to compare fish passage performance of a newly installed advanced turbine to an existing Kaplan turbine. For either model, probability of injuries for juvenile Chinook Salmon after passing through a Kaplan turbine were <6%.Thus, larger fish are more susceptible to injury via blade strike then smaller fish; however, it appears mortality can occur in all size and life stages.

There are few research gaps that remain in relation to blade strike/mechanical wounding as it was often the first injury mechanism examined and blade strike models have existed since the 1950s (Ferguson et al. 2008). However, there are no current peer-reviewed studies that have examined the effect fish morphology has on the probability of mechanical wounding. There are however, industry laboratories that have tested blade-strike on species of different morphology (Rainbow trout, American Eel and White sturgeon; *Acipenser transmontanus*) (Amarel et al. 2011).

Furthermore, knowledge gaps still exist with mortality from turbine entrainment. For instance, it is still not clear from the studies stated above exactly what factors are responsible for differences in mortality rates among turbine types. However, Pracheil et al. (2016) speculate that blade strike may be the most significant factor as different turbine types (Kaplan, Francis and crossflow) have been found to have similar pressure profiles, despite having differences in mortality rates. They attribute this difference in mortality to blade spacing and number as Francis and crossflow turbines contain many more blades that are closer together than Kaplan turbines. To address these knowledge gaps, Pracheil et al. (2016) suggest that future work should focus on characterizing the range of forces exerted by stressors on fishes across many turbine types.

While these models appear theoretically sound, many of these models remain untested under real world scenarios. Future work should focus on testing these models at various hydroelectric facilities to determine whether they reflect the true entrainment of the species present.

2.2 MORTALITY RISKS ASSOCIATED WITH SCREEN/RACK IMPINGEMENT

Table 4: Summary of the mortality risks associated with impingement - Key messages and knowledge gaps

Key Messages	Knowledge gaps
- Poor swimming fish with an elongated morphology (e.g., American Eel) are more susceptible to impingement than strong swimming fish (e.g., juvenile salmonids) - Physical factors contributing to impingement include the approach velocity, sweeping velocity, screen openings and screen construction	- Different screen dimension need to be tested to develop screens that protect multiple species from impingement spanning multiple life stages

In order to minimize the entrainment of objects and fish into turbines without compromising the flow of water, intake louvers, trash racks, and fish screens are installed (Moyle and Isreal 2005; Boys and Baumgartner 2012). Louvers are a series of vertical slats, each of which are at right angles to the direction of the flow. The angle of the screen across the flow can vary between 10° and 15° where the spacing between slats varies from 2.5 cm to 15 cm depending on the target species being diverted (Larinier and Travade 2002). Generally, the role of trash racks (or bars) is to protect equipment, such as wicket gates and turbines, from debris or fish that are too large to pass through without causing harm. Typically, a trash rack consists of stationary rows of parallel carbon steel bars located at the dam intake (ORNL and Mesa Associates, 2011). Fish screens are more versatile than louvers and trash racks as they have three main functions: 1) to physically exclude entrained fish from diverted water; 2) reduce approach velocity by increasing the intake surface area and/or orienting the screen surface so that it is slanted to the intake flow; and 3) promote fish movement past the diversion and screen, usually by means of a sweeping velocity (velocity parallel to the screen face) (Hayes et al. 2000). Unfortunately, these devices intended to prevent the entrainment of fish at hydropower facilities can result in injury (descaling or bruising) or mortality if fish contact, or become impinged upon, the screen face (Swanson et al. 1998).

Fish that are good swimmers (sub-carangiform locomotion: stiff fish body, move with rear half) and exhibit behavioural avoidance when encountering velocity gradients (e.g., juvenile salmonids) are less susceptible to impingement (Kemp et al. 2005). However, fish that are have an elongated morphology and are poor swimmers (anguilliform locomotion: long slender fish e.g., Eel species) are generally unable to react until they physically encounter the structure, which leads to an increased potential for impingement (Russon et al. 2010). Thus, a significant amount of research has been dedicated to focusing on the mortality risks of impingement have focused on elongated, poor swimming fish such as eels and lampreys, in particular endangered American and European Eel (Boubee and Williams 2006; Calles et al. 2010; Russon et al. 2010; Pederson et al. 2012; Moser et al. 2015).

Studies examining impingement mortality have documented severe mortality for eels at high flow velocities. For instance, Calles et al. (2010) radio-tagged European Silver Eels (*Anguilla anguilla*) to estimate the proportion of silver eels that are able to escape to sea after passing through a hydropower facility. They found, 41% of the tagged reservoir eels that entered the intake channel of the dam were impinged and killed on an intake rack with 20 mm spacing. Studies such as this one, has led research to shift focus and identify physical parameters that limit impingement.

There are a variety of factors that contribute to impingement. These include approach velocity (velocity at the screen), sweeping velocity, screen openings and screen construction. Researchers examining the ideal conditions for reduced impingement mortality have been fairly successful. Building from Calles et al. (2010), Calles et al. (2013) found that by reducing the trash rack spacing from 20 mm to 18 mm, decreasing the rack slope from 63 to 35°and increasing the trash rack surface area by 58%, the mortality of eels was reduced to <10%. Studies like this have been critically important in developing fish screen criteria for species of importance depending on their size, swimming performance and downstream migratory life stage.

There are only a few recent studies on impingement mortality; this is largely due to the fact that much of this work was conducted early on (e.g., Page et al. 1977). Based on this earlier work, and experience with impingement mortality, some jurisdictions have developed good practice guidelines for fish screen designs and installation (NMFS 2008; Environmental Agency 2012). For instance, in the United States, the National Marine Fisheries Service (NMFS) guideline for anadromous salmon species outline specific guidance regarding fish screen design, site conditions, structure placement and screen hydraulics specific to those fish species (NMFS 2008).

Fish screening criteria will need to be customized for every hydropower facility and will be dependent on not only the species, but the life-stages of species found in the impounded water body as well. Research gaps that need to be explored include developing screens that are able to protect multiple species from impingement spanning multiple life stages.

2.3 BEHAVIOURAL AND OPERATIONAL ENTRAINMENT/IMPINGEMENT RISKS

Fish behaviour and the operations of hydropower facilities are associated with their own mortality risks as they can encourage increased entrainment and impingement. In this section, we will examine how different fish behaviours and dam operations (forebay hydraulics) may increase the probability of fish entrainment and impingement.

Fish Behaviour

Table 5: Summary of fish behaviour - Key messages and knowledge gaps

Key Messages	Knowledge gaps
- Juvenile salmonids react to accelerating flow with strong swimming and avoidance behaviour - A consequence of milling behaviour is an increased probability of alternate route choices, which may result in increased entrainment/ impingement - Juvenile salmonids may be more susceptible to entrainment /impingement at night when avoidance behaviour is less pronounced and they are deeper in the water column of the forebay - When eels encounter a constricted flow, a switch to more energetically costly avoidance behaviours occurs - Some resident species actively utilize the habitat immediately upstream from hydropower facilities and are more susceptible to entrainment/ impingement	- Need to identify, quantify and categorize what species exhibit behaviour that increase their vulnerability to entrainment/ impingement - What factors influence species behaviour (seasons, time of day, temperature etc.)

As mentioned above, entrainment and impingement can cause fish mortality in a variety of ways. However, one factor that has warranted increased investigation is how fish behaviour can influence fish entrainment and impingement at hydroelectric facilities (Coutant and Whitney 2000; Williams et al. 2012; Martins et al. 2013; Piper et al. 2013; Gutowsky et al. 2016). Different species will have different behavioural responses to changes in flow and when contact is made with physical structures (Russon et al. 2010). Going through each individual behavioural trait for a variety of species would be extensive, therefore, for this report; we focus on some of the different behaviour attributes documented for salmonids and a few select non-salmonid species.

Behaviour of Salmonids

Understanding the behaviour of juvenile salmonids as they approach hydro facilities is crucial to our understanding of the mortality risks associated with downstream passage. Early studies originally suggested that the fundamental behavior pattern of juvenile salmonids was surface oriented and involved following the flow, reflecting obligate passive displacement (Coutant and Whitney, 2000). However, recent studies have since contradicted this notion, as juvenile salmonids have been found to react to accelerating flow with strong swimming and avoidance behaviour (Kemp et al. 2005; Enders et al. 2009; Svendsen et al. 2011).

This avoidance behaviour is often referred to as holding or milling behavior and is defined as the behaviour of turning, changing direction, and making multiple passes in front of an obstacle (Johnson and Moursund 2000; Grote et al. 2014). This behaviour is often found with downstream migrating smolts when they encounter a velocity gradient, such as those in the forebays of hydroelectric facilities. While this behaviour is intended for salmonids to avoid negative impacts, milling behaviour has been documented to have negative impacts on the fitness of smolts. These negative impacts on fitness include: additional energetic costs (Nestler et al. 2008), increased predation risk (Plumb et al. 2006) and, most importantly, increased probability of alternate route choices (other than by-pass systems) that may lead to an increased probability of impingement and entrainment (Enders et al. 2009).

Many studies examining milling/avoidance behaviour of juvenile salmonids associated with velocity gradients, have studied how this behaviour can be altered by other sensory stimuli (Kemp and Williams 2009; Kemp 2012; Vowles and Kemp 2012; Vowles et al. 2014). For instance, Vowles et al. (2014) examined that effect light and dark changes avoidance behavior of juvenile Chinook Salmon in an experimental flume. Their results indicated that the majority of fish exhibited an observable response on encountering accelerating velocity, with avoidance behaviour elevated when light (45%) in comparison to when dark (12%). This may imply that juvenile salmonids may be more susceptible to entrainment in a turbine intake area at night where avoidance behaviour is less pronounced.

Since the probability of mortal injury from hydro facilities is dependent on the ratio of pressure change, salmonid acclimation depth in forebays of dams as they approach turbine intakes has been studied to identify ways to reduce the risk of barotrauma. Li et al. (2015) examined the depth distributions of ~ 28,000 individually tagged subyearlings and yearling Chinook Salmon and juvenile Steelhead passing two dams on the Snake River in Washington State. The median depth at which the juvenile salmonids approached turbines ranged from 2.8 to 12.2 m, with the depths varying by species/life history, year, location (which dam) and diel period (between day and night). The largest differences in depth distributions were associated with diel period. Subyearling Chinook Salmon and Steelhead were consistently detected deeper in the water column of the forebay during the night than during the day, whereas there was no difference for yearling Chinook Salmon. The authors speculate that salmonids who display this behavioural attribute may be more susceptible to turbine entrainment at night, when they cannot see the dam and consequently are quickly entrained into the flow, in comparison to the day where they can visually see the dam face and may take a longer time to search for a passage route (Li et al. 2015).

Behaviour of Non-Salmonids

There has also been a significant amount of research examining the behaviour of non-salmonid species (Travade et al. 2010; Piper et al. 2013; Martins et al. 2013; Martins et al. 2014; Piper et al. 2015).

After salmonids, the most investigated species in regards to the mortality risks associated with hydropower are catadromous European and American Eel. Similar to salmonids, eel behaviour during downstream migration is influenced by flow acceleration (Piper et al. 2015). European Eel have also been described displaying milling behaviour in front of hydroelectric facilities (Winter et al. 2006). Findings differ when describing the hydrodynamic stimuli and avoidance behaviour by eels. Many laboratory and field studies have suggested that the majority of eels do not respond to changes in flow and only respond once contract is made with excluding structures (e.g., screens) (Brown et al. 2009b; Russon et al. 2010). However, other studies have suggested that eels do respond to changes in flow (Piper et al. 2015). In their study, Piper et al. (2015) tracked the movements of 40 tagged adult European Eel through the forebay of a hydropower intake under two manipulated hydrodynamic treatments. Tracking the eels, they found that initially, eels approached the intake semi-passively. However, a switch to more energetically costly avoidance behaviours occurred on encountering constricted flow, prior to physical contact with structures. Under high water velocity gradients, eels then tended to escape rapidly back upstream, whereas exploratory behaviour was common when acceleration was low.

Whereas migratory species are well studied in regards to behaviour in front of turbine intake areas, few researchers have examined the mortality risks associated with the behaviour of resident fish in forebays (Martins et al. 2013; McDougall et al. 2013; Martins et al. 2014). These species are vulnerable to entrainment when they use habitats near water intake structures, with vulnerability to entrainment varying with factors such as species, life stage, time of day and season (Coutant and Whitney 2000). In a study that used acoustic telemetry to assess entrainment vulnerability of adult Bull Trout (*Salvelinus confluentus*) and Burbot (*Lota lota*) in a hydropower reservoir, Martins et al. (2013) provide evidence of this varying entrainment vulnerability. Their results indicated that: 1) adult Bull Trout and Burbot made little use of the forebay; 2) Bull Trout used the forebay more and had higher rates of entrainment than Burbot; and 3) both forebay use and entrainment varied among seasons with Bull Trout using the forebay more in the fall and winter whereas limited data suggests that Burbot are more vulnerable to entrainment in the fall (Martins et al. 2013).

Although Burbot and Bull Trout make little use of the forebay in general, some species actively use habitat that is immediately upstream from hydropower facilities which may make them more susceptible to entrainment (Coutant and Whitney 2000). One species that does use this habitat is Lake Sturgeon. Using acoustic telemetry, McDougall et al. (2013) tracked the movement patterns of juvenile, subadult and adult Lake Sturgeon residents in a small hydropower reservoir in the Winnipeg River. Their results show that all size-classes utilized the habitat immediately upstream of hydroelectric facilities, and that 27% of subadults tagged in the lowermost section of the reservoir, and 8.7% of adults tagged throughout the reservoir were entrained (McDougall et al. 2013).

Research gaps exist relating to fish behaviour and turbine entrainment susceptibility (e.g., determining which specific species behaviours are most likely to increase vulnerability to entrainment), however it is apparent that fish species react to hydroelectric facilities in a variety of ways and behaviour should be considered by engineers and operators when managing the forebay hydraulics of the hydropower facility.

Forebay Hydraulics

Table 6: Summary of forebay hydraulics - Key messages and knowledge gaps

Key Messages	Knowledge Gaps
- The evaluation of fish entrainment risk based on threshold hydraulic criteria is a relatively new concept - During freshet scenarios, fish may have a higher risk of entrainment - At a run of the river facility, large adult fish (>300 mm) may not be susceptible to entrainment during the fall and winter whereas small and/or juvenile fish may be at risk of entrainment year round - For a run of the river facility, the greatest impact on fish entrainment probability is the development of fish habitat, caused by forebay hydraulics, near the intakes - When high-head dams are operating under low water level scenarios, the risk of entrainment and impingement of fish species is much higher in comparison to operating under normal water level scenarios.	- Velocity and acceleration thresholds to limit entrainment/ impingement are required for different types of dam operations - How entrainment/impingement risk from forebay hydraulics may change in relation to different abiotic factors (e.g., temperature, precipitation, etc.)

As a hydropower facility operator, it is very difficult to manage fish behaviour that increases their vulnerability to become entrained into turbine intakes or impinged onto screens. Dam operators can theoretically manage their hydropower operations to ensure entrainment of fish is minimized. But, hydropower operations are generally run to maximize efficiency and operations can influence the flow patterns upstream of the intakes and spillway and thus increase the risk of fish entrainment/impingement into turbines or onto screens. If operators have a better understanding of the intake-induced flow field, it could allow the hydropower operators to optimize their operations and reduce the risk of intake-induced fish entrainment/ impingement (Huang et al. 2015). However, the potential for this scenario is largely dependent on the site.

Computational fluid dynamic (CFD) modeling have been used in studies as a flow modeling tool to evaluate the flow field upstream of hydropower dams (Bryant et al. 2008; Rakowski et al. 2012). Yet, despite the use of CFD, the evaluation of fish entrainment/impingement risk based on threshold hydraulic criteria is a relatively new concept (Huang et al. 2015; Langford et al. 2015). Using CFD modeling, Langford et al. (2015) assessed the risk posed to Mountain Whitefish (*Prosopium williamsoni*) and Westslope Cutthroat Trout (*Oncorhynchus clarki lewisi*) under a low-flow and spring freshet scenario upstream of the run-of-the-river Aberfeldie Dam in British Columbia. They showed that: 1) during freshet scenarios, fish may have a higher risk of entrainment; 2) large adult fish (>300 mm) may not be susceptible to entrainment during fall and winter periods when flows are low; and 3) small and/or juvenile fish may be at risk of entrainment year round. Additionally, the authors noted that the majority of the entrainment risk may be associated with indirect factors such as the formation of a sediment infilled head pond, with a local scour hole. Langford et al. (2015) found that within the scour hole there is deeper overwintering habitat and foraging opportunities that attract both of these species. However, the scour hole is partially occupied by a fast-moving entrainment zone. Due to the fish attraction to this zone, fish density increases greatly adjacent to the intakes (Langford et al. 2015). Thus, for this run-of-the-river facility, it appears the greatest impact on fish entrainment probability is the creation of fish habitat, caused by forebay hydraulics, near the intakes.

Another study examined the risk zones for fish entrainment under different operational scenarios at a high head dam in China (Huang et al. 2015). The five scenarios they examined were: 1) all nine left intakes operating under the normal reservoir water level (825m); 2) the same characteristics as scenario one but with three spillways in operation; 3) nine intakes in operation under the ‘dead’ water level (765m - low water level); and 4) & 5) both have four left intakes operating but with different arrangements. Each of these scenarios was associated with specific thresholds of velocity and acceleration. Results indicated that for scenarios when spillways are in operation (scenario 2) or when the dam is running under the dead water level (scenario 3), the risks zones for fish entrainment are larger and the velocity of the surface water is much greater than under normal operating conditions. Under these scenarios, the authors suggest that the potential risk of fish entrainment extends much further in the approach channel of the dam, which could cause dangerous conditions for those fish species that inhabit the forebay (Huang et al. 2015).

The field of forebay hydraulics and the use of CFD to evaluate entrainment/impingement risk is an emerging field as there are only a few studies available and as for right now, the results are site-specific. However, while our knowledge is still growing on how forebay hydraulics can influence fish entrainment/impingement, there is potential for greater use of CFD in the future to better manage forebay hydraulics of dams to reduce the mortality risk to fish. Research gaps still exist (e.g., velocity and acceleration thresholds for different types of dam operations), however these studies do provide the foundation of a mechanism for operators to use in order to manage fish entrainment/impingement at their hydroelectric facility.

2.4 MORTALITY RISKS ASSOCITED WITH RAPID FLOW ALTERATIONS

One of the reasons that hydroelectricity is an attractive option for power-generation is its flexibility to provide power for peak demand periods. Consequently, this results in dams potentially producing many types of flow pulses at different times of the year, and at different times of day. Young et al. (2011) reviewed the different types of flows and identified six categories.

1) Peaking flows: water is held in a reservoir when electrical demand is low (e.g., at night) and released during periods of increased electrical demand (e.g., late afternoon) (Cushman et al. 1985).
2) Load-following flows: flows generated when electricity is produced in response to immediate system load demands (Geist et al. 2008).
3) Flushing flows: Known as remedial flushing flows or maintenance flushing flows, and are optional flow releases usually timed with peaks in the natural hydrograph that can be used to remove sediment accumulations. The characteristics of these flows are designed to mimic naturally occurring pulses in the specific watershed (Petts 1984).
4) Spill flows: Flows that are the result of spring freshet or precipitation that exceeds the regulated capacity of a given hydroelectric storage reservoir (Lundqvist 2008).
5) Recreational flows: Flows released for the purpose of recreational activities (e.g., kayaking or white-water rafting).
6) Discretionary operational flows: Flows that bypass out-of-service hydroelectric facilities so that downstream facilities can generate electricity.

These flows can have a wide variety of adverse effects on the resident and migratory stream fish further downstream ranging from fish stranding to altering fish migrations (Young et al. 2011). While it is recognized that a variety of adverse effects can negatively impact fish species (e.g., altered migration) only a few can be linked to direct mortality of fish and as such reporting all the adverse effects is beyond the scope of this report. Of the adverse effects reported, mortality can be attributed to a few mechanisms: 1) fish stranding; 2) nest site dewatering leading to reduced rearing survival and 3) total dissolved gas supersaturation.

Fish stranding

Table 7: Summary of fish stranding - Key messages and knowledge gaps

Key Messages	Knowledge gaps
- The number of fish stranded can vary significantly from year to year and from site to site - A stranding event is affected by a combination of abiotic (e.g., water temperature) and biotic (e.g., life stage) factors - General consensus is that a low base water flow, shallow shoreline slopes, heavily structured littoral zones, cooler water temperatures and abrupt water levels changes are conditions that increase the likelihood of fish stranding events - The biological response of flow reductions on individual fish can range from minor sub-lethal impacts to direct mortality	- Characterize which species are most vulnerable to stranding - Quantify the proportion of fish stranding mortality in comparison to entrainment/impingement mortality

Fish stranding is any event where fish become trapped in pools and isolated from a main body of water or are beached due to rapid fluctuations in flow regime leading to injury or mortality (Hunter et al. 1992). This experience can occur in both lentic and lotic environments and is caused by natural and anthropogenic processes that can rapidly alter water levels. In the case of hydropower, this is most evident in hydropeaking operations where water is typically stored in a reservoir during times of low energy demand and released through turbines when energy demand is high (Cushman et al. 1985). This storing and releasing of water can result in rapid fluctuations of water levels and flow in the downstream river of the hydroelectric facility.

The number of stranded fish can vary significantly from year to year and from site to site, making it difficult to quantify consistently. For example, eight years of monitoring data by BC Hydro and Golder and Associates has focused on assessing the extent of fish stranding on the Kootenay and Lower Columbia Rivers (BC Hydro 2011; BC Hydro 2012; BC Hydro 2013; BC hydro 2014; BC Hydro 2015). In their fourth year of monitoring, they conducted fish stranding assessments during 19 of the 21 reduction events between 1 April 2010 and 1 April 2011. The results varied significantly with one site having over 7747 stranded fish identified in 11 visits to other sites that had only one fish identified in eight visits (BC Hydro 2011). Out of all 21 reduction events, the majority (n=15,630 or 77%) of stranded fish found during the study were observed during three reduction events (BC Hydro 2011). Comparing these results, the same site that was identified to have stranded 7747 fish in 11 visits only was recognized in stranding 53 fish in 9 visits the following year (BC Hydro 2012). This reflects the variability in severity of reduction events and demonstrates the importance of understanding abiotic and biotic factors when discussing fish stranding potential.

The extent of stranding after a flow reduction can be affected by a number of abiotic and biotic factors. Abiotic factors include water temperature, time of day/light conditions, duration of shoreline inundation (wetted history), water flow rate, minimum discharge level (river stage), substrate characteristics and bathymetric morphology (Bradford et al. 1995; Bradford 1997; Saltveit et al. 2001; Halleraker et al. 2003; Bell et al. 2008; Irvine et al. 2009). Biotic factors include fish morphology, life stage and fish behaviour (Bradford et al. 1995; Saltveit et al. 2001). While all of these factors are considered to contribute to fish stranding, the general consensus is that a reduced water flow, shoreline slopes less than 6%, heavily structured littoral zones, cooler water temperatures and abrupt water levels changes are conditions that increase the likelihood of fish stranding events (Hunter 1992; Saltveit et al., 2001; Halleraker et al. 2003; Bell et al. 2008; Irvine et al. 2009; Irvine et al. 2015).

For example, after three years of experiments, Irvine et al. (2009) found higher natural fish density, longer periods of wetted history and higher ramping rates all led to higher probabilities of pool stranding. Irvine et al. (2015) examined ten years of data from the Columbia and Kootenay Rivers and found stranding risk was associated with minimum river stage, day of the year (summer) and whether a site had been physically altered (channels). The combination of factors giving the highest probability of stranding was a large magnitude reduction completed in the afternoon in midsummer, at low water levels when the near shore had a long wetted history (Irvine et al. 2015).

Biotic factors also have a significant influence in fish stranding potential. Stranding is life-stage dependent. Newly emerged fry are more vulnerable to stranding because they use substrate as cover in shallow water habitats, and have limited swimming ability, whereas larger juveniles tend to reside in deeper, higher velocity waters where they are less susceptible to stranding (Bradford 1997). Stranding is also very species-specific, for instance, Bradford et al. (1995) showed that at night Coho Salmon (*Oncorhynchus kisutch*) and Rainbow Trout were active in the water column and the incidence of stranding during flow reductions was greatly diminished. Conversely, Schmutz et al. (2015) examined the effect of stranding on the European Grayling (*Thymallus thymallus*) and found that larvae and juveniles use shallow marginal habitats and shift to even more shallow habitats at night, making them more exposed to stranding.

While it is important to understand the abiotic and biotic factors that contribute to stranding, stranding events can also be dictated by random events that cannot be controlled or planned for (e.g., drought). For such cases, it is important understand and address this uncertainty for the chance a random event could occur.

The reason fish stranding research has become vital in assessing the impact hydroelectric facilities have on stream fish populations is the consequences stranding has on fish health. The biological response of fish stranding on individual fish can range from minor sub-lethal impacts to direct mortality. Stranding mortality can occur for a variety of reasons ranging from desiccation, predation, hypoxia and temperature stress (Young et al. 2011; Quinn and Buck 2001; Donaldson et al. 2008). If a fish does survive a stranding event, there are many sub-lethal effects that must be considered as well. For example, when pools become isolated during flow reduction events, water quality of that pool can decline (e.g., a reduction in dissolved oxygen, change in temperature).

Nest site dewatering/reduced rearing survival

Table 8: Summary of nest site dewatering/reduced rearing survival – Key messages and knowledge gaps

Key Messages	Knowledge Gaps
- Lithophillic spawning fish are the most vulnerable to nest site dewatering - Tolerance to dewatering appears to be dependent on life-stage and species - Eggs are more tolerant than intergravel life stages - Intrusions of groundwater may assist in egg development and alleviate the impact of dewatering - Dewatering have been shown to have cascading effects that resulted in the decline of productivity in a salmonid population - In order to maintain a high survival	- Further examination is required to determine whether dewatering has an effect at the ecosystem level - Limited studies examining the effect nest site dewatering has non-salmonid fishes

	throughout the developmental stage, spawning beds should be constantly inundated	

While hydrological regimes influence fish directly through stranding, they also have substantial indirect effects on spawning habitat and rearing survival. In particular, during hydropeaking operations, the dewatering of spawning areas may occur for various periods and lengths of time (Young et al. 2011). Lithophillic spawning fish may be the most vulnerable to changes in river stage as they deposit eggs on or within the substrate in shallow water. This is a common reproductive strategy utilized by many riverine fishes including Cyprinidae (minnows), Esocidae (pike), Catostomidae (suckers), Salmonidae (salmonids) and Acipenseridae (sturgeons) (Grabowski and Isley 2007). Redd dewatering has been documented for a variety of salmonids including Chinook Salmon (McMicheal et al. 2005), Kokanee (*Oncorhynchus nerka*) (Fraley et al. 1986), Atlantic Salmon (Saltveit and Brabrand 2013; Casas-Mulet et al. 2015), Rainbow Trout and Brown Trout (Becker and Neitzel 1985), with recent studies expanding to examine non-salmonids such as the endangered Robust Redhorse in the southern United States (*Moxostoma robustum*) (Grabowski and Isley 2007; Fisk et al. 2013).

All of these species are vulnerable to dewatering, but tolerance to dewatering may vary depending on life-stage and species. Many studies have found that when exposed to dewatering conditions, eggs are much more tolerant to dewatering than the post-hatching intergravel stage of development (McMicheal et al. 2005; Harnish et al. 2014; Casas-Mulet et al. 2016). After examining egg and hatching survival rates in a dry river bed compared to river water, Casas-Mulet et al. (2014) found that there was no difference in the survival rate of eggs between the two sites (~91%). However, the eggs in the dry river bed had a lower survival rate from fertilizing to hatching (~57%) where the eggs in the river had no additional mortality towards hatching (~91%).The reason this occurs is because of differences in respiratory systems. Following the development of functional gill structures, alevins require a more constant supply of oxygenated water than eggs (Becker et al. 1983).

Despite the fact that eggs are more tolerant than the intergravel life stages, eggs can be subject to mortality depending on the dewatering conditions. Under experimental laboratory conditions, salmon eggs could survive for up to 5 weeks in dewatered gravel as long as they were moist (at least 4% moisture by weight) and not subjected to extreme temperatures, heat or near freezing (Becker et al. 1985; McMicheal et al. 2005). Since most salmon spawn in the late fall/early winter, spawning during high flows in a hydropeaking river that have long duration drawdowns during very cold periods, is a potential source of the most likely cause of mortality in the ramping zone (Casas-Mulet et al. 2014). Groundwater-surface water interaction is another important factor when considering the influence of rapid flow alterations on egg survival (Saltveit and Brabrand 2013; Casas-Mulet et al. 2014; Casas-Mulet et al. 2015). In spawning streams, subsurface water is typically warmer than surface water during winter and not deficient in oxygen. As such, eggs of Atlantic Salmon may survive for longer periods even if the air temperatures are below zero. This implies that in some cases, where groundwater chemistry is suitable, intrusions of groundwater may assist in egg development and alleviate the impact of alternating flows.

In addition to the moist environment required by the eggs, alevins need to be continuously inundated to survive (Casas-Mulet et al. 2016). Differences in alevin survival rates have been linked to differences in hydropower operation strategies. Casas-Mulet et al. (2016) examined two different hydropower operation strategies in Norway (Suldalslagen and Lundesokna Rivers) and found in the Lundesokna River, which has shorter and more infrequent de-watering episodes due to lower hydropeaking activity, survival of alevins was higher as a result of almost permanent high discharges inundating the egg boxes during the hatching period (Casas-Mulet et al. 2016).

Mortality from nest dewatering can have cascading effects. High mortality of the intergravel life stages of autumn Chinook Salmon was attributed to de-watering of redds, resulting in a pronounced decline in the productivity of the population (Harnish et al. 2014).In particular, de-watering events that occurred after hatching but prior to swim-up resulted in low egg-to-pre-smolt survival, whereas dewatering events that occurred prior to egg hatching had little effect on pre-smolt survival (Harnish et al. 2014). Thus, it is evident that in order to maintain a high survival throughout the developmental stage, that spawning beds should be constantly inundated.

Total dissolved gas supersaturation

Table 9: Summary of total dissolved gas supersaturation – Key messages and knowledge gaps

Key Messages	Knowledge Gaps
- The phenomenon of total dissolved gas supersaturation (TDGS) has been of scientific interest since the 1960's and 70's, however, interest in the topic has grown recently with dam operations increased use of spillways - The cause of TDGS mortality has generally been attributed to chronic and acute gas bubble trauma/disease (GBT). - Sub-lethal and lethal effects of GBT - Some investigations claim that some fish species are more susceptible to TDGS than others where other studies failed to show a difference among species - Greater resistance to TDGS during egg development in comparison to the fry stage for salmonids - Low exposure for adult salmonids has been attributed to their preference to remain deep in the water column which allows them to avoid any adverse effects of TDGS	- Studies just beginning to use CFD modeling to better understand the hydraulic criteria surrounding plunge pools and TDGS - Population effects of TDGS and GBT

When spill from a dam occurs, atmospheric gases (e.g., nitrogen and oxygen) and water become mixed leading to high levels of total dissolved gas (TDG) in the discharged water (Weitkamp and Katz 1980). Under equilibrium conditions, water is limited in how much TDG can be held in solution (i.e. up to 100%). However, if spilled water is allowed to plunge to depth (as is the situation with spillway discharge), the hydrostatic pressure of water is increased, thus increasing the solubility of gases in water, which can lead to supersaturation (>100%) (Weitkamp and Katz 1980; Clarke et al. 2008). The phenomenon of total dissolved gas supersaturation (TDGS) has been of scientific interest since the 1960's and 70's due to observations on the Columbia River of TDGS levels in surface waters as high as 143% (Beiningen and Ebel 1970). However, interest in the topic has grown recently with dam operations increased use of spillways to balance electricity demands or as a method to pass migrating fish (Clarke et al. 2008). The literature on TDGS is extensive and to cover all the factors that contribute to TDGS is beyond the scope of this review, thus, we will only focus on the mortality risks as it relates to TDGS. For further information on the factors that contribute to TDGS susceptibility, (i.e. depth distributions, hydrostatic compensation and behaviour) see Weitkamp and Katz (1980) and Weitkamp (2007) including their citations.

TDGS has been recognized for decades in the scientific literature for being a considerable mortality risk for fish downstream from hydropower facilities (Ebel and Raymond 1976; Weitkamp and Katz 1980; Clarke et al. 2008). The cause of this mortality has generally been attributed to chronic and acute gas bubble trauma/disease (GBT). GBT is a non-infectious disease that is physically induced and is often associated with exophthalmia and the formation of gas bubbles in the blood, fins, gills, and tissues (Bouck 1980).

Sub-lethal effects of GBT can include reduced feeding, reduced growth, blindness, increased stress, and decreased lateral line sensitivity, which can lead to delayed mortality or increased predation (Schiewe 1974; Weitkamp and Katz 1980). Lethal effects of GBT are generally attributed bubble formation in the cardiovascular system, causing blockage of blood flow (Weitkamp and Katz 1980). However, other signs of GBT that cause death or high levels of stress in fish include over-inflation and rupture of the swim bladder in young or small fish (Shrimpton 1990), bubble formation in gill lamella of large fish or in the buccal cavity of small fish, leading to blockage of respiratory water flow (Fidler 1988), and emphysema on body surfaces, including the lining of the mouth which may contribute to the blockage of respiratory water flow (Fidler 1988; White et al. 1991).

There is a considerable amount of literature that exists examining the incidence and severity of GBT in relation to mortality in a variety of different fish species and life stages (Ebel and Raymond 1976; Krise and Herman 1991; Mesa et al. 2000; Backman and Evans 2002; VanderKooi et al. 2003; Geist et al. 2013; Wang et al. 2015).

Some studies have found differences in fish species susceptibility to TDGS. Using LT_{50} times, (duration of exposure corresponding to a cumulative mortality of 50%

for the exposed individuals) VanderKooi et al. (2003) found that at 125% TDG, the order of relative sensitivities of various species was Northern Pikeminnow (*Ptychocheilus oregonensis*) ≥ Largescale Sucker (*Catostomus macrocheilus*) > Longnose Sucker (*Catostomus catostomus*) > Redside Shiner (*Richardsonius balteatus*) > Walleye. When TDG was increased to 130% the LT_{50} times were half as long at 125% TDG with a similar order of species sensitivities.

Differences in susceptibility also exist among life stages. For example, salmonid embryos have been previous found to be resistant to TDGS (Weitkamp and Katz 1980) and that this resistance is attributed to higher hydrostatic pressure within the egg capsule than atmospheric pressure. These internal pressures have been documented to increase through development, where pressures are at least 15 mm Hg in eggs, 50 mm Hg in embryos and as high as 90 mm Hg near hatching (Weitkamp 2007). These internal pressures of 50-90 mm Hg are equivalent to 107-112% saturation at atmospheric pressure (Weitkamp 2007). Resistance then appears to decrease between the larval and juvenile stages. Nebeker et al. (1978) found that there were differences in susceptibility among Steelhead life stages to TDGS where eggs, embryos, and pre-swim-up larvae were more resistant than swim-up and fry stages. There also appears to be less exposure to TDGS by adults in comparison to juveniles which decreases their susceptibility (Backman and Evans 2002). This low exposure has been attributed to behaviour which keeps adults deep in the water column which allows them to avoid any adverse effects of TDGS (Johnson et al. 2005).

Recent research that examines TDGS have begun to use computational fluid dynamic modeling to create 2D models of flow to better understand the complexities of plunge flows (Ma et al. 2016). This area of research is still in the infancy stage and there are many areas in which modeling for high dam plunging spills could be improved. Some of these areas include 1) modeling the process of gas bubble breakup and coalescence; 2) collect *in situ* data for the bubble size distribution in a plunge pool to replace assumed distributions based on laboratory results and 3) developing 3D models to examine TDGS in plunge pools (Ma et al. 2016). Furthermore, while there is extensive research related to the mortality risks associated with TDGS and GBD, one knowledge gap that could be addressed is scaling up TDGS and GBT risks to population-level effects (Weitkamp 2007).

3.0 SUMMARY OF THE MORTALITY GUIDELINES CURRENTLY USED INTERNATIONALLY

For this section of the report, we will provide an overview of the mortality guidelines related towards hydropower currently used in four international jurisdictions. The countries chosen include: two from the European Union (Sweden, Netherlands), Norway and the United States. These countries were chosen as each differs in their methods for regulating mortality. Though each of these countries differs in their regulatory methods, each country is required to undergo an environmental impact assessment for new hydropower projects to assess their impacts on aquatic ecosystems, which is not discussed in specific detail here.

3.1 EUROPEAN UNION

The European Union has directives that set mandatory targets for each member state. While there are a few directives that relate to hydropower (e.g., Habitats Directive, Renewable Energy Directive) the main directive that regulates the environmental impact of hydropower is the Water Framework Directive (WFD) (Directive 2000/60/EC). This directive establishes a framework for the protection of inland surface waters, transitional waters, coastal waters, and groundwater. It ensures that European Union water bodies will achieve “Good Chemical and Ecological Status” by 2015 and no later than 2027. Generally, these objectives have been seen as over-ambitious in terms of time-scale (Hering et al. 2010). In 2012, the directive aim for ‘good status or potential’ for all water bodies was predicted to not be achieved, with an estimated ~53% of EU water bodies covered by the Directive being able to achieve the goal (European Commission 2012).

Within this framework, water bodies can be designated as “heavily modified water bodies” (HMWB), which includes water bodies affected by hydropower. These water bodies have less stringent environmental targets and need to reach the less strict Environmental Quality Standard requirement of “Good Ecological Potential” (GEP) rather than “Good Ecological Status” (GES).

To achieve GES, the quality of biological elements for surface water must show minimal change resulting from human activity and deviate only slightly from those normally associated with the surface water found in pristine natural conditions (Directive 2000/60/EC). The quality of biological elements is based on the status of the biological (phytoplankton, macroalgae, macrophytes, benthos, and fishes), hydromorphological and physico-chemical quality elements in surface waters (Borja and Elliott 2007). GEP on the other hand, refers to slight changes in the values of the relevant biological quality elements as compared to the values found for “Maximum Ecological Potential” (MEP). MEP is considered as the reference condition for HMWB, and is intended to describe the highest quality natural aquatic ecosystem that could be achieved given the hydromorphological characteristics that cannot be changed without significant adverse effects on the economic viability of the project or the wider environment (Borja and Elliot 2007).

Implementation of the WFD will have implications about how hydropower is developed in the future. A *Common Implementation Strategy Workshop* was held in 2007 in Berlin that discussed the implications for hydropower with respect to the WFD (Ecologic 2007). Some conclusions were reached at the end of the workshop as it relates to fish mortality and hydropower. These conclusions include: 1) biological continuity (upstream and downstream migration) and ecologically acceptable flow were identified as priority considerations for the improvement of water ecological status; 2) much research leading to technical innovations has still to be undertaken, especially as related to downstream migration in combination with impacts of turbine passage on aquatic biota; and 3) there should be a clear insight into all costs & benefits of hydropower. This insight will help sustainable decision-making on hydropower projects and implementing the polluter pays principle.

While this framework is legally mandated across all members of the European Union, each country still has their individual laws when referring to hydropower and fish mortality. Here we provide examples of Sweden and Netherlands to show the difference in approaches.

Sweden

Sweden is similar to Canada as it is among the top ten hydropower producers in the world (Karlberg 2015). Hydropower in Sweden accounts for approximately 45 % of the total produced electricity per year in Sweden (Karlberg 2015). The Environmental Code is the primary legal authority for the regulation of hydropower. The Environmental Code is sectioned into chapters that indirectly protect fish species from hydropower operations. For instance, chapter 2 of the Code establishes what is referred to as "general rules of consideration." It requires operators to demonstrate that they operate in an environmentally acceptable manner in line with the requirements of the Environmental Code. Chapter 2 also establishes the "polluter pays" principle where operators that cause an environmental impact must pay for preventive or remedial measures. The WFD is imposed through chapter 5 in the Environmental Code, which lays out provisions regarding environmental quality standards, including the maximum or minimum level or value relating to the water level or the flow in water systems, watercourses, groundwater or parts thereof (Swedish Environmental Code 2001). The Code also requires using the best possible technology in the operation of an enterprise, which, for hydro dams, includes the best technology for fish passage. Chapter 11 of the Environmental Code specifically addresses water operations, including the construction or modification of hydropower facilities and production conditions. This chapter specifies that water operations may only be undertaken if the benefits to public and private interests are greater than their environmental impacts.

Though the Environmental Code provides a strong, albeit, indirect legal base for fish protection from hydropower facilities, one detrimental aspect of Sweden's regulation of hydropower is their licensing. In Sweden, license reviews are optional and must be initiated by a public agency or by the operator. This means that the term of licences for dams can theoretically be unlimited. As a result, only 73 of the 3727 hydropower plants and regulatory dams in Sweden have permits that are in compliance with the Environmental Code (Lov 2013). The reason this has occurred is due to the difficulty in engaging proponents to undergo a licence review. When a licence is up for review, the public agency or a third party must show that additional environmental measures are needed and that these measures will not unreasonably interfere with hydropower production (Rudberg et al. 2014). This has led to very few (in comparison to other countries with similar capacity) licensing reviews and fish improvement measures (Rudberg et al. 2014). Between 1990 and 2010, the Land and Environmental Court reviewed a total of 90 hydropower licenses, resulting in 132 biodiversity and fish improvement measures (Rudberg et al. 2014). There is also no evidence that the Court required any dam removals through this license revocation process (Rudberg et al. 2014). Another reason Sweden is criticized for this approach is that hydro facilities are only obligated to operate under the environmental laws that were present at the time of licencing. Therefore, older dams may operate with little consideration for fish mortality.

Though Environmental Code presents a method for regulating the environmental damage caused by hydropower, there appears to be some flaws within the system that still need to be addressed. Additionally, the underlying element is that there is no specific reference to hydropower-induced mortality within the Environmental Code.

Netherlands

The Netherlands does not possess a large installed hydropower capacity (World Energy Council 2013). However, the Netherlands regulates fish mortality from hydropower with a 10% cumulative mortality standard for prioritized fish species (e.g., eels and salmon). This benchmark is based on expert judgments from the task force established by the Department of Public Works and the Ministries of Agriculture, Nature, Nutrition, and Economic Affairs (Manders et al. 2016). The reasoning behind this standard is to lessen the mortality that is caused from downstream passage through hydropower facilities. The standard (which has been in place since 2001) was chosen because it limits the pressure endangered fish endure passing through hydroelectric facilities. The goal of the standard is that it will comply with the precautionary principle as a necessary safety margin to ensure the stability of the species in relation to mortality from causes other than hydropower plants (e.g., other adverse environmental factors, natural mortality, fishing etc.). If the 10% threshold is already exceeded by existing power plants, new projects are only allowed to be completed when an additional <0.1% fish mortality for prioritized species is ensured (Berg et al. 2015).

There have been a variety of different opinions on this 10% cumulative mortality guideline. On one hand, the guideline has made the policy and laws towards fish mortality transparent, but on the other hand it has made it much more challenging for dam builders to obtain permits. Furthermore, it has been a challenge for industry and other stakeholders to meet this guideline. In 2012, environmental organizations in the Netherlands appealed the granting of two licenses to establish the Borgharen hydro plant. According to these organizations, the licenses disregarded the fact that when migrating fish are on their route towards the future Borgharen plant, they would be severely stressed, since they have to already pass through two other existing hydro plants situated on the Meuse River. Since the two existing plants already exceeded the benchmark for fish mortality of prioritized species, these organizations claimed there was no option for a third hydro plant (Manders et al. 2016). Furthermore, the Borgharen hydro plant was proposed to be located in an ecologically important Natura 2000 designated location (Manders et al., 2016). Stressing the ecological importance of this location, the fish interest organizations insisted that if the hydro plant is built, it could not cause any additional damage to fish within the Meuse River (Manders et al. 2016).

Conversely, the proponent of the Borgharen hydro plant questioned the empirical validity of the benchmark. The 10% benchmark currently serves as the standard to define policy for hydro plants in the Netherlands. However, the Council of State (an advisory body to the Dutch Government and States General that consists of members of the royal family and Crown-appointed members) emphasized that this benchmark is not based on empirical fish population research (Deerenberg and Machiels 2014). For this reason, the proponent of the Borgharen hydro plant argued that the two existing hydro plants should not restrict the establishment of a third hydro plant. In the proponent's view, every plant should be treated equally, so all three plants should comply with the same fish mortality percentage (Manders et al. 2016). Thus, there is still uncertainty associated with this cumulative mortality guideline.

3.2 NORWAY

Norway possesses Western Europe's largest hydropower resources (World Energy Council 2013). Nearly 100% of Norway's electricity comes from hydropower (Norwegian Ministry of Petroleum and Energy 2015). Similar to other countries described in this review, when a hydro company in Norway proposes to build a hydropower plant, they must apply for a licence from the licencing authorities. In Norway, the licencing authorities are the Norwegian Water Resources and Energy Directorate (NVE), the Ministry of Petroleum and Energy, the Government, and the Norwegian parliament (Gonzalez et al. 2011). There are no laws and regulations in the licencing process that specifically relate to fish survival, however there are laws and regulations that indirectly relate to fish including: Protection Plans for Water Resources, the Master Plan for Water Resources, the Watercourse Regulation Act, and the Water Resources Act (Norwegian Ministry of Petroleum and Energy 2015).

The goal for the protection plans for water resources is to reduce the risk to river systems from the effects of hydropower development. In total, 388 river systems with a hydropower potential of 49.5 TW·h per year are under protection plans (Norwegian Ministry of Petroleum and Energy 2015). As the Protection Plans are legally binding for all watercourses, the Government developed a Master Plan of Water Resources. This Master Plan of Water Resources has an economic focus, but also incorporates environmental protection. The plan sets out an order of priority for projects that can be considered for licensing, and divides them into two categories (Category I & II). Category I include projects where licensing procedures may begin immediately, whereas Category II projects can be considered for licencing in the future but not presently (Norwegian Ministry of Petroleum and Energy 2015). The result of this categorization is that projects with the lowest impacts and the cheapest power gain generally become implemented first (Gonzalez et al. 2011).

Due to Norway's dependence on hydropower, it is economically necessary to regulate the output of a hydro plant according to the current need. Thus, it is critical that water be stored in a regulation reservoir (Gonzalez et al. 2011). The ability to use water from a regulation reservoir is determined by the Watercourse Regulation Act (Norwegian Ministry of Petroleum and Energy 2015). The measures of the Watercourse Regulation Act are meant to balance fluctuations in the water flow during the year. In addition, the act allows the authorities to demand a compensation for a damage caused by the regulation, for example a fish fund for damaging fish stocks (Gonzalez et al. 2011). Also included in this act is the authority of the NVE to decide whether the regulations for the specific plant are revised after 30 or 50 years to adjust to changes or unforeseen damages in the environment.

The Water Resources Act gives regulations to compensate for and mitigate the adverse impacts of developments in river systems (Norwegian Ministry of Petroleum and Energy 2015). This Act is applicable for any kind of works in a watercourse and all measures that are needed to exploit the hydropower potential. The aim of the act is to make sure that the benefits gained through the plant outweigh the caused damage or inconvenience to the surrounding watercourse.

There does not appear to be much opposition towards Norway's method of regulating environmental damage caused by hydropower facilities, which may be a result of Norway's dependence on hydropower. It is important to note that while Norway does not belong to the EU, they do tend to follow the rules of the EU, including the implementation of the WFD. There are some that believe that when the WFD was implemented in 2006 that challenges may exist for Norway in the future as it relates to hydropower and enhancing aquatic biodiversity. In the coming years, Europe has the goal of transiting to a renewable energy system where the European Union hopes Norway can contribute by serving as a 'green battery' for Europe (Gullberg 2013). Since hydropower results in nearly 100% of the renewable electricity in Norway, it is implied that Norway will have to expand hydropower development in the future. With implementation of the WFD, there will be a greater emphasis on restoring biodiversity of aquatic systems, an effort that some believe will conflict with this expansion of hydropower (Ruud et al. 2011). This may result in trade-offs of biodiversity at regional hydropower projects in order to meet the demand for a renewable energy system and perhaps explain why there is no specific reference to hydropower-induced mortality within Norway's national laws and regulations.

3.3 UNITED STATES OF AMERICA

The United States, in particular, the northern states, are the most comparable country to Canada with respect to fish species, hydropower production, and ecosystems. In the United States, the Federal Energy Regulatory Commission (FERC) has the authority to regulate non-federally operated hydropower projects by granting a license through the Federal Power Act (FPA) where federally operated facilities require congressional approval.

Presently, there are a variety of laws that relate indirectly to fish survival that FERC uses during the relicensing process. Due to the Electric Consumer Protection Act (ECPA) of 1986, FERC is required to give equal consideration to non-development interests such as recreation, fish and wildlife or instream flow needs (Tonka 2015). Thus, FERC must conduct an environmental analysis under the National Environmental Policy Act (NEPA) of 1969, including the preparation of an Environmental Assessment or Environmental Impact Statement, which summarizes the environmental impacts of the proposed project and assesses measures to mitigate such impacts (Rudberg et al. 2014). In addition to the FPA and NEPA, FERC must also comply with the Endangered Species Act (ESA) of 1973, prior to issuing a license. Under ESA section 7(a)(2), FERC must consult with the state and federal resource agencies to demonstrate that the new license will not jeopardize endangered or threatened species or habitat designated critical for such species. The Fish and Wildlife Coordination Act (FWCA) of 1965 also requires FERC to give full consideration to the recommendations of the U.S. Fish and Wildlife Service (USFWS), the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS), and state resource agencies on the wildlife aspects of a project.

To conform to the NEPA, ESA, and FWCA as part of FERCs relicensing agreements, Habitat Conservation Plans (HCPs) must be developed by the proponent in partnership the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Fish and Wildlife Service (USFWS) to ensure safe passage of fish species at non-federally operated hydroelectric facilities. These HCPs are state and site-specific and include survival standards for federally listed fish species at hydro facilities.

For federally owned facilities, either the Fish and Wildlife Service (USFWS) or the NMFS are required to issue a Biological Opinion (BiOp) assessing the impacts on listed species. If a hydropower facility or action can harm a listed species, reasonable and prudent alternatives (RPAs) are proposed (Tonka 2015).

As for relicensing, FERC can only grant licences for a term of 30 years to a maximum of 50 years. Two years before the existing licence expiries, the operator must notify FERC as to whether it intends to seek a new license. During the relicensing process, the hydropower project is subject to all applicable environmental laws at the time of relicensing. Given that environmental laws are much more stringent than they were in the past, the operator should assume that a new license will be issued on different terms than the previous license. In order to achieve a greater understanding of the laws regulating fish mortality at hydropower facilities, we will examine the role of the federal resource agencies (USFWS and NMFS) and review the case of Washington State, how survival standards are set through HCPs and BiOps.

Role of the federal resource agencies

There are two federal agencies that are primarily responsible for the conservation and management of fish and wildlife resources in the United States, USFWS and NMFS. Under authorities granted by the Fish and Wildlife Act (FWA) of 1956; the FWCA; the NEPA and the ESA, the USFWS has the responsibilities to protect and enhance fish and wildlife within the United States (OTA 1995). Conversely, NMFS has federal jurisdiction over marine, estuarine, and anadromous fishery resources under the FWCA, NEPA, ESA, and the Magnuson Fishery Conservation and Management Act (MFCMA) (OTA 1995). Below are two examples of the role USFWS have in hydropower developments taken from a USFWS publication: Hydropower Licensing: The Fish and Wildlife Service Role (USFWS 2016).

Jordan Dam, Alabama

“When the Jordan Dam was built, approximately eight miles of the river became a series of ponds. The lack of flow through the system hindered the livelihood of endangered Tulotoma snail (*Tulotoma magnifica*), paddlefish (*Polyodontidae*), and trophy striped bass (*Morone saxatilis*). USFWS were contacted to provide recommendations to FERC on the impact to fisheries resources caused by the dam. Based on Service recommendations, FERC required the power company to increase the minimum flow release below the Jordan Dam on the Coosa River in Alabama. Numbers and diversity of fish and numbers of Tulotoma snails have since increased with the release of flows downstream.”

Salmon River projects, Idaho

“In the early 1980's, the USFWS petitioned FERC to consider the cumulative impacts of multiple hydroelectric developments in the Salmon River Basin in Idaho. At one point, there were over 60 active proposals to build hydropower projects on tributaries of the Salmon River. Most would have harmed anadromous and resident fish as well as wildlife. Thanks to cooperative efforts by a number of federal and state agencies and various Indian tribes, FERC chose to delay licensing of most of these projects until a basin-wide environmental impact statement considering cumulative impacts was completed. After a large-scale study of fifteen projects, eight applications were denied because of the potential for significant environmental degradation. The others are still pending before FERC and may require additional Service consultation.”

Washington State

In certain areas of the United States, mortality of fish from hydropower is regulated more rigorously. The Pacific Northwest has the largest hydropower capacity in the United States, and the rivers contain important populations of Pacific Salmon species (Pracheil et al. 2016). Thus, in Washington State, survival standards for fish passage at hydro projects have been established by resource agencies to help assure viable populations of salmon. However, the smolt passage survival standards differ substantially between the federally operated and non-federally operated dams, known as public utility district (PUD) dams.

In the middle portion of the Columbia River, three PUD dams are guided by HCPs and two other dams are guided under relicensing agreements (Skalski et al. 2012). The survival standard is based on a project passage survival rate for salmon smolts passing through the hydro system (i.e., dam and reservoir) of ≥0.93 for listed species (i.e., juvenile Chinook salmon). As part of the licence agreement, three annual estimates are required with an average greater than or equal to the survival standard. For an individual assessment to be accepted, the project passage survival must be estimated with a standard error (SE) of ≤0.025, and river flow conditions must be within the middle 90% of the historical distribution. If a PUD fails to achieve compliance with survival standards under the HCP agreement, it could result in turning over partial control of the dam operations to the resource agencies (Skalski et al. 2012).

Within the Federal Columbia River Power System (FCRPS), 13 species of Columbia River Basin salmon and steelhead are listed for protection under the Endangered Species Act (ESA) (NOAA 2016). The three FCRPS operating agencies are the Army Corps of Engineers, Bonneville Power Administration, and the Bureau of Reclamation. The FCRPS Biological Opinion guides the agencies in operating the FCRPS and requires a series of mitigation measures, called Reasonable and Prudent Alternatives (RPA). The 2008 BiOp on the FCRPS requires dam passage survival to be ≥0.96 for spring stocks (i.e., yearling Chinook salmon and steelhead) and ≥0.93 for summer stocks (i.e., subyearling Chinook salmon) (Skalski et al. 2012). Unlike PUD dams, compliance requires only two annual estimates with an average greater than or equal to the survival standard (Skalski et al. 2012). For an individual study to be acceptable the estimate of dam passage survival must have a SE ≤0.015 and river flows must be within the middle 90% of historical distributions (Skalski et al. 2012).

While legislation, the roles of federal resource agencies, HCPs and BiOps have clarified how fish mortality is regulated for hydropower facilities, there are still many that think the process can be improved. Some of the issues that have been highlighted include better balancing of the developmental and non-developmental values of the project, defining a baseline for mitigation and improving the process time of projects (OTA 1995). While improvements can still be made, the laws that currently are in place provide adequate protection of fisheries resources and ensure increased protection for endangered species.

Table 10: Summary of the jurisdictional approaches to regulating fish mortality at hydropower facilities

Country	Licensing (Y/N) and term	Relevant Acts	Management Responsible	Elements of Approach	Mortality threshold (Y/N) and %	Issues
Sweden	Yes and unlimited term	EU WFD, the Environmental Code	Ministry of Environment and Energy	Principle based (polluter pays principle, general rules of consideration)	No	Unlimited terms have led to a large number of dams in Sweden have permits that are not in compliance with the Environmental Code
Netherlands	Yes	EU WFD, Nature Conservation Act, Water Act, Water Policy	Dept. of Public Works, Min. Agriculture, Min. Nature, Min. Nutrition and Min. Economic Affairs	Case-by-case	Yes – 10% cumulative mortality	Mortality threshold has been questioned as the threshold is not based on empirical fish population research

Norway	Yes – 30 to 50 years	Protection Plans for Water Resources, the Master Plan for Water Resources, the Watercourse Regulation Act and the Water Resources Act	Norwegian Ministry of Petroleum and Energy	Case-by-case	No	No strong opposition, however, it is speculated that not all objectives for the WFD will be met with continued expansion of hydropower
United States	Yes – 30 to 50 years	FPA, ECPA, ESA, NEPA, FWCA, FWA, MFCMA	FERC, USFWS, NMFS	Case-by-case	No – But specific states do through HCPS and BiOps (e.g., Washington state)	There needs to be better balancing of the developmental and non-developmental values of the project, defining a baseline for mitigation and improving the process time of projects

4.0 CONCLUSION

The purpose of this report was to evaluate the scientific research to determine the mortality risks associated with downstream passage through hydroelectric facilities and to review how different jurisdictions regulate this mortality. After reviewing the scientific literature, four main mortality risks were identified: 1) turbine mortality; 2) screen/rack impingement; 3) behavioural and operational entrainment/impingement; and 4) rapid flow alterations.

Achieving compliance with mortality thresholds could be easier to attain depending on the type of hydropower facility (run-of-the-river, impoundment or pumped-storage) and the size (large, small, and micro). For example, a small run-of-the-river facility could in theory achieve mortality thresholds with less fish protection measures than a large pumped-storage or impoundment facility that has to include protection for fish from flow alterations caused by hydropeaking operations. That being said, it is also recognized that mortality standards may vary depending on the fish populations present in rivers. For example, different mortality standards could apply for a run-of-the-river facility located on a river that contains endangered or threatened species per the *Species at Risk Act* (e.g., Pacific Salmon) in comparison to rivers that have a large hydropeaking system with only abundant resident fish. These situations require case-by-case evaluation to determine specific thresholds that are beyond the scope of this report.

The scientific literature review provided an insight into the mortality risks fish are exposed to when encountering a hydropower facility. Turbine mortality is a significant source of mortality for fish passage through hydroelectric facilities. Fish that become entrained may be subjected to rapid pressure changes, shear stress, and mechanical wounding. Each of these factors can cause significant injury or mortality with severity of injury/mortality varying depending on a range of factors including but not limited to life stage, fish species, and turbine type.

Screen/rack impingement is also a significant source of mortality although impingement mortality is more common with poor swimming fish (e.g., American Eel) rather than strong swimming fish (e.g., juvenile salmonids). High mortality rates from impingement have been documented in the scientific literature; however, modifications to screens that target specific species have been shown to reduce impingement mortality significantly.

Fish behaviour and dam operations (forebay hydraulics) can affect the probability of entrainment/impingement and thus contribute to the mortality risks observed at hydropower facilities. Fish behaviour, such as avoidance behaviour to accelerated flows, is not always pronounced and is dependent on a variety of factors including biotic (e.g., species, life stage) and abiotic factors (e.g., diel period). On the other hand, forebay hydraulics can induce entrainment/impingement of fish when operating under suboptimal conditions.

Mortality sources associated with rapid flow alterations can arise from three results; fish stranding, nest site dewatering leading to reduced rearing survival and total dissolved gas supersaturation. A fish stranding event is often dictated by a combination of abiotic (e.g., water temperature) and biotic (e.g., life stage) factors. Lithophillic spawning fish appear to be the most vulnerable to nest site dewatering events and TDGS has long been recognized for being a considerable mortality risk for fish downstream from hydropower facilities where the cause of this mortality has generally been attributed to chronic and acute gas bubble trauma/ disease (GBT). While all three of these effects generally occur downstream from hydroelectric facilities, they are largely dependent on the actions taken by the dam, and thus, should be considered a significant mortality risk for fish.

We found jurisdictions have their own approach to regulating fish mortality from hydropower operations. Some jurisdictions, such as Sweden, use an indirect approach to regulate fish mortality, through over-arching laws that hydropower operators are required to meet as part of their licensing agreement. Other jurisdictions, such as the Netherlands and Washington state in the U.S. have a more direct approach, by setting mortality standards, which provide clarity as to the requirements that proponent's and operators must meet. Each of these approaches has been criticized to some extent and it is clear from the four assessed countries, that a single model approach to regulating fish mortality has not been identified.

Building off the research focused on the mortality risks fish are exposed to upon downstream passage, many scientists and engineers have been examining mitigation options that can reduce the risk to fish. This includes designing fish friendly turbines

(Cada 2001; Neitzel 2009; Brown et al. 2012d; Trumbo et al. 2014) screens/ racks (Raynal et al. 2013a; Raynal et al. 2013b) and by-pass systems/spillways that can allow for safe passage of migrating fish (Williams et al. 2012). While this report recognizes that this research can help reduce the risk to fish from hydropower, effectively covering all the various mitigation options related towards downstream passage would be extensive and is beyond the scope of this report.

As stated earlier, the environmental advantages of hydropower generation are fairly well understood. Despite the considerable scientific literature, what is not as well-known is the extent of the negative impacts on the fish populations and all the measures that are needed to minimize those impacts. By examining the current thinking and highlighting the causes, challenges, and knowledge gaps, it is hoped that more can and will be done to diminish the existing and future hydropower generation damage to Canada’s fish and fisheries. It is hoped that this report, along with the current best practices used in Canada, can be combined to establish a knowledge base that will help guide the Canadian government in establishing a national framework for managing mortality of fish undergoing downstream passage through hydropower facilities.

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