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Upstream passage and entrainment of fish at hydropower dams: lessons learned from NSERC's HydroNet 2010-2015

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Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

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ABSTRACT

River ecosystems require connectivity to sustain productive habitats whereas hydro -electric generation requires river flows be stored, diverted and passed through turbines. Clearly these two requirements are at odds. However, advancements in technology, engineering and biology have collectively helped toward reconciling these issues. HydroNet, a National Science and Engineering Research Council of Canada Strategic Network Grant and Collaborative Research and Development Grant, was designed in part to investigate the key variables related to hydropower that affect the productive capacity of fish habitats around hydropower facilities. This included investigating the behavioural and ecological correlates of upstream fish passage (as occurs at fishways designed to afford bidirectional movement of fish past barriers including dams) and adult fish entrainment (the process by which fish are displaced from reservoirs by water diversion structures at dams). Here we summarize and synthesize results from a number of studies generated under the HydroNet grant. From this synthesis we generate a list of lessons learned to help direct future studies on fish passage and entrainment in Canada and abroad. Research was performed in the Vianney-Legendre fishway on the Richelieu River in Quebec and the Mica Dam on Kinbasket Reservoir in British Columbia, Canada. From the beginning both research problems were tackled through collaborations with engineers and biologists who generated results under the assumption that informed assessments require a complete understanding of both the physical and biological components related to upstream passage and entrainment. Using a number of techniques including radio telemetry and Computational Fluid Dynamics modeling (CFD), fishway passage efficiency was found to be strongly dependent on species-specific physiology and the hydraulic conditions present throughout the structure. In addition, there was also evidence that some fish species were spawning downstream of the dam such that fish passage may not always be needed. Future fishway research would benefit from collaborative relationships between engineers and biologists to help design fishways and improve passage efficiency. In addition, there is need to consider under what conditions fish passage is necessary and what passage efficiency targets are necessary for a given system. CFD modeling and acoustic telemetry showed that entrainment was dependent on species' spatial ecology and behaviour. Fish were entrained during winter when the system was isothermal and dam operations would have minimal effect on thermal regimes. Similar to our recommendations on fishway research, studies on entrainment should include collaborative relationships, utilize new technologies, and consider how hydropower operations and design of water diversion structures influence entrainment. This research synthesis should provide a considerable contribution toward understanding the physical and behavioural correlates of fishway passage and entrainment at dams. We hope that some of the lessons learned will help to direct future research to better align the objectives of energy development with the hydraulic and ecological conditions necessary to maintain the productive capacity of fish habitats around hydropower facilities.

Passage en amont et entraînement des poissons aux barrages hydroélectriques : enseignements tirés du réseau HydroNet du Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG) 2010-2015

RÉSUMÉ

Les écosystèmes des rivières ont besoin d'être reliés les uns aux autres afin de préserver des habitats productifs, alors que la production d'hydroélectricité exige que le flux des rivières soit stocké, dévié et passé dans des turbines. De toute évidence, ces deux exigences se contredisent. Cependant, des progrès en matière de technologie, d'ingénierie et de biologie ont contribué à résoudre ces questions. HydroNet, qui est financé par une subvention du Réseau stratégique pour les océans du Conseil de recherches en sciences naturelles et en génie du Canada et une subvention du Programme de recherche et développement coopératif, a été conçu afin d'étudier les principales variables reliées à l'hydroélectricité et qui touchent la capacité de production des habitats du poisson autour des installations hydroélectriques. Cela comprenait l'étude des corrélations écologiques et comportementales du passage des poissons en amont (comme aux passes à poissons conçues pour le déplacement bidirectionnel du poisson après avoir franchi des barrières, notamment des barrages) et de l'entraînement des poissons adultes (le processus par lequel les poissons sont déplacés des réservoirs par structures de déviation de l'eau aux barrages). Ici, nous résumons et faisons la synthèse des résultats provenant de nombreuses études entreprises grâce aux subventions d'HydroNet. Nous produisons une liste des enseignements tirés de cette synthèse afin d'aider à orienter les futures études sur le passage et l'entraînement des poissons au Canada et à l'étranger. Les recherches ont été menées à la passe Vianney-Legendre sur la rivière Richelieu au Québec et au barrage Mica sur le réservoir Kinbasket en Colombie-Britannique (Canada). Dès le départ, les deux problèmes de recherche ont été abordés grâce à la collaboration avec les ingénieurs et les biologistes qui ont produit les résultats en supposant que des évaluations éclairées nécessitent une compréhension approfondie des composantes physiques et biologiques qui se rapportent au passage en amont et à l'entraînement. À l'aide d'un certain nombre de techniques comprenant la télémesure et la modélisation dynamique numérique des fluides, on a déterminé que l'efficacité des passes à poissons était fortement dépendante de la physiologie propre à chaque espèce et des conditions hydrauliques présentes partout dans la structure. En plus, des éléments probants ont permis d'attester que certaines espèces de poissons frayaient en aval du barrage; par conséquent, le passage des poissons n'est peut-être pas toujours nécessaire. Les futures recherches sur les passes à poissons pourraient tirer profit de la collaboration entre les ingénieurs et les biologistes pour aider à concevoir des passes à poissons et à améliorer l'efficacité du passage. De plus, il est nécessaire d'examiner dans quelles conditions le passage des poissons est nécessaire et quelles cibles en matière d'efficacité du passage sont nécessaires pour un système donné. La modélisation dynamique numérique des fluides et la télémétrie acoustique ont démontré que l'entraînement dépendait du comportement et de l'écologie spatiale de l'espèce. Les poissons ont été entraînés pendant l'hiver, lorsque le système était isotherme, et que les activités du barrage auraient un effet minimal sur les régimes thermiques. Tout comme nos recommandations en matière de recherche sur les passes à poissons, les études sur l'entraînement devraient comprendre des relations de collaboration, utiliser les nouvelles technologies et examiner la façon dont les activités hydroélectriques et la conception des structures de déviation de l'eau ont une incidence sur l'entraînement. Cette synthèse de recherche devrait permettre de contribuer grandement à la compréhension des corrélations physiques et comportementales du passage des poissons et de l'entraînement aux barrages. Nous espérons que certains des enseignements tirés permettront d'orienter les recherches futures afin de mieux harmoniser les objectifs en matière

de développement énergétique avec les conditions écologiques et hydrauliques qui permettent de maintenir la capacité de production des habitats du poisson autour des installations hydroélectriques.

CONTEXT

NSERC HydroNet is a national research network whose overall mission is to provide government and industry with the knowledge and tools that will improve the capacity of scientists and managers to assess and minimize the effects of hydropower installations and operations on aquatic ecosystems. HydroNet intends to inform the decision-making process, and thereby to contribute to the sustainable development of hydropower in Canada. HydroNet is a collaborative research partnership between universities, government agencies, and hydropower companies. In 2009, HydroNet was granted a 5-year research mandate by the Natural Sciences and Engineering Research Council of Canada (NSERC). This mandate was recently extended to 2015 to allow for the completion of papers and reports. The research platform of HydroNet consists in a series of projects that focus on two themes:

1) modeling of fisheries productivity in rivers, and;
2) modeling of fish-habitat interactions in reservoirs.

The theme “modeling of fisheries productivity in rivers” includes projects on productivity of fisheries and its chemical, physical, and biological drivers in rivers. The theme “modeling of fish-habitat interactions in reservoirs” comprises projects on the mesoscale modeling of fisheries productivity metrics in reservoirs and on the prediction of fishway passage and fish entrainment risk in reservoirs. The present report focuses on the assessment of upstream passage and entrainment of fish at dams.

BACKGROUND

RATIONALE FOR ASSESSMENT

Ecological connectivity is a key component of healthy hydrologically intact river ecosystems (Calles and Greenberg 2009). While dams are built with the intention of providing goods and services, e.g., through the generation of hydroelectricity, flood control and navigation, these structures inherently undermine the ecological connectivity of rivers. By fragmenting river ecosystems, dams reduce the quality of fish habitat and prevent the bidirectional passage of fish. Both upstream and downstream movement in river systems are critical in the life histories of many fish species. As such, the disruption of historically occurring unimpeded bidirectional fish movement in rivers can have profound consequences for fisheries production (Budy et al. 2002, Calles and Greenberg 2009, Castro-Santos et al. 2009).

In some locations, dams are paired with fishways to facilitate the upstream movement of fish. At times such devices also enable downstream passage but most fishways are not designed for that purpose. Interestingly, the attraction and passage efficiency of fishways is almost never evaluated (Calles and Greenberg 2005). There is limited information on the effectiveness of fish passage systems and prior to 2012 there was no searchable database containing specific information on fishways in Canada (see Hatry et al. 2013, title page figure 1). Fishways are generally built to accommodate the passage of commercially important species (e.g., salmonids) with the current assumption that fish passage technologies maintain connectivity and allow for movement of most if not all species. However, the degree to which multiple fish species utilize fishways remains largely understudied.

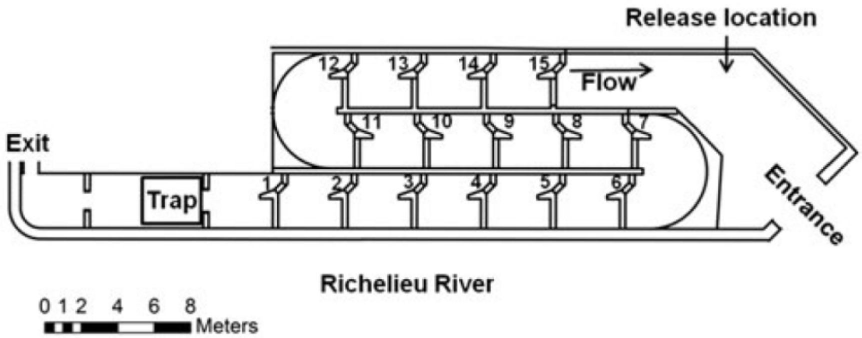

Figure 1: The Vianney-Legendre fishway on the Richelieu River, Quebec.

Volitional or non-volitional downstream passage through turbine intakes (i.e., entrainment) or spillways can lead to injury, death and net productivity losses to upstream fisheries. Assessing fish entrainment risk at new hydropower intakes is one of the requirements of the Canadian Environmental Assessment Act. Despite the importance of entrainment for regulating fish populations, there is no widely accepted systematic method to assess the risk of entrainment to migratory and resident fish (Smokorowski et al. 2011).

Much of the research on the bidirectional movement of fish past dams has focused on river hydraulics or migratory biology (as with salmon). Rarely has an interdisciplinary approach by engineers and biologists been used to understand the causes and consequences of upstream passage and turbine entrainment of fish at dams.

To better understand upstream passage and turbine entrainment of adult fish, research projects were undertaken at the Vianney-Legendre vertical slot fishway on the Richelieu River, Quebec and Kinbasket Reservoir (Mica Dam), British Columbia from 2010 to 2015. Upstream passage was examined in 18 species whereas entrainment was studied in Burbot *(*Lota lota*)* and Bull trout (Salvelinus confluentus), which are top-predators and constitute important recreational and aboriginal fisheries in Kinbasket Reservoir. A diverse group of experts including engineers and biologists used multiple technologies to assess upstream passage and entrainment. All work was supported by NSERC's HydroNet Collaborative Research and Development Grant (CRDPJ 387271-09). This report serves two purposes:

1) report and integrate the research used to study upstream passage and entrainment and
2) summarize the lessons learned from this work.

STATEMENT OF PROBLEM

UPSTREAM PASSAGE

In an attempt to restore river connectivity and mitigate the effects of dams on fish populations, engineers and biologists have been working together to develop structures, known as fishways, that facilitate upstream passage of fish at barriers (Calles and Greenberg 2009). The design and operation of a fishway is mainly related to the target species (e.g., fish species, size of the fish, and migration period) and site-specific hydraulic characteristics (e.g., flow and gradient). Although fishways facilitate passage of migrating fish, several unintended ecological consequences can be associated to their use, such as delays, fallback of fish, passage of invasives, and selective passage of native species. If a fishway is not ascended by the target species, the extent to which migrating fish use the tailrace (the area immediately downstream of a dam) or habitat near the dam for spawning is often unknown. These consequences can compromise the sustainability of fish populations and influence metapopulation dynamics by increasing the susceptibility of fish to predation, increase risk/transference of disease, and lead to energetic exhaustion of fish and incomplete or new biotic communities (Budy et al. 2002, Caudill et al. 2007, Roscoe and Hinch 2010, Cooke and Hinch 2013). From a biological perspective a fishway should enable any individual of a native species or any species for which passage is consistent with fisheries management and conservation plans to find and enter the fishway without experiencing any delay. Fishway entry should be immediately followed by successful upstream or downstream passage, with minimized energetic stress, disease, injury, predation, or other fitness-relevant costs associated with passage (Castro-Santos et al. 2009).

Effective fishway design requires extensive integration of biological and hydraulic data. Many relevant biological parameters remain poorly characterized, however, and the lack of adequate biological data has been recognized as a central weakness in fish passage technology. This is particularly concerning given the growing recognition of the importance of passing a broad diversity of species. Part of the reason for this weakness is the difficulty of identifying relevant biological, hydraulic, and other physical parameters. By exploring questions suggested by current knowledge, and refining the methods with which fishways are evaluated, two outcomes can be achieved: improve our understanding of design effectiveness so that future fishways can be designed to more effectively pass target species, and research questions can be prioritized through adaptive management. Although the trade-offs between biological and operational decisions vary in importance from system to system, the main goal of fisheries managers and fish passage engineers are to optimize designs to maximize the effectiveness of fish passage facilities.

METHODS

STUDY SITE

The Richelieu River originates in Vermont and New York, USA, and after exiting Lake Champlain empties into the St. Lawrence River near the town of Sorel, Quebec. The river is 124 km long with an average annual discharge of 362 $m^3 \cdot s^{-1}$. The St. Ours dam is located 18 km upstream of the confluence between the Richelieu and St. Lawrence Rivers. The dam is 180 m wide and 3.4 m high with a series of 5 submersible 30 m wide gates plus the Vianney-Legendre fishway (Figure 1). The main function of the dam is to stabilize water levels upstream for navigation purposes (Thiem et al. 2011).

Volitional upstream passage research was conducted at the Vianney-Legendre fishway located on the Richelieu River near the town of St. Ours, Quebec (45°52’N, 73°09’W). The structure was built on the west side of the St. Ours Dam in 2001. The fishway is 85 m long with 17 pools total (13 regular pools (3.5 x 3.0 m), 2 turning basins (2.75 m radius), and a large entrance and exit basin). There are 16 vertical slots (each 0.6 m width, 2.3-4.0 m height per slot, becoming higher toward downstream) throughout the fishway. The total rise is approximately 2.55 m with a total slope of 2.8%. Basins have a drop of 0.15 m, moving downstream (Hatry et al. 2014). The top of the fishway contains a fish trap (2.2 x 2.0 x 2.15 m) in which fish that traveled up the fishway could be captured and enumerated. The fishway passes approximately 1 $m^3 \cdot s^{-1}$of water with a capacity for an additional 6.5 $m^3 \cdot s^{-1}$ attraction flow near the entrance basin (Thiem et al. 2011, Marriner et al. 2014).

The Vianney-Legendre fishway was intended to afford passage to a variety of key native fish species including lake sturgeon (*Acipenser fulvescens*), copper redhorse (*Moxostoma hubbsi*), river redhorse (*Moxostoma carinatum*), American shad (*Alosa sapidissima*), American eel

(*Anguilla rostrata*), and Atlantic salmon (*Salmo salar*). The Richelieu River contains a diverse fish assemblage with the Vianney-Legendre fishway being known to successfully pass at least 36 species (Desrochers 2009).

STUDY SPECIES

Globally, most fishways are designed based on the original design criteria developed to accommodate passage of anadromous salmonids (Roscoe and Hinch 2010). Nevertheless, a broad diversity exists among swimming abilities, migration windows and migratory motivation of fish species that are assumed to pass, including potomodromous species. At the Vianney-Legendre fishway, researchers examined the passage efficiency of 18 species found in the Richelieu River, including those in the following families: Acipenseridae, Catostomidae, Cyprinidae,Centrarchidae, Hiodontidae, Ictaluridae, Lepisosteidae, Percidae, Salmonidae, Sciaenidae. Key migratory species included lake sturgeon, copper redhorse, river redhorse, American shad, and American eel and Atlantic salmon. While the biology and ecology of the 18 study species are diverse, the majority are obligate riverine migrators that spawn during the spring (Thiem et al. 2013a).

Lake sturgeon were of specific interest in this body of work given that the Vianney-Legendre Fishway is one of the few facilities where sturgeon have been documented to pass a fishway. Lake sturgeon are among the most recognizable freshwater fish species in Canada. However, the species is listed as endangered by the Committee on the Status of Endangered Wildlife in Canada, and are considered imperilled globally (Thiem et al. 2011). Sturgeons are long-lived late-maturing organisms that are distributed across the temperate regions of Europe, Asia and North America (Bemis and Kynard 1997). Historically an important food source, exploitation and habitat modification have placed the majority of sturgeon species under threat of extinction throughout their broad geographic range (Birstein 1993). Sturgeons exhibit a variety of life history strategies throughout their distribution but all species undertake upstream migrations to spawn (Bemis and Kynard 1997). Anthropogenic barriers in rivers have been recognised as a key threat to all sturgeon species and have been implicated in their imperilment (Rochard et al. 1990). Restoring connectivity of riverine systems that have been fragmented is a critical step towards rebuilding sturgeon populations and preventing extinction (Auer 1996, Jager 2006). For sturgeon, the limited information on fishway passage suggests efficiency is low and dependent on fishway construction and hydropower operations (Parsley et al. 2007).

Lake sturgeon are found in large lakes and rivers from the St. Lawrence River east to the North Saskatchewan River in Alberta, south to the Tennessee River in Alabama and in north Mississippi, and north to Hudson Bay (Scott and Crossman 1973). They are distinguished by a heterocercal tail, a ventral protrusible suctorial mouth, and ventral barbels. Adults, which have a large round body covered with minute dermal denticles on very tough skin, can reach large sizes (>200 cm total length) and are commonly 90-140 cm. Lake Sturgeon typically migrate into rivers and travel upstream to swift water where natural or manmade barriers prevent further migration. Although the conditions at which Lake sturgeon spawn vary with latitude, spawning generally occurs from early May to late June at 13-18°C and at depths of 0.6-4.5 m (Scott and Crossman 1973). Fertilized eggs are deposited in batches onto the substrate and are left unguarded.

INTERSPECIFIC DIFFERENCES IN PASSAGE EFFICIENCY RELATED TO PHYSIOLOGY AND SWIMMING PERFORMANCE

Fishway passage success relative to physiology and swimming performance was compared among three species of redhorse (Silver, *M. anisurum;* River; Shorthead*, M. macrolepidotum*) which were captured directly from the fishtrap. Respirometry data were collected between 30 May and 13 June 2011 whereas swimming performance, blood physiology and passage efficiency data were collected between 22 April and 25 May 2012. Additional passage efficiency data were taken from Thiem et al. (2013a). Water temperature was recorded daily to estimate water temperatures at peak species-specific migration windows as individuals were encountered in the fishtrap. Captured redhorse were placed in large (2250 L) on-site flow-through hatchery tanks. Fish were not fed during the 24 hour holding period to allow for gut clearance (Hatry et al. 2014). Following exhaustive exercise, metabolic recovery time (metabolic rate 4 hours post-exercise) was measured at four time intervals while fish were left undisturbed in respirometry chambers. Relative swimming ability was measured by swimming individual fish to exhaustion in an annular swim flume (130 cm diameter, 40 cm deep water). Physiological recovery profiles were calculated by placing fish in hypolon fish-carrying bags (FT940 recovery bags; Dynamic Aqua Supply, Vancouver, British Columbia). Blood glucose, lactate, and pH levels were sampled at 6 time intervals with no individuals sampled more than once (Hatry et al. 2014).

LAKE STURGEON REPRODUCTION, BEHAVIOUR AND PASSAGE SUCCESS

Lake sturgeon passage was assessed using a passive integrated transponder array (PIT) consisting of 16 (one in each basin) complete-pass-through antennas throughout the fishway (Thiem et al. 2011). Each antennae was connected to a remote tuner box that recorded tag identification number, antenna number, and a date/time stamp. Sturgeon (n = 107, mean TL = 1213 mm ± 145 SD) were captured near the fishway (< 700 m downstream) using stretched mesh gill nets which were checked twice daily. Captured fish were immediately transferred to on-site holding facilities where they were measured and implanted with a PIT tag (32 x 3.85 mm, HDX, Texas Instruments, Dallas, TX, USA) into the abdominal wall. The entire handling process took < 2 minutes. Anaesthetics were not used. Sex was determined when possible through the expulsion of gametes or through blood steroid analysis (Thiem et al. 2013b). Sturgeon were held indoors for 1-3 days before being released in 5 groups into the entrance of the fishway which was blocked to prevent escape downstream. Sturgeon were given 40 to 86 hours to volitionally enter and pass the fishway, after which time the fishway was slowly dewatered and the fish allowed to escape.

Lake sturgeon reproductive behaviour and endocrinology were assessed using gill-net surveys, nonlethal blood sampling, radio telemetry, and egg collection at a suspected spawning location below the St. Ours dam (Figure 2). Sturgeon were captured between 4 May and 3 June 2011 using the same gill netting procedure as noted above. Sturgeon were taken to the indoor holding facility and fitted with a PIT tag. In addition, individuals (n =51) were fitted with an external radio transmitter (149 MHz, 30 mm x 8 mm, 8 g mass in air, burst rate 2 s, 90 day battery life, Sigma Eight Inc., Newmarket, Ontario, Canada). Sturgeons were released and tracked using an array of fixed station radio receivers (SRX 600; Lotek Inc., Newmarket, Ontario, Canada) and yagi antennas for a total of 15 monitoring stations within 200 m of the dam. Egg collection mats (n = 68) were deployed in a grid design below the dam to determine location and time of sturgeon spawning. Egg mats were checked every 2-6 days between 12 May and 13 June, 2011 (Thiem et al. 2013b).

PASSAGE EFFICIENCY OF MULTIPLE SPECIES AND LIFE-STAGES

Fish were sourced from the fishtrap located at the upstream end of the fishway before the first basin (Figure 2). The fishtrap was raised twice daily beginning 31 May 2010 for 11 days. This research used the PIT array and captured individuals were each implanted with a uniquely coded PIT tag (23 X 3.85 mm HDX; Texas Instruments) into the peritoneal cavity. No anaesthetics were used and the handling process took < 1 minute. Tagged fish were immediately transferred to a flow-through net pen located in the fishway entrance basin where they recovered for 1-2 hours. Fish were then released and allowed to volitionally re-ascend the fishway (Thiem et al. 2013a).

DELAYS, STRESS, AND ENERGETIC EXPENDITURE

Delays, stress, and energetic expenditure during fishway passage was examined using a combination of PIT tags and biologging accelerometers on migratory silver redhorse (*Moxostoma anisurum*). Fish were captured opportunistically in the fishtrap between 20 April and 5 May 2012. Triaxial accelerometers (model X6-2, 25 Hz recording frequency or model X6-2mini, 20 Hz recording frequency, Gulf Coast Data Concepts, Waveland, MS) were fixed at the base of the dorsal fin. Tags mass was 1.3-3.0% body mass, which only slightly exceeded the general 2% rule for tag to body mass ratio (Brown et al. 1999). Silver redhorse were not anesthetized because previous experience showed that redhorse species do not respond well to anesthetic (Bunt and Cooke 2001). After tagging, fish were released into the entrance basin in three groups (to reduce the number of animals in the fishway at one time). Trials were run for 72 hours when fish were able to volitionally ascend the fishway. A block net at the entrance basin and the fishtrap beyond basin 15 stopped fish from escaping during the trials. Once the trials were complete, the fishway was dewatered so all silver redhorse could be captured, the accelerometers removed, and the fish released (Silva et al. 2015).

HYDRAULICS WITHIN FISHWAYS

The assessment of fishway hydraulics was conducted 18-29 July 2011 in basins 11-15 (Figure 1). Velocity point measurements were recorded in both turning basins using a three-dimensional (3D) Acoustic Doppler Velocimeter (ADV). All ADV measurements were taken at a fixed depth from the surface (0.5 m). Velocity readings were recorded for 180 s at a sampling frequency of 25 Hz (Marriner et al. 2014).

DATA MANAGEMENT AND ANALYSES

Accelerometer data were time calibrated with the PIT array system by manually applying a linear correction factor to account for time drift between systems (Silva et al. 2015). Accelerometer output was divided into relevant static and dynamic acceleration components using a weighted smoothing interval of 1.5 s in Igor Pro (version 6.0, WaveMetrics Inc., Lake Oswego, Oregon, USA). Data were visualized using AutoCAD (Autodesk, Sausalito, CA) and ArcGIS 10.1 (Environmental Systems Resource Institute, Redlands, California) and various data plotting software, depending on the study. Hydraulic profile data are summarized and presented visually. More detailed information on data management and statistical methodologies can be found in the cited references.

RESULTS

INTERSPECIFIC DIFFERENCES IN PASSAGE EFFICIENCY RELATED TO PHYSIOLOGY AND SWIMMING PERFORMANCE

Of the three redhorse species examined, shorthead redhorse had higher maximum metabolic rates and were faster swimmers than silver and river redhorse at their species-specific peak migration temperatures (Hatry et al. 2014). Blood lactate and glucose concentrations recovered more quickly for river redhorse than for silver and shorthead redhorse, and river redhorse placed second in terms of metabolic recovery and swim speed. Interestingly, fish sampled from the top of the fishway (in the fish trap) had nearly identical lactate, glucose, and pH levels compared to fish that were manually exhausted. Passage success and duration were highly variable among redhorse species and were not consistent among years, suggesting that other factors such as water temperature and river flow may regulate passage success (Table 1).

Table 1: Summary table ranking silver, river, and shorthead redhorse according to their respective experimental performance.

	Silver redhorse	River redhorse	Shorthead redhorse
Metabolic recovery	3	2	1
Lactate recovery	2	1	3
Glucose recovery	1	1	1
pH recovery	2	1	3
Swim speed	3	2	1
Time to exhaustion	2[a]	3[a]	1[a]
Passage success 2010	3	2	1
Passage success 2012	1	3	2
Duration 2010	1[b]	2[b]	3[b]
Duration 2012	1[b]	2[b]	3[b]

Note. 1 = highest rank; 3 = lowest rank. a

[a]As a longer time to exhaustion is seen as beneficial rather than detrimental to passage success, a score of 1 was given to shorthead redhorse, 2 to silver redhorse, and 3 to river redhorse.

[b] Median value used.

LAKE STURGEON REPRODUCTION, BEHAVIOUR AND PASSAGE SUCCESS

Although most sturgeon entered and attempted to pass the fishway (82.2%), passage efficiency was only of 36.4%. Passage failure mainly occurred in the downstream portion of the fishway and the turning basins presented a potential obstacle to sturgeon passage. Of the 56 individuals that failed passage, 20 failed in the two larger “turning” basins and fish spent disproportionately more time in the turning basins than in regular basins (Figure 3A). The greatest failure rate occurred at the first turning basin. There was no effect of body size on passage efficiency. Sturgeon that failed to pass swam an additional 49 m farther within the fishway, compared with those that passed on their first attempt.

Spawning population estimates ranged from 285 – 1282 individuals with an estimated 2.1:1 male to female ratio. Most radio tagged individuals were detected downstream of the dam over an 8 day period in late May. The presence of eggs (n = 155) confirmed that lake sturgeon were spawning below the dam. Residence time of spawners ranged from 1-27 days.

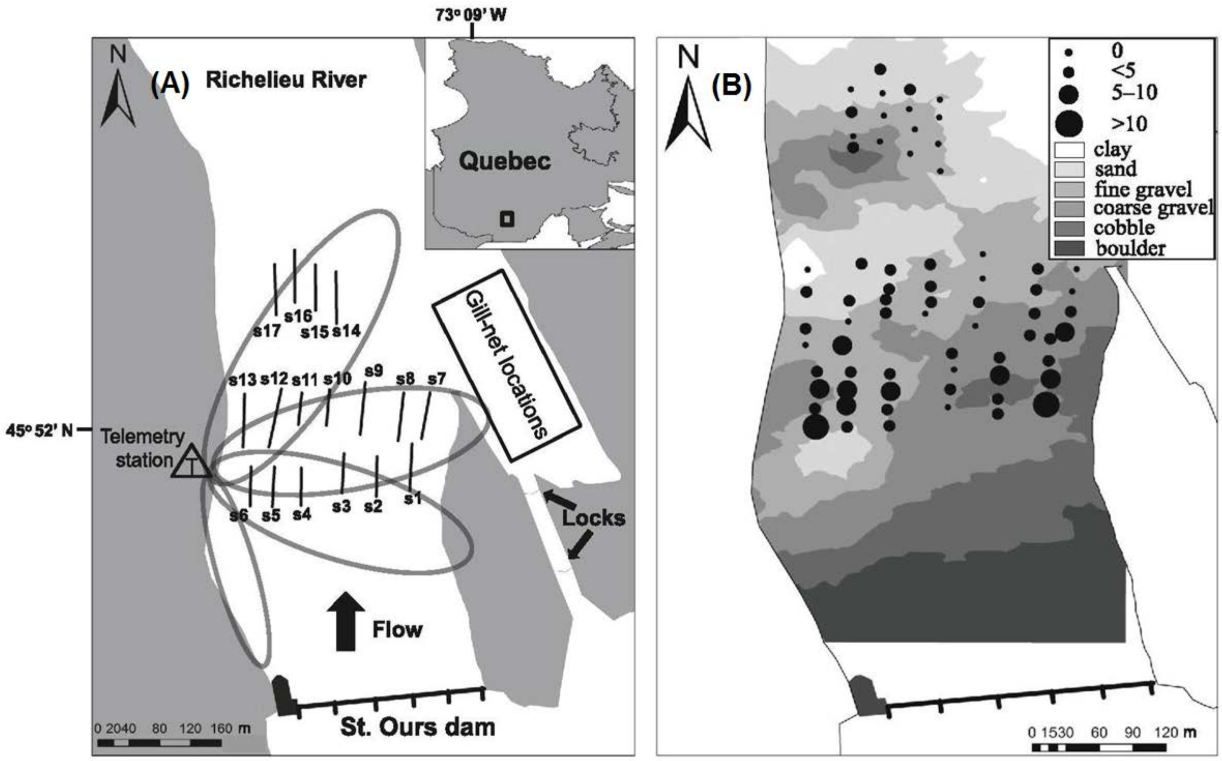

Figure 2: (A) Location of the St. Ours dam on the Richelieu River, Quebec, showing egg collection stations, gill-net locations, and the location of the radio telemetry monitoring station used to determine residence of radio-tagged lake sturgeon. Approximate detection ranges of antennas are indicated by ellipses. (B) Location of lake sturgeon egg collection stations, with circles indicating the total number of viable eggs collected at each location and shading indicating dominant substrate.

PASSAGE EFFICIENCY OF MULTIPLE SPECIES AND LIFE-STAGES

The Vianney-Legendre vertical-slot fishway design was used by all 18 study species and was successfully re-ascended by 14 of these species. Seven species exhibited passage efficiency estimates greater than 50%, including Atlantic salmon (n = 8, 100%), channel catfish (*Ictalurus punctatus*, n = 36, 53%), smallmouth bass (*Micropterus dolomieu*, n = 11, 64%), walleye (*Sander vitreus*, n = 7, 57%), white sucker (*Catostomus commersoni*, n =33, 76%), and common carp (*Cyprinus carpio*, n = 2, 100%). Passage duration was highly variable among individuals and within species (e.g. 1-450 hours in smallmouth bass). Although catostomids represented the dominant group of fishes in this study, with successful re-ascension, extensive delays and low passage efficiency was observed.

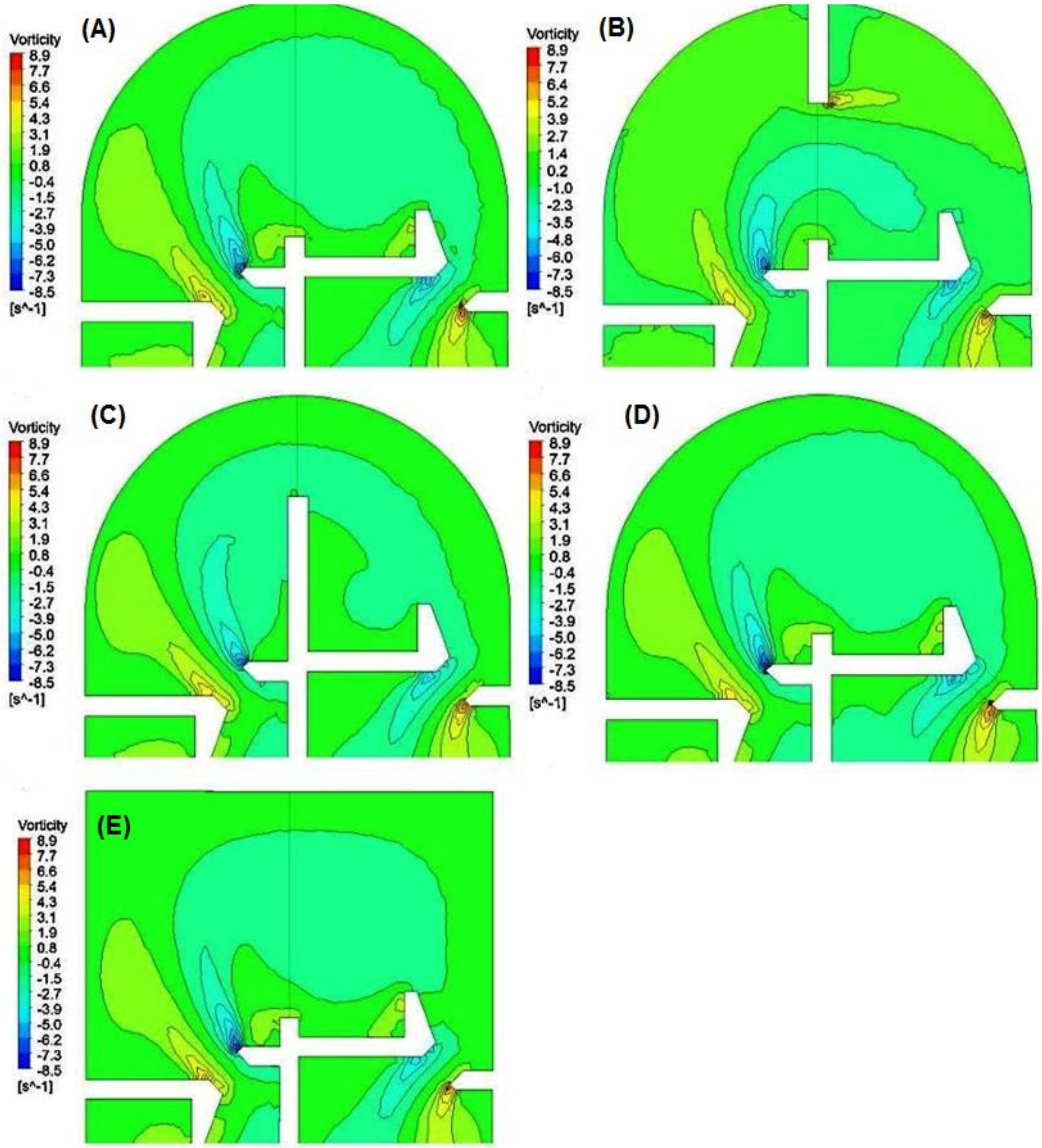

Figure 3: Vorticity levels at depth z = 0.5h in turning pool designs: (A) Design 1, (B) Design 3, (C) Design 4, (D) Design 6, and (E) Design 7.

DELAYS, STRESS AND ENERGETIC EXPENDITURE

Silver redhorse made up to 12 attempts to pass the fishway with variable passage time among individuals. Fish spent the longest time in the final basin and spent less time per basin on each successive attempt to pass the fishway. Accelerometry data indicated that energetic expediture was lowest through the turning basins and highest in the immediate upstream basin. Individuals showed progressive increases in energetic expenditure during upstream fishway passage. Turning basins and the most upstream basin were found to delay passage of silver redhorse (Silva et al. 2015).

HYDRAULICS WITHIN FISHWAYS

Both velocity and turbulent kinetic energy were within the acceptable values for the target species that commonly use this fishway (Marriner et al. 2014). Field hydraulic measurements, CFD modeling, and observations of passage efficiency revealed that vortices with length and width dimensions greater than that of the largest fish using the fishway were present in all designs (Figure 3). CFD modeling indicated that the addition of a baffle wall extending from the inside center wall of the pool reduced the size of the vortex and provided a resting area for ascending fish. Design 7 (Figure 3C) is recommended for its relatively low construction cost and flow field velocities (Marriner et al. 2014).

DISCUSSION

INTEGRATIVE APPROACH FOR BETTER FISHWAY EVALUATIONS

Ideally, a fishway should enable the unrestrained movement of a broad range of fish species to free-flowing historically passable reaches above and below an obstacle (Castro-Santos et al. 2009). The Vianney-Legendre fishway passed all 18 study species with highly variable passage success within and among species (Thiem et al. 2013a). Designing efficient multispecies passage remains one of the greatest challenges for biologists and for engineers. Despite the steadily increasing number of fishways constructed in Canada since the 1970’s (Hatry et al. 2013), there continues to be a lack of research that together considers species-specific biology including swimming ability in the biological design criteria of fishways. Cooperation between engineers and biologists is imperative, especially where the goal is to pass multiple species with a suite of swimming abilities (Hatry et al. 2014). An interdisciplinary approach that combines disciplines like behavior, physiology, and hydraulics is needed to achieve a sound engineered solution (Marriner et al. 2014).

The immediate downstream habitat of the St. Ours Dam was found to provide suitable spawning habitat for several species including lake sturgeon (Thiem et al. 2013b). While fishways should be designed to maximize upstream passage efficiency for multiple species (Thiem et al. 2013a, Marriner et al. 2014), it is apparent that provided suitable habitat, some individuals will spawn below dam structures. To ensure the maintenance of river connectivity it is important to perform accurate biological evaluations to inform decisions regarding fishway and dam operation to provide suitable habitat for individuals that chose to spawn downstream of dams, rather than ascend fishways. Indeed, inaccurate efficiency estimates may lead to incorrect decisions that can be ecologically and socio-economical costly (Cooke and Hinch 2013). Ultimately, good decision-making requires thorough consideration of both the benefits (ecological, biological and economical) and costs associated with the options available to managers.

Difference in passage success derives from a number of factors including interspecific and inter-individual differences in swimming ability (Thiem et al. 2013a, Hatry et al. 2014). Retention time is greater in turning basins and the energy requirements for passage increase along the length of the fishway (Silva et al. 2015). It would also appear that while stress indicators from redhorse at the top the fishway and control fish were similar (Hatry et al. 2014), physiology could be used as a tool for determining whether the impediments to passage success are related to behavioural or physiological capacity (Hatry et al. 2014). Given the results from these studies, higher passage success could theoretically be achieved by minimizing fishway length and by building turning basins to include center wall baffles to reduce flows and presumably the time and energetic requirements to pass through the fishway (Thiem et al. 2011, Marriner et al. 2014). Of course, a shorter fishway would mean steeper gradient so at some point there would be a trade-off between length and gradient – and that trade-off would be species and body-size specific. The current designs in the Vianney-Legendre fishway appear to disorient or destabilize fish, thus delaying passage (Tritico and Cotel 2010, Silva et al. 2011). Delays and high energetic expenditure associated to fishway passage may increase susceptibility of fish to predation, increase risk/transference of disease and lead to energetic exhaustion of fish impacting their fitness and population dynamics (Budy et al. 2002, Caudill et al. 2007, Roscoe et al. 2010, Cooke and Hinch 2013). Fishways need to be highly efficient and effective at passing fish upstream quickly and with minimum energetic expenditure (Castro-Santos et al. 2009).

GENERAL FISH PASSAGE CONSIDERATIONS

The broad aim of NSERC Hydronet was to apply an interdisciplinary approach utilizing aspects of applied science to investigate fishway passage in an effort to provide a transferable model for future studies to improve our understanding of fishway use by multiple species. Research developed through NESRC's HydroNet moved beyond simple effectiveness monitoring and explored the mechanistic basis for failed passage. The results provided a broader perspective on the factors that lead to successful fishway passage. For instance, while some sturgeon successfully passed the fishway presumably for the purpose of reaching upstream spawning grounds, others deposited eggs immediately downstream of the dam, indicating the area contains suitable spawning habitat for this and other species (Thiem et al. 2013b). Although it is clear that maintaining river connectivity is critical for the movement, migratory or otherwise, of a large number of fishes (Thiem et al. 2013a), dams may also create suitable spawning habitat. Future assessments should consider the migratory cues that lead some individuals to spawn below dams while others attempt to pass fishways on their journey further upstream. In addition, research should assess whether migratory fish that fail to pass fishways will subsequently spawn below the dam structure where the fishway is located. Indeed, in some locations fishways may be unnecessary to facilitate spawning migrations when spawning habitat below dams is of high quality or upstream habitat was never used historically (Thiem et al. 2011). It is abundantly clear that the design and construction of fishways is highly dependent on the biology of target species, local habitat characteristics, and obstacle-specific hydrodynamics. Thus decisions about fishway design and construction cannot be made without an interdisciplinary team that includes engineers and biologists.

Successful passage through a fishway can continue to have negative effects on fish, including stress and delayed mortality. Nevertheless research evaluating fishway performance usually only quantifies passage efficiency, and rarely considers post-passage effects and survival after passage (Roscoe and Hinch 2010). Fishways need to enable passage without subsequent negative effects on fitness (Castro-Santos et al. 2009) to ensure they do not compromise the welfare status of fish (Schilt 2007). New technologies will allow scientists to address new questions regarding the consequences and mechanisms of passage, as well as to better understand how organismal performance and environmental conditions interact with fishway features. Future research should combine biotelemetry/biologging and behavioural evaluations in fishways to determine individual-level characteristics of passage efficiency, stress, and post-passage survival/reproduction.

Here we synthetize some key points that are needed to be taken into consideration in the improvement of existent and future fishways:

- **Conduct more biological fishway evaluations focusing on passage and attraction efficiency as well as on post-passage effects and fish survival and reproduction after passage.** These evaluations should target multi-species (migratory or resident fish species) and different ontogenetic stages.

- When evaluating attraction and passage efficiency, it is important to have a priori biologically-based criteria to determine what "numbers" would constitute success. That is, there is a greater need to **consider habitat supply, production dynamics and population biology when determining if a given efficiency estimate is low or high and thus whether a fishway is effective.**
- Improvements on fishway design criteria are known to depend on the understanding of how fish use hydrodynamic cues to guide fine-scale swim path selection. Therefore, **consider how variation in hydrodynamic variables influences fish passage efficiency, swimming ability, and behaviour.**
- **Evaluate existing turning basin designs and explore options to modify or remove them if needed.**
- **Consider the interplay between hydraulics and fish behaviour, physiology and biomechanics in the development of future research in fishways.**
- Fishways may impose a particularly high energetic expenditure and physiological (i.e., stress) consequences. Research should i**dentify the relative species-specific physiological tolerance to the hydraulic conditions presented by existing and future fishway designs.**
- **Incorporate physiological tools and knowledge to determine whether the impediments to passage success are behavioral or related to physiological capacity.** A rapid assessment technique could involve measuring blood and muscle physiology of fish sampled from the top of a fishway and control fish sampled 30 minutes following exposure to manual chasing to elicit physiological exhaustion. Such an approach could identify species (or size classes) that are physiologically taxed from fishway passage and should thus be studied further.
- A new array of assessment tools are available that can substantially improve the study of fish movement, behaviour and fishway hydraulics. Therefore, future research should **incorporate and combine novel tools in the development of fishways studies.**
- Attraction and passage efficiency have been evaluated for only a small number of fishways in Canada (8%), many of which are vertical slot (Hatry et al. 2013). In order to understand the effectiveness of various fishway designs, including passage efficiency for non-salmonids, we encourage research to **evaluate the biological effectiveness of all fishways designs including nature-like and pool and weir.**
- Transfer of salmonid fishway designs to non-salmonid waters has resulted in poor success of passage for non-salmonids species. Fishway design and operations should be adjusted to the swimming abilities of each species. Thus, **fishways should be modified or constructed while considering the entire fish assemblage and species-specific swimming abilities.**
- **Technical changes in fishway design should be considered to facilitate faster fish passage, an overall reduction in energetic cost and possibly a reduction of post-passage mortality.**
- **Apply an interdisciplinary approach that combines disciplines like fish behavior, fish physiology, hydraulics and bioengineering is required.**
- Passage efficiency studies should **consider bidirectional movement at fishways including the likelihood of downstream movement through the fishway compared to the likelihood of entrainment.**

- **There is need for greater conceptual thinking and modeling exercises to determine if and when fish passage is needed**. At present the default assumption is that passage should be provided when a barrier exists. This assumption needs to be challenged given the potential for ecological traps to be formed.

STATEMENT OF PROBLEM

ENTRAINMENT

Fish entrainment occurs when fish volitionally or non-volitionally travel from the upstream reservoir, through a hydro dam, and into the tailrace through turbine or spillway intakes. The consequences include immediate injury or death by striking turbine blades, injury through abrasion along the intake and tailrace walls, barotrauma, disorientation and predation once in the tailrace, and delayed mortality caused by stress and wound infection (Coutant and Whitney 2000). Unless a fishway exists and the animal survives to ascend the fishway and return to the reservoir, entrained fish are lost to upstream systems. Entrained fish therefore represent a loss to fisheries productivity. This is of particular importance in Canada where the federal Fisheries Act protects recreational, commercial, and aboriginal fisheries from serious harm. Thus fisheries and industry managers are interested to understand the entrainment process and take the necessary action required to mitigate or off-set entrainment related losses to fisheries productivity.

Despite growing concerns about fish entrainment, there remains a general lack of understanding about the factors leading to entrainment. Much of the current work has placed emphasis on early life history stages thought to be vulnerable to entrainment and those species that are economically valuable. While much entrainment research has focused on migratory fishes, particularly salmonids, resident fishes (i.e., those that do not emigrate from reservoirs) are vulnerable to entrainment when they use habitats near water intake structures (Martins et al. 2013). Little is known about the mechanisms responsible for entrainment of resident adult fish that are also important to fisheries. Fish behaviour is largely influenced by external factors including water current and temperature (Brett 1971) which can be drastically altered by the presence of dams (Angilletta et al. 2008). Moreover, the behavioural correlates of entrainment are further complicated by foraging strategy, the seasonal distributions of vulnerable species, and the engineering and operational aspects of hydropower intakes. Similar to assessments of upstream passage, a truly informed understanding of entrainment cannot be achieved without taking an interdisciplinary approach including engineers and biologists to perform a systematic investigation of flow dynamics, water temperature changes, and fish behaviour. Based on research performed under HydroNet, here we integrate results from research that included engineers and biologist to generate an informed understanding of entrainment of adult resident fish. Our aim is to help guide future entrainment research based on the outcomes and lessons learned from HydroNet.

METHODS

STUDY SITE

Entrainment of adult resident fish was investigated at the Mica Dam facility on Kinbasket reservoir, British Columbia (Figures 4 and 5). Kinbasket Reservoir is located in the Kootenay-Rocky Mountain Region of British Columbia, Canada (52◦ 8′ N, 118◦ 28′ W; Figure 4) where the Mica dam (244 m high) was completed in 1978 as the furthest upstream impoundment of the Columbia River (Figure 5A). The dam’s powerhouse currently consists of four Francis-type turbines, each with a rated maximum discharge of 283 $m^3 \cdot s^{-1}$ and capacity of 465 MW. During high pool in the summer, the top of the turbine intakes are located near the lake bed at a depth of 56 m. Intakes reduce from the mouth to a 5.26 m x 6.7 m cross-section that joins a circular vertical shaft (Bhuiyan et al. 2009). Turbines are operated seasonally with drawdown beginning in late summer and lasting until low pool in early to late spring. Reservoir elevation fluctuates up to 47 m seasonally (Martins et al. 2014). At high pool during summer and fall, Kinbasket is one of the largest lakes in British Columbia, covering at least 425 km^2.

Dissolved oxygen is high (> 8 $mg \cdot L^{-1}$) throughout the reservoir over much of the year and only drops slightly (0.5 $mg \cdot L^{-1}$) in the summer below 60 m (Bray 2011). Water turbidity and conductivity in the reservoir vary as a result of the many glacial and snowmelt streams that drain into the system. On average, turbidity is low and at times the system is remarkably clear, e.g., 1% light penetration to 30 m in October (Bray 2011). The reservoir is characterized by steep, rocky shorelines, sand, rock, and mud substrates, and little aquatic vegetation. Temperatures in Kinbasket Reservoir are known to range from 2-15°C from April to May and in places can reach 25°C at the surface in August and September (Bray 2011). The average depth is approximately 57 m whereas maximum depths approach 190 m.

In addition to bull trout and burbot, Kinbasket Reservoir also contains native populations of several species of piscivore rainbow trout (*Oncorhynchus mykiss*) and northern pike minnow (*Ptychocheilus oregonensis*). Kokanee salmon were stocked in Kinbasket Reservoir (ca. 1980) with the intention of increasing fisheries productivity. Diatoms (mainly *Asterionella formosa*) are the dominant primary producers, whereas cladocerans and chironomids are the most abundant zooplankton and benthic organisms, respectively (Bray 2012). The reservoir is oligotrophic, having low plankton biomass and low rates of primary productivity (Bray 2012).

BURBOT

A number of reservoir fish species carry out much of their life processes at or near the substrate. Although the majority of fish entrainment research has focused on species that orient near the surface (Coutant and Whitney 2000), the intakes at many hydropower facilities are located along the substrate/dam interface. While it follows that benthic fishes would be vulnerable to entrainment at such facilities, prior to HydroNet there had been no formal research on this potential issue. The work presented here will be a summary of results generated through HydroNet on the behavioural, ecological, and hydraulic correlates of entrainment in free-ranging adult burbot (*Lota lota*, Linnaeus 1758), a common yet relatively understudied benthic resident of cold-water lakes including hydropower reservoirs (Hofmann and Fischer 2002).

Burbot are geographically distributed in aquatic ecosystems around the northern hemisphere. The species has an elongated body with a rounded caudal fin and two distinct barbels protruding from its mandible. Background body colour is typically brown to tan with a darker lace-like overlay pattern. Individuals can reach 100 cm in length, though the average size is 38.1 cm (Scott and Crossman 1973). Burbot is one of the few species that spawns in midwinter and below ice. They may spawn in deep to shallow water and in rivers or lakes. Spawning occurs at night when panmictic aggregations of 10-12 individuals writhe together releasing milt and eggs. Fertilized eggs are deposited onto the substrate where they are left unguarded. During the daylight hours of the non-reproductive period, burbot are restricted to cooler temperatures (15.6-18.3°C) near the hypolimnium. At night, burbot exhibit partial migration where some individuals may move into shallower waters where they likely forage. Adult burbot are considered a top piscivore with their diet comprising of 60-99% fish. Burbot is listed as a species of least concern under the IUCN and currently lacks status under the Committee on the Status of Endangered Wildlife in Canada. However, the decline of some North American burbot populations is under investigation, as the species is important to recreational fishers and aboriginal communities (Stapanian et al. 2010).

BULL TROUT

The extraordinary migration of anadromous adult salmonids is equalled only by their offspring which must travel from headwater streams to the ocean past the same obstacles as their parents, including hydropower dams. The economic importance of anadromous salmonids has supported an abundance of research into managing the entrainment of juveniles along their migration routes (e.g., in the Pacific northwest). To date, limited research has been invested into addressing questions about the entrainment of resident salmonids, despite their importance to inland fisheries. The work presented here will be a summary of results generated through HydroNet on the behavioural, ecological, and hydraulic correlates of entrainment in free-ranging adult resident bull trout (*Salvelinus confluentus,* Suckley 1859) in a large reservoir.

Bull trout are native to the Western United States and Canada. The species exists in four life histories that include river resident, fluvial, adfluvial, and anadromous. Bull trout are characterized by a large head and jaw compared with that of other char. Bull trout are usually olive-green to blue-grey with pale round spots on their flanks and back. Body size is largely dependent on the available forage, with maximum body sizes usually attained in adfluvial and anadromous populations (up to 100 cm total length). At least for adfluvial populations and depending on latitude, individuals expend energy for reproduction at 1-3 year intervals. The proportion of annual spawners is thought to be negatively related to population density COSEWIC 2012). As with other char, bull trout migrate to suitable cold-water spawning habitats during the autumn when water temperatures reach 10-12°C. Spawning behaviour is similar to that of other salmonids, where females are accompanied by a male that vigorously defends her from other males. Eggs and milt are deposited into a redd that is eventually covered with substrate by the female. Once spawning has concluded, both sexes migrate to the habitat that offers the greatest fitness benefits, e.g., lake habitats for adfluvial populations. Given their sensitivity to changes in water quality and vulnerability to overharvest (Johnston et al. 2007), bull trout are currently listed as threatened under the US Fish and Wildlife Service (U.S. 1999) and designated as special concern or threatened under the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2012). The species is important to both aboriginal and recreational fisheries (Gutowsky et al. 2011).

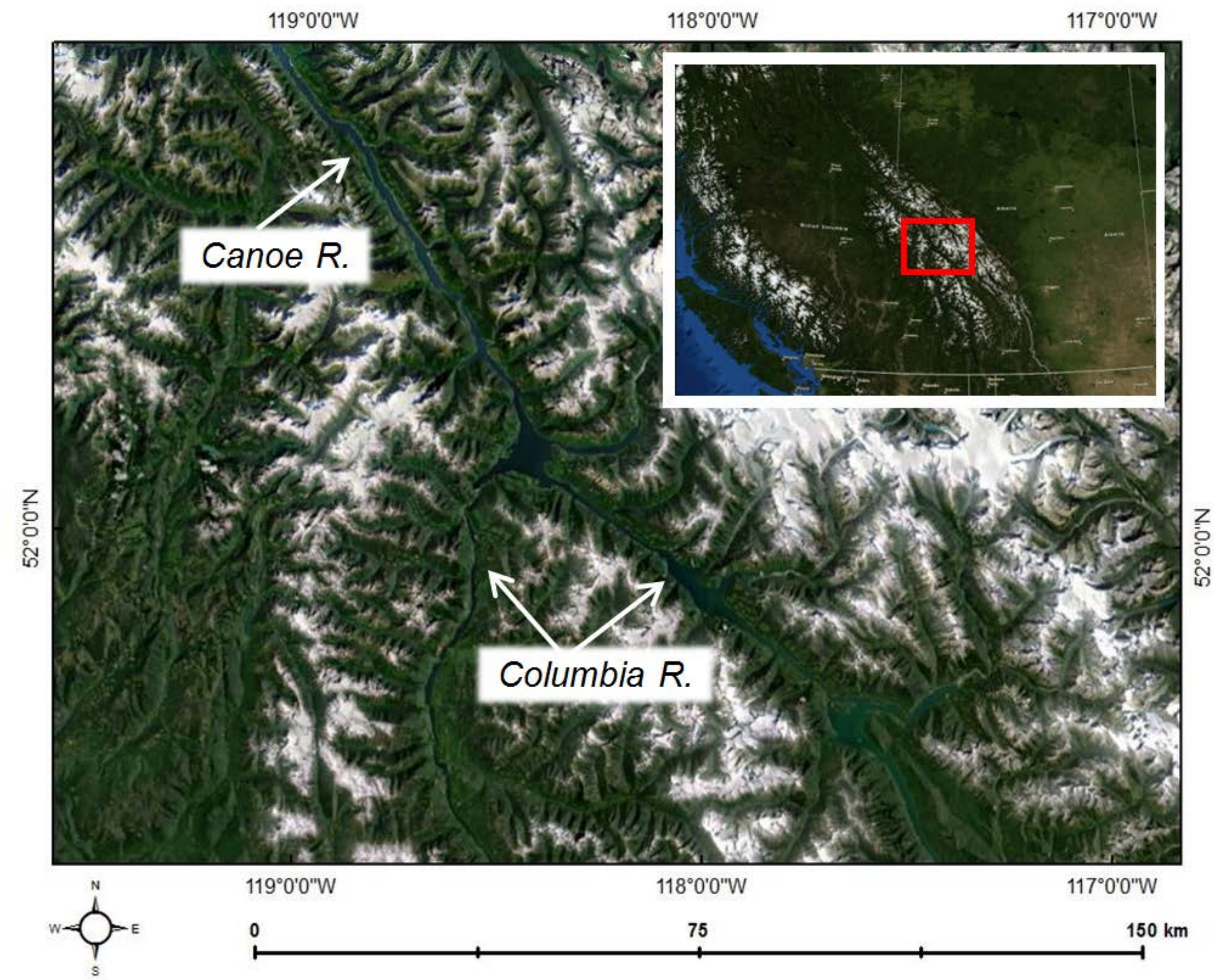

Figure 4: Satellite image of Kinbasket Reservoir, British Columbia. The confluence of the Columbia River to the southeast and the Canoe River to the northwest is shown at center. The inset map illustrates the location of Kinbasket in relation to BC and Alberta.

(A)

(B)

Figure 5: (A) Mica Dam downstream of Kinbasket Reservoir, British Columbia. The spillway is seen to the right (Photo credit: L. Gutowsky). (B) Upstream of Mica Dam facing northeast with the confluence at center and the forebay at the bottom (Photo credit: K. Bray).

HYDRAULICS INCLUDING FLOW FIELD AND TEMPERATURE PROFILES

Mica Dam forebay hydraulic features were first assessed in 2008 with the use of CFD modeling and potential flow solution (PFS) calculations, and validated using lab-based experimental procedures (Bhuiyan et al. 2009). The experimental reservoir was 1.22 m x 0.91 m x 0.6 m with circular outlets of 7.62 cm and 15.24 cm diameter on the vertical wall. Outlet shape, the number of operational intakes, forebay bathymetry, and discharge scenario was manipulated or included into models to replicate conditions at the Mica Dam. To verify CFD models, empirical evaluations of flow field dynamics, including the influence of thermal profiles, were carried out in the Mica Dam forebay from 2011 to 2012 (Figure 6; Robertson et al. 2011, Langford et al. 2012).

Continuous temperature profiles were measured from13 May to 3 November 2011 using a fabricated thermister chain (total of 31 loggers; 5 minute recording intervals; 2 m spacing) deployed in front of (~300 m) the dam face (Onset Tidbit v2 thermistor model UTBI-001; accuracy: 0.2°C, Bourne MA). Flow profiles in the forebay were measured July 11-13, 2011 and August 8-10, 2011 using an acoustic Doppler current profiler (ADCP) from a boat (Teledyne RDI Workhorse Sentinel, frequency: 600 kHz, velocity accuracy: 0.3%, Poway, CA, Figure 6). Temperature profiles in the main reservoir basin have been collected historically through a BC Hydro ecological productivity monitoring program started in 2008 and scheduled annually to 2020 (Bray 2011, 2012). To determine the contribution of tributary water to the thermal characteristics of Kinbasket Reservoir, temperatures at local tributary mouths have been measured with a handheld thermometer. From 2008 to 2010, instantaneous temperature profiles were measured using a Sea-Bird Electronics SBE 19plus V2 profiler (Bellevue, WA) during ice-free months (May – October in 2010) at various locations throughout Kinbasket Reservoir.

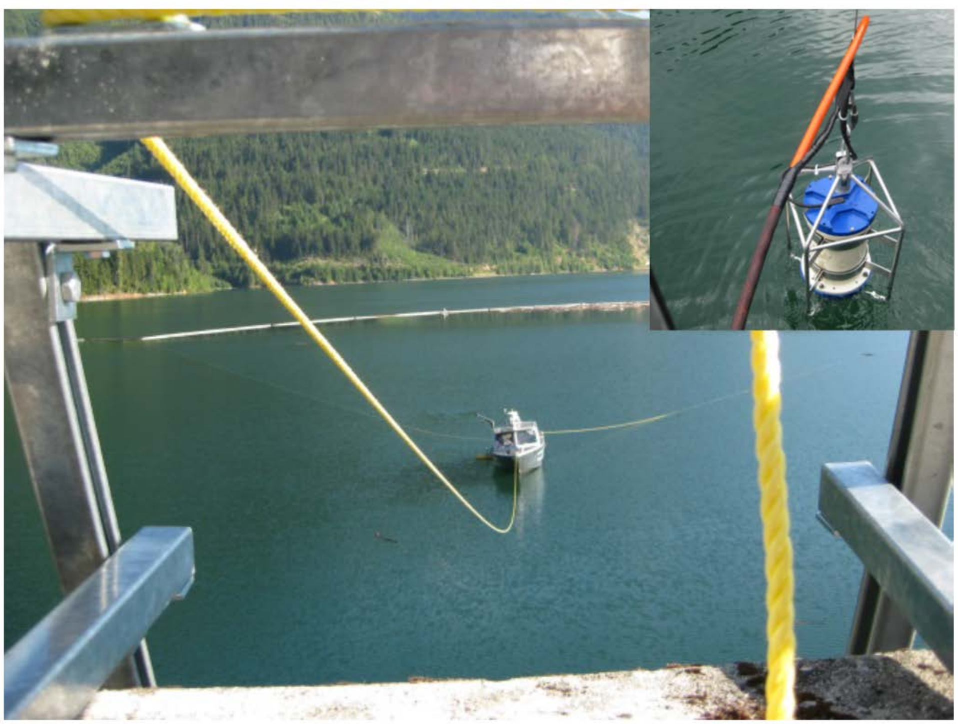

Figure 6: 3-point mooring system used to secure the boat during flow and temperature sampling in the forebay of Mica Dam. The inset image shows the ADCP unit used to collect flow and temperature data.

ASSESSMENT OF SPATIAL ECOLOGY AND ENTRAINMENT

Burbot and bull trout entrainment was assessed using two different acoustic biotelemetry systems on individually tagged animals. To assess coarse-scale spatial ecology and entrainment, 42 omni-directional acoustic hydrophones (VR2W, VEMCO Division, AMIRIX systems) were deployed throughout Kinbasket Reservoir at low pool in the spring of 2010. These hydrophones were fixed to a rope that was suspended by a yellow buoy and anchored with rock-filled sandbags. The array also included six hydrophones placed in the immediate forebay area (Figure 7). To detect post-entrained fish, one hydrophone was deployed in the dam tailrace in 2010 with another hydrophone added in 2011. However, one of these hydrophones was lost some time after it was deployed in 2011 and before retrieval in 2012. Therefore only a single hydrophone was used to detect post-entrained fish in 2011 and 2012. (Figure 7). In year one (2010-2011), no hydrophones were lost in the main reservoir basin. However, five of the 42 hydrophones were lost in year two (2011-2012), likely due to unusually low water levels and ice movement.

To assess fine-scale behaviour and entrainment, an array of seven autonomous acoustic hydrophones (model WHS 3150; Lotek Wireless) was installed in the immediate vicinity (approximately 300 m) of the Mica Dam powerhouse. This technology uses Code Division Multiple Access (CDMA), which operates well under ambient noise and multipath, and facilitates the tracking of multiple animals on a single frequency without code collision (Niezgoda et al. 2002). Through triangulation and a high tag signal transmission rates (3 to 5 seconds), CDMA can be used to determine fine-scale animal movement tracks. Five hydrophones (35 kg each) capable of receiving CDMA transmissions were suspended with additional weight (15 kg) at a fixed depth (25 m) from a floating log boom adjacent to the dam. An additional two of these hydrophones were fixed at a depth of 15 m above turbine intakes 1 and 5 (Figure 7).

To capture burbot, baited cod traps were deployed throughout the confluence at depths of 5-27 m during spring of 2010 and 2011. To avoid barotrauma (i.e., the bends), decompression procedures were performed (see Harrison et al. 2013). A total of 75 burbot were captured and tagged (model VEMCO V13TP-1L, dimensions 45 x 13 mm, weight in water: 6 g, weight in air: 12 g, signal transmission rate: random between 60 and 180 s (mean 120 s), expected battery life: 1028 days, VEMCO Division, AMIRIX Systems) for the investigation of course-scale spatial ecology and entrainment. To capture bull trout, angling procedures were used in the spring (2010 and 2011) and fall (2010, details in Nitychoruk et al. 2013). In total, 187 bull trout were captured and tagged for the investigation of course-scale spatial ecology and entrainment. For the fine-scale investigation of behavior and entrainment vulnerability, 85 adult bull trout were captured and tagged (models MM-M-16-33-TP and MM-M-16-50 TP, size 16x64 to 81 mm; weight in air 27-33 g; fixed signal transmission rate 3, 4, 5 s; temperature accuracy ± 0.8°C; depth accuracy ±3.5 m; frequency 76 kHz; battery life 163-433 days; Lotek Wireless, Newmarket, ON, Canada) in the spring of 2011. Preliminary analysis indicated that burbot seldom used the forebay, thus fine-scale behaviour was not assessed for burbot. Surgical tagging procedures were similar for both species and transmitter types, with the exception that anaesthetic dosing (clover oil emulsified in 95% ethanol at a 1:9 ratio) was higher for burbot (burbot: 90 ppm; bull trout: 40 ppm; details in Martins et al. 2012). Bull trout and burbot were sampled at a variety of body sizes which were maintained within the 2% rule for tag to body mass ratio (Table 2). Following tagging, fish were released to swim at liberty. Data were uploaded and recorded onto one or more hydrophones when free-swimming tagged animals moved within the propagation range of their transmitter (~500-750 m). Course-scale data were downloaded yearly at low pool in 2011 and 2012. Fine-scale detection data were downloaded every three to five months between May 2011 and October 2012. ALPS software (Lotek Wireless) was used to compute position data from the fine-scale array.

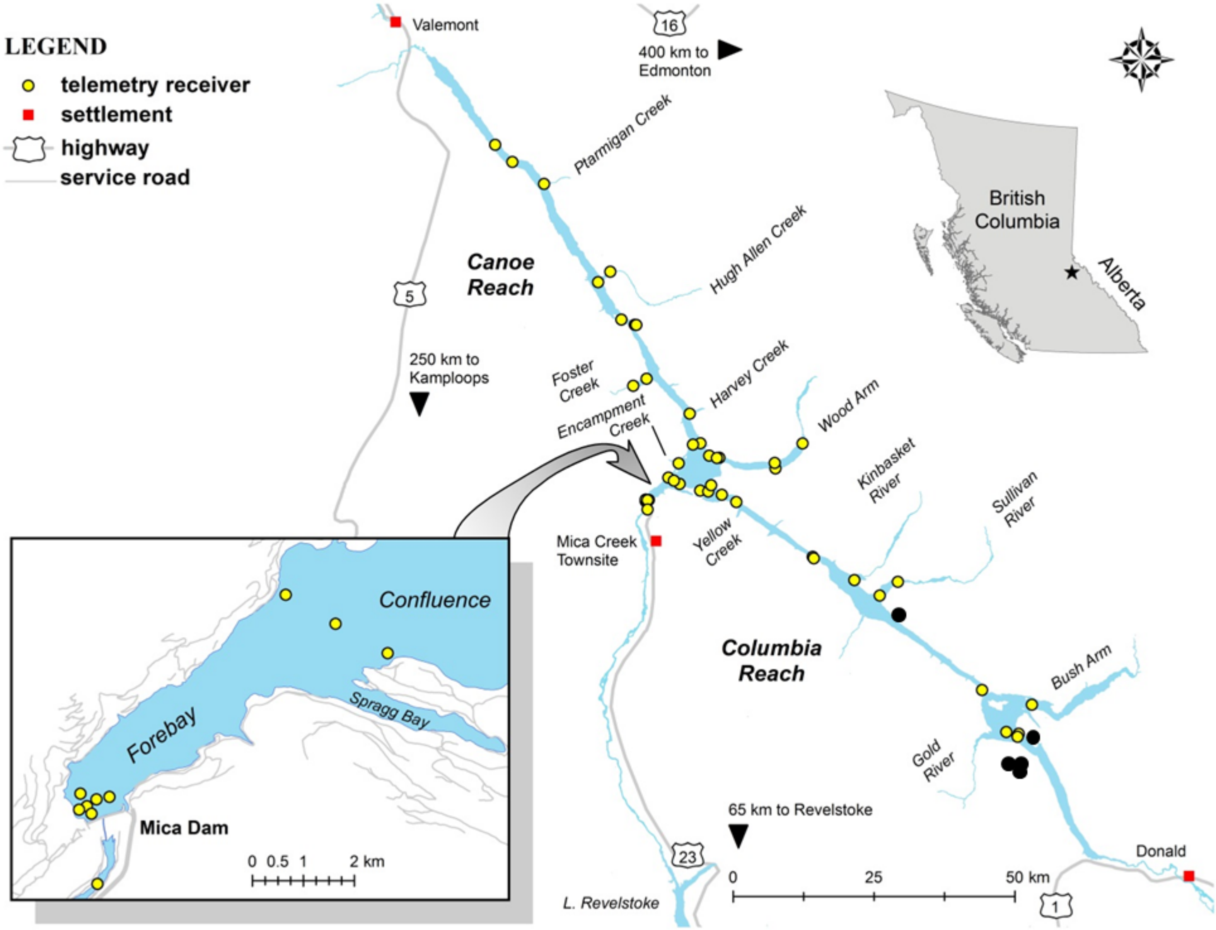

Figure 7: The course-scale (forebay area, inset map) acoustic biotelemetry arrays to -assess burbot and bull trout spatial ecology and entrainment vulnerability in Kinbasket Reservoir. Receivers lost in the second year are denoted with a black circle. The fine-scale array is not shown but is similar to the forebay array seen in the inset map.

Table 2: Total lengths (TL mm) and masses (g) of bull trout and burbot tagged to assess entrainment of adult fish in Kinbasket Reservoir.

Species	Years	Biotelemetry array	Median TL (mm)	Min TL (mm)	Max TL (mm)	Median mass (g)	Min mass (g)	Max mass (g)
Burbot	2010-2012	Course-scale	561	425	975	794	465	4801
Bull trout	2010-2012	Course-scale	585	355	881	1784	310	5857
Bull trout	2011-2012	Fine-scale	659	534	840	2560	1280	5420

DATA MANAGEMENT AND ANALYSES

Course-scale biotelemetry data were filtered to remove erroneous information that resulted from environmental noise, incomplete tag-to-receiver transmission, or code collision. Filtering was performed in Microsoft Access and the R statistical environment (R Core Development Team 2012). Movement, depth, and temperature estimates were visualized using ArcGIS 10.1 (Environmental Systems Resource Institute, Redlands, California) and plotting functions in Microsoft Excel and R. Depending on the source, telemetry data are presented monthly, seasonally, or based on biologically relevant periods, e.g., prespawn and spawn, postspawn). For the fine-scale biotelemetry data, erroneous position estimates (e.g., positions on land) were accounted for using state-space modeling (Jonsen et al. 2005). Hydraulics and temperature profile data are summarized and presented visually. More detailed sampling, data filtering, and statistical methodology (e.g., state-space models) can be found in the cited references. The results here are mainly presented visually as an integration of biotelemetry results, CFD modeling, and environmental temperature data available for burbot and bull trout.

RESULTS

FLUID DYNAMICS AND TEMPERATURE

Preliminary theoretical work investigated fluid dynamics under nine potential operational scenarios and with changes to pool level to account for the large yearly water-level fluctuations at Mica Dam. Velocity and acceleration increased significantly along the centerline axis of the vertical intake shaft. Turbine intake flow field velocities interacted with the dam structures and other intake flows creating a weakly turbulent environment. A vortex-like flow pattern and identical velocity profile occurred above the intakes when any operations included the left most turbine (Bhuiyan et al. 2009). Surface water intake increased when multiple turbines were in operation. Water withdrawal zones extended to the forebay surface when 5 and 6 turbines were in full-capacity operation. Depending on the intake, field measurements confirmed that flow velocity degrades with distance from the intakes, where the highest measured velocity was 0.5 m/s at 15 m from the dam face (Langford et al. 2012). As expected, water velocity was highest for higher values of discharge and where the left most intake (turbine 1) is located (Langford et al. 2012)(Figure 8). Following CFD modeling, a velocity of 0.1 $m \cdot s^{-1}$ was found to extend up to 100 m upstream of each intake. The two-dimensional size of this zone increases with the number of operational intakes and when surface water elevations were lower. Relatively high velocities (>0.5 $m \cdot s^{-1}$) can be expected to the surface above the left most intake.

Temperature profiles in the forebay were isothermal during winter and spring until June when the top layers began to warm. By mid-summer (~July 29, 2011) the forebay contained a well-defined gradient of temperatures from a maximum surface temperature of 20°C down to ~4°C at 63 m. As the summer progressed into autumn, warmer water temperatures expanded into deeper water. For instance, the 11°C isotherm shifted from ~20 m on July 29, 2011 to ~35 m on September 11, 2011, after which time the forebay began to mix and cool throughout. In general, both the forebay measurements and instantaneous measurements from the reservoir indicated that during summer, temperature profiles were nearly linear from the surface down to the hypolimnium layer (Robertson et al. 2011). Inflow temperatures are on average cooler (~4°C) than reservoir surface temperatures (Robertson et al. 2011, Bray 2012). Measurements collected from 2008-2011 indicated that reservoir thermal profiles generally became more gradual from May to September. However, depending on the sampling location in the reservoir, temperatures varied as much as 5°C for given depth with the forebay generally reaching the warmest temperatures (Figure 9). However, temperatures may fluctuate rather dramatically over a short time frame (Robertson et al. 2011). Dam operations affected temperature profiles on a daily basis at depths greater than 30 m in the forebay (recorded from 38 - 61 m). For example, on October 15-18, 2011, a decrease in discharge of ~ 300 $m^3 \cdot s^{-1}$ was associated with an increase in temperature of ~ 4-5°C (Robertson et al. 2011). While dam operations may affect the temperature profile in the forebay area, most rapid internal temperature profile changes were attributed to wind, waves, and seiche effects which can cause mixing and a shift in reservoir and forebay temperatures over the course of one to several days. For example, on September 12-14, the first ~10 m of water in the forebay was ~17°C. As wind increased over the next two days (up to 36 $km \cdot hr^{-1}$), the top layer cooled (~13°C) and stretched down to ~15 m (Robertson et al. 2011). In addition, relatively high volumes of cold inflow water may prevent mixing and the development of a well-defined epilimnion.

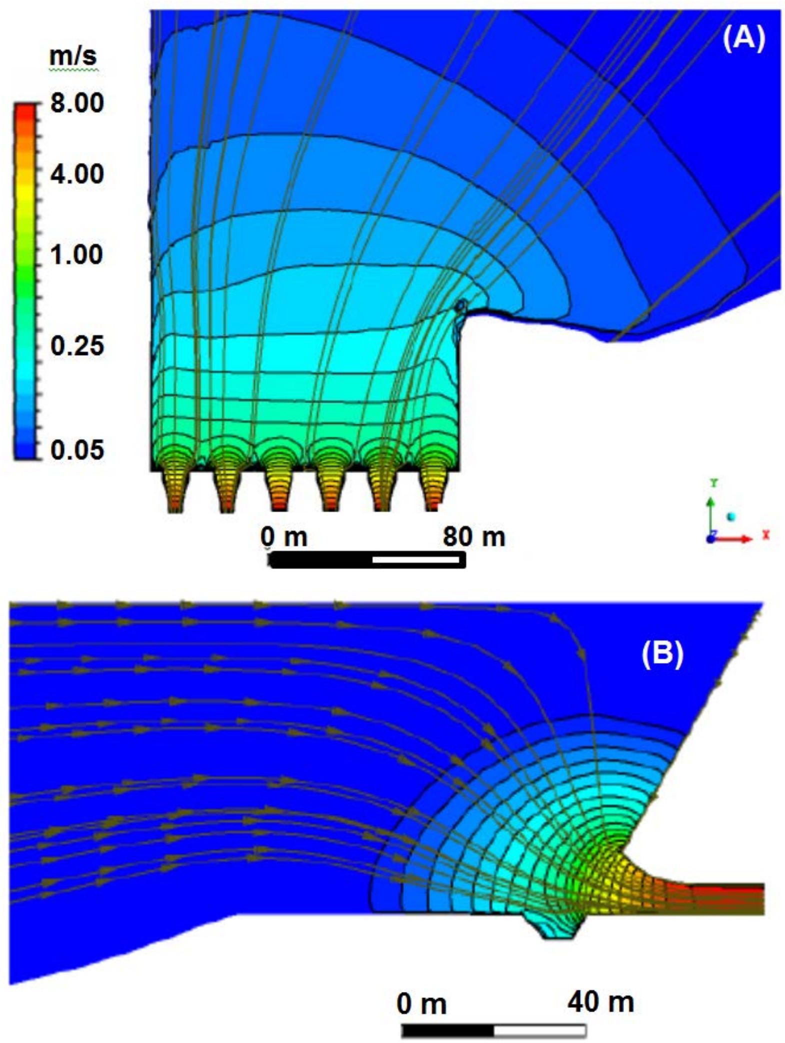

Figure 8: Horizontal centerline velocity profile in the Mica Dam forebay when all six turbines are in operation (A). Vertical velocity profile of intake 1 at the Mica Dam (B).

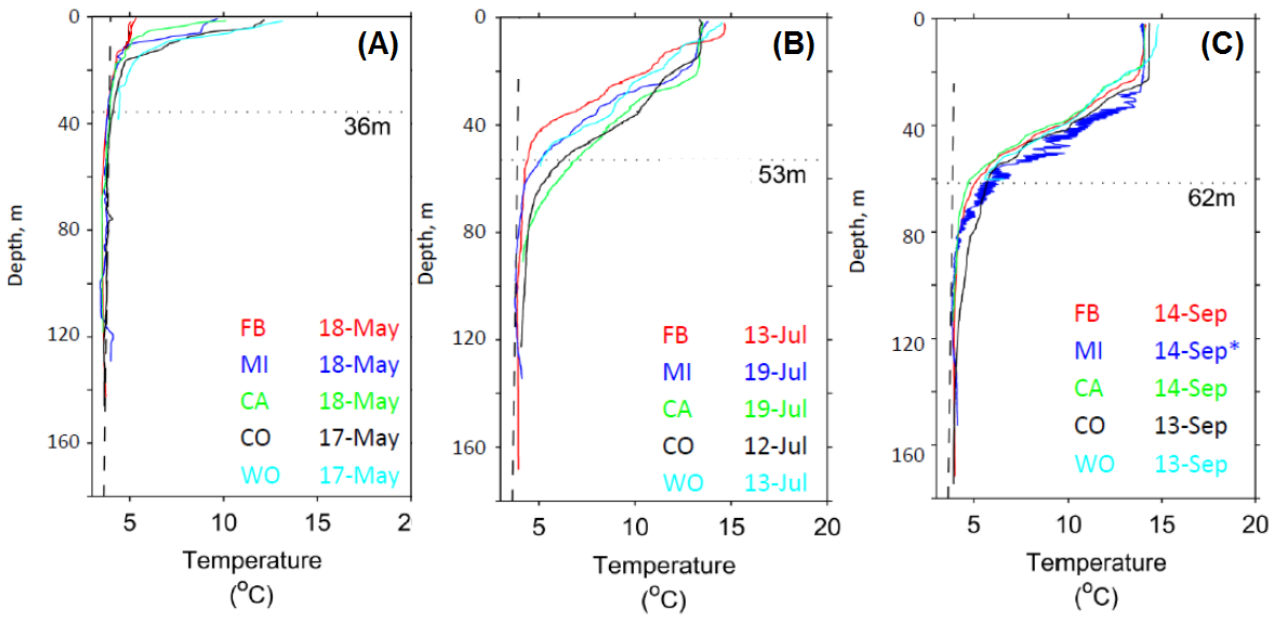

Figure 9: Instantaneous temperature profiles measures in May (A), July (B), and September (C) 2010 in Kinbasket Reservoir. Coloured lines represent sampling locations: Forebay (FB), middle of the reservoir (MI), Canoe Reach (CA), Columbia Reach (CO), and Wood Arm (WO) are illustrated in colour. The dashed horizontal line indicates the approximate intake depth. Figure modified from Robertson et al. 2012.

REVIEW ON BURBOT SPATIAL ECOLOGY

Burbot home range sizes were repeatable and ranged from 0.204 $km^2 \cdot mo^{-1}$ to 14.7 $km^2 \cdot mo^{-1}$ with a median of 1.45 $km^2 \cdot mo^{-1}$ (n = 37 burbot, 95% utilization distribution, (Harrison et al. 2014). Burbot showed some level of site fidelity, as those captured closer to the forebay possessed home ranges that were also closer to the forebay in both years (Martins et al. 2012). Lateral movement was also repeatable and ranged among individuals (0-162 km/mo, median: 15.6 km, (Harrison et al. 2014). Rates of vertical movement were highest during the night for all seasons and large burbot tended to occupy shallower water at night during the prespawn and spawning period (November-January), post spawn (February-April), and during summer (May-October, Harrison et al. 2013). Overall mean daily and nightly swimming depths differed by approximately 11 m (day: 37.09±1.3 m, night: 25.9±1.5 m, Harrison et al. 2013). However, burbot were found at depths in excess of 100 m where water temperatures were 4°C (Figure 10). Dissolved oxygen is not limiting in Kinbasket reservoir, as concentrations are high (up to 9 mg/L) throughout the year and only decline slightly (≤1 mg/L) below 60 m (Bray 2012). During the summer months, a typical burbot occupied an average depth of 20 m and experienced an average temperature of 10.5 °C (Harrison et al. 2013). Although pooled across several months, burbot temperature history and depth corresponded well with instantaneous temperature profiles at several locations in Kinbasket Reservoir during summer months (e.g., July, 2010) when a temperature of 10.5°C was found between 20 and 40 m (Figure 9).

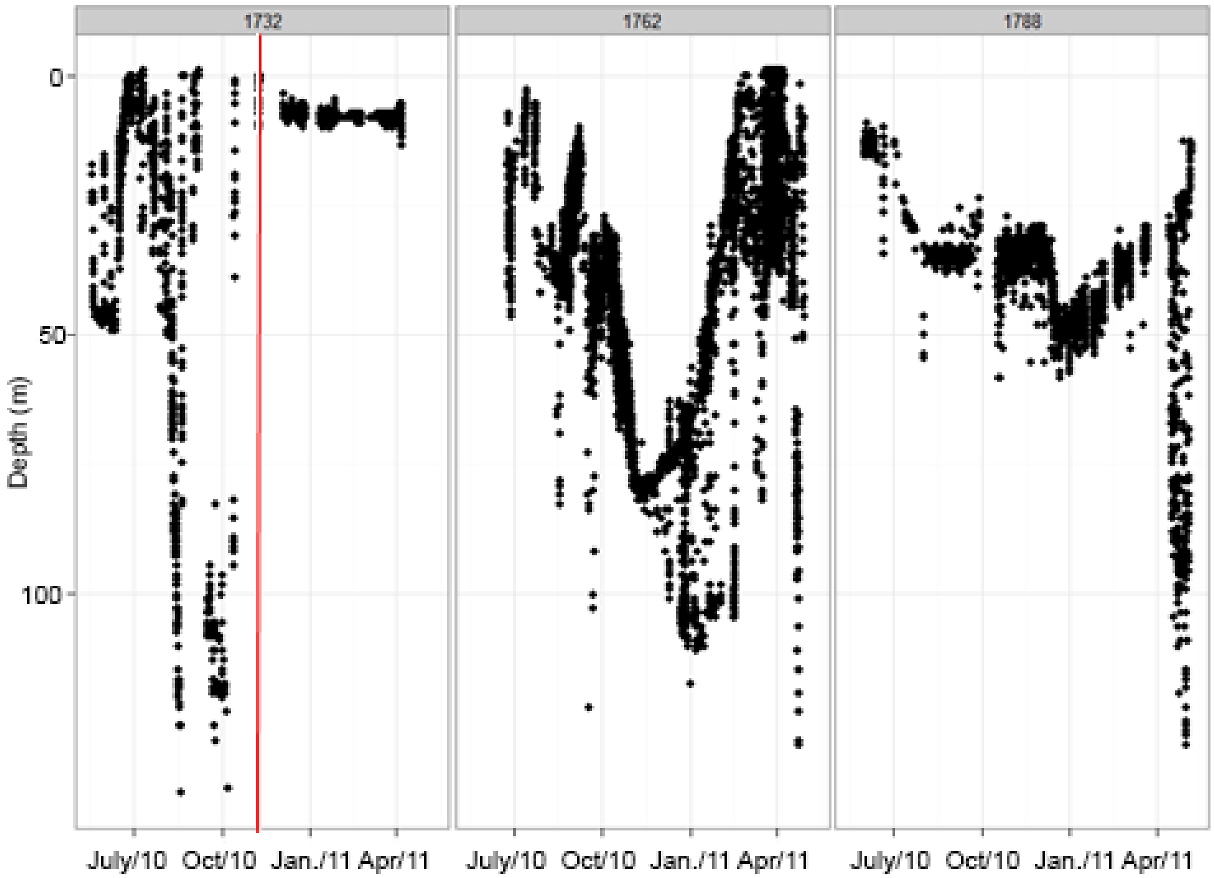

Figure 10: Depth (m) detections from three burbot that were surgically implanted with course-scale telemetry transmitters, including an individual (left panel) that was detected in the tailrace November 8, 2010. The red vertical line marks the final detection in the reservoir main basin prior to entrainment. Figure modified from Martins et al. (2012).

REVIEW ON BULL TROUT SPATIAL ECOLOGY

For resident bull trout, home range size varied according to season. Based on 90% minimum convex polygon estimates, bull trout were estimated to occupy a home range of approximately 50 km^2 during spring and fall, compared to 35 km^2 winter and summer (Gutowsky et al. 2016). Bull trout were more mobile than burbot and individuals may move up to 100 km·mo^{-1}. Seasonal distributions show that bull trout congregate in the confluence area during the winter and utilize much of the reservoir during autumn. From May 2010 to May 2012, bull trout utilized much of the entire system (Figure 11). Despite tagging 28 individuals in the lower reaches of the Columbia River basin and deploying several hydrophones in this location (Figure 11), few bull trout from this extent of the system were detected elsewhere (Figure 11). Swimming depth data have shown that bull trout perform diel vertical migration in Kinbasket Reservoir and at times exploited depths below 50 m (Gutowsky et al. 2013). Large individuals tended to occupy the shallowest water in a given season. The deepest swimming depths were generally achieved in the summer. Conversely, the spring was characterized by relatively shallow swimming depths (~ 5-8 m) for all body sizes. Vertical activity also varied seasonally and throughout a 24 hour period with the greatest activity occurring during daylight hours. According to fine-scale behaviour in the forebay area, bull trout were most likely to engage in exploratory (i.e. slow speeds and frequent turns) behavior during the night (Martins et al. 2014). Although found in depths over 50 m, bull trout most often swam at depths of less than 30 m. Average daily temperature data showed that individuals occupied a narrow range of temperatures, even during the summer when a wide range of temperatures were available along the thermal gradients present in Kinbasket Reservoir (L. Gutowsky, unpublished data).

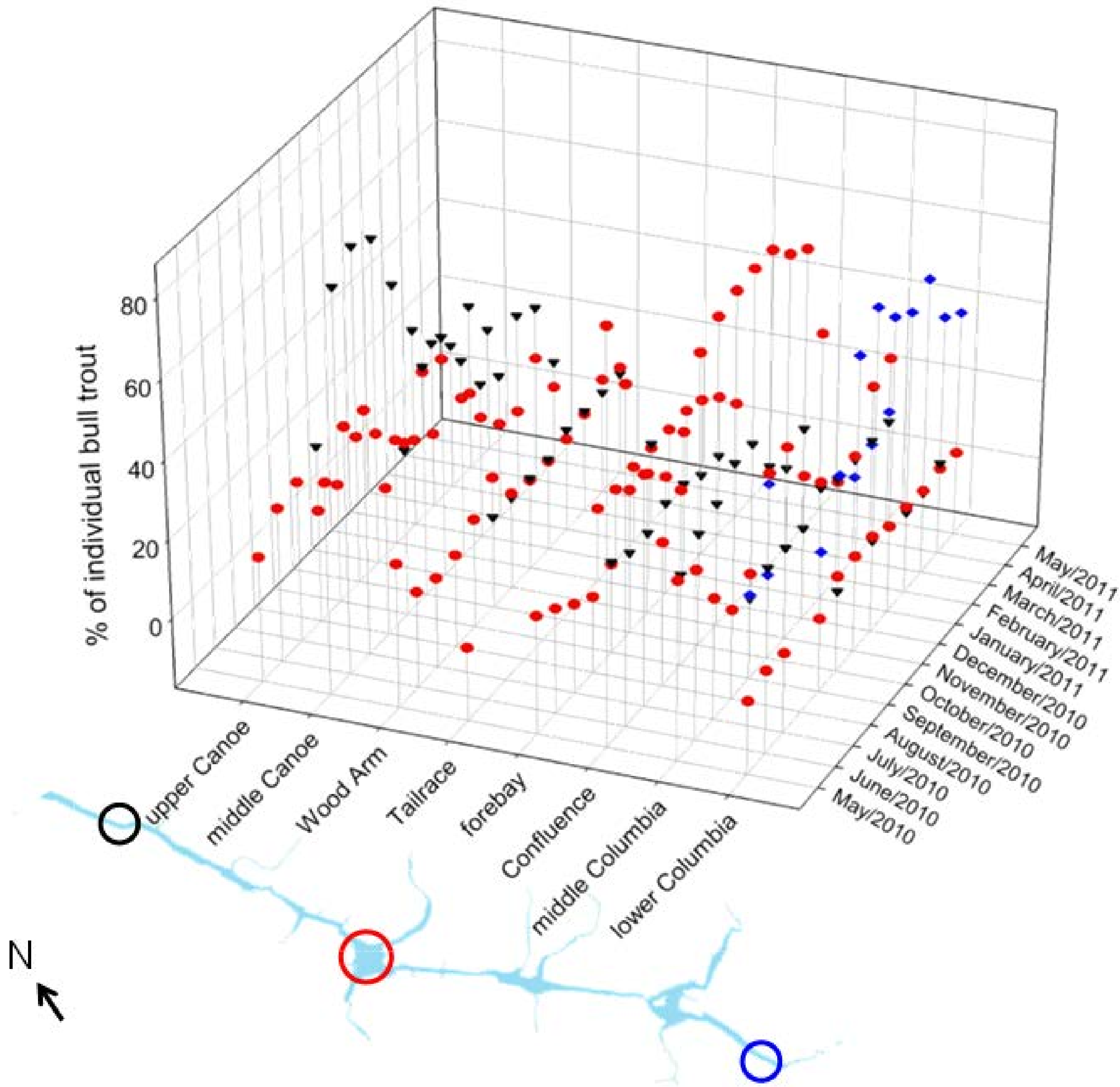

Figure 11: Bull trout sample group [blue diamond = Columbia Reach (n = 28), Red circle = confluence (n = 122), black triangle = Canoe Reach (n = 37)] habitat selection by receiver group and month in Kinbasket Reservoir from May 2010 to May 2011. Tagging locations are shown by black (Canoe Reach sample), red (confluence sample), and blue (Columbia Reach sample) circles. Note that bull trout from either reach were tagged in August 2010 and therefore were not detected until after this period.

DISCUSSION

AN INTEGRATED APPROACH TO EVALUATE ADULT FISH ENTRAINMENT

Burbot

With sufficient oxygen and suitable cold water temperatures throughout the system (Robertson et al. 2011), burbot were able to exploit habitat as deep or deeper than the Mica Dam intakes (Martins et al. 2012). Nevertheless, no home ranges overlapped the forebay and only six individuals (10.6% of the total tagged) were detected in the forebay. It should be noted that due to signal transmission issues and environmental noise, the expected detection frequency was at times < 1% (Martins et al. 2012). One animal (ID 1732, 442 mm TL, Figure 10) was detected in the tailrace on November 8, 2010. Not unlike two conspecifics, this individual frequently occupied depths below the turbine intakes (> 60 m) where water temperatures were isothermal at this time of year (Langford et al. 2012). In mid-October 2010, Mica dam was in operation when water temperatures at the intake level were suitable for burbot (6°C at 64 m, (Robertson et al. 2011). Prior to the first tailrace detection on November 8, 2010, burbot 1732 (442 mm TL) was detected almost exclusively in a local creek (98.7% of detections), and at two receivers in the outer forebay area. Given the isolated entrainment event and limited forebay use, entrainment likely poses minimal threat to adult burbot in Kinbasket Reservoir.

Bull Trout

Bull trout typically exploited depths that were 10-20 m above the turbine intakes during all seasons. Hydrophone median detection efficiency was only 0.34% during the two-year study period over which time approximately 52% (n = 97) of all tagged bull trout were detected in the forebay (Martins et al. 2013). Individuals were generally detected throughout Kinbasket Reservoir with the exception of the southern extent of the system. Those tagged in small tributaries of the Canoe River were detected throughout Kinbasket in 2010 whereas those tagged from similar tributaries in the southern Columbia River were only detected near their original capture location (Figure 11). The greatest concentration of individuals was observed in the confluence region during winter when seven of the eight entrained individuals were detected in the tailrace (Table 2; Figure 12; Martins et al. 2013). Similar to most tagged bull trout, entrained individuals possessed winter home ranges that overlapped the forebay (Figure 12). Depending on the time of day and body size, bull trout mainly swam at depths of 5-14 m during winter when the reservoir was at high pool (Robertson et al. 2011, Gutowsky et al. 2013). Prior to their final detection in the reservoir or forebay, entrained individuals did not exhibit exceptional swimming depths compared to turbine intake depth (Martins et al. 2012, Figure 13). Water temperatures in the forebay were isothermal and not subject to dramatic fluctuations elicited by meteorological events or dam operations (Robertson et al. 2011).

State-space models of fine-scale movement within the forebay indicated that bull trout resided longer in the vicinity of the powerhouse and moved closer to turbines during the fall and winter. In addition, the likelihood of exploratory behaviour increased slightly at night or when body temperatures were above or below 6°C (Martins et al. 2014). Combined with the course-scale telemetry data, these results suggest that entrainment may only be an issue in the fall and winter, and for stocks that spawn in tributaries north of the Bush Arm (Figure 11). The effects of turbine operations on the thermal profile of the forebay is not likely an important factor for entrainment risk as bull trout were only entrained during periods of the year when water temperatures were isothermal. Although the risky zone for entrainment is theoretically maximized at low pool and when dam operations are at full capacity (Bhuiyan et al. 2009, Robertson et al. 2011), entrainment occurred under the opposite conditions. Given that each of the entrained bull trout would be easily capable of sprints upward of 0.5 $m \cdot s^{-1}$ (Martins et al. 2014), these individuals would have needed to move into very close proximity of the intakes to be non-volitionally entrained. In other words, given their swimming depth behaviour prior to entrainment, entrained bull trout likely engaged in exploratory behaviour that brought them near to or inside the intakes at depths over 40 m.

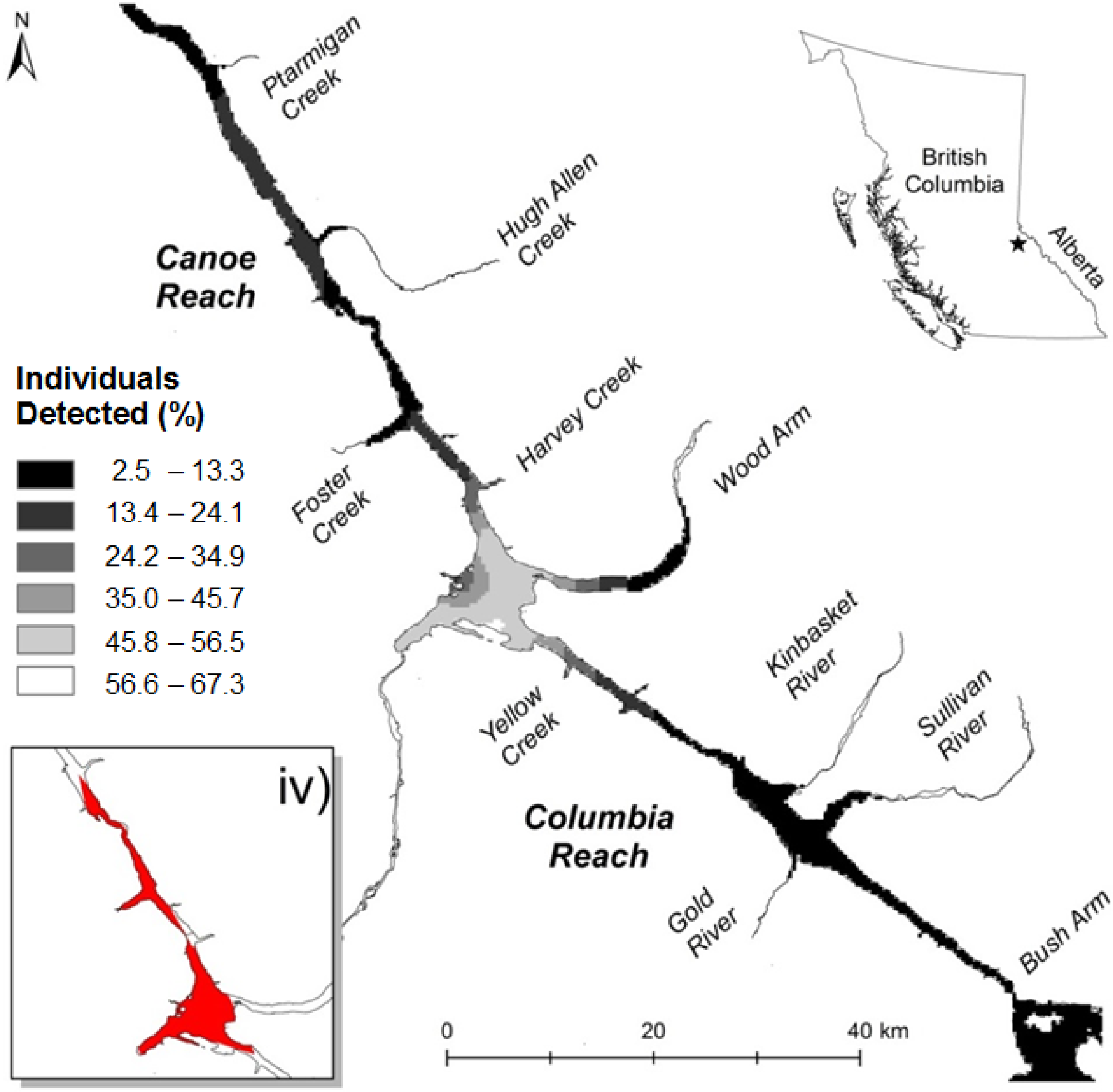

Figure 12: Percent of the total number of individual bull trout detected (n = 146) across Kinbasket Reservoir during the winter of 2011. The inset map (i) illustrates the combined 90% minimum convex polygon winter homeranges of the bull trout (n = 6) that would eventually be entrained at Mica Dam. Homerange estimates in the winter were available for Tag ID 1672, Tag ID 1686, 1720, Tag ID 1800, Tag ID 1992, and Tag ID 1974.

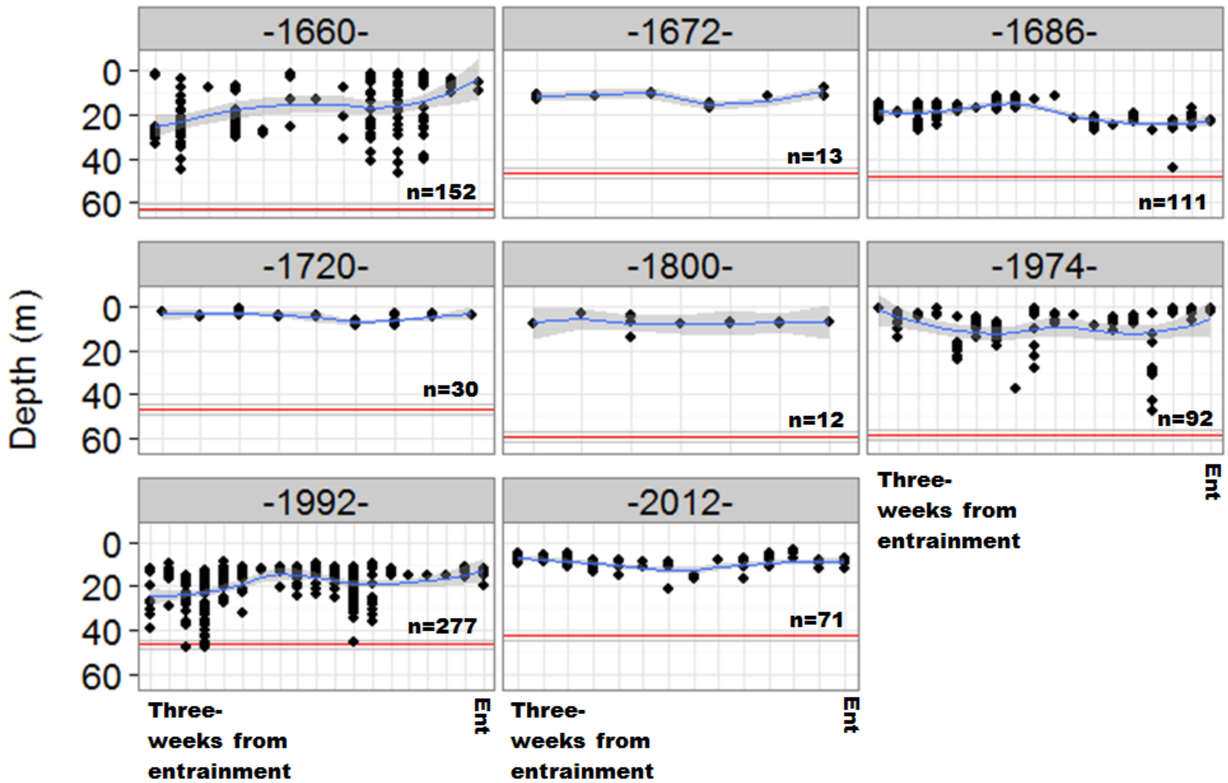

Figure 13: Recorded swimming depth (m) for each entrained bull trout three weeks prior to the final within-reservoir acoustic hydrophone detection and subsequent detection in the tailrace. Bull trout were detected in the tailrace between Dec 24, 2010 and March 29, 2012. Vertical gridlines illustrate a span of days that include the number of detections within a 24 hour period up to three weeks prior to entrainment for each entrained individual. The total number of detections per individual is shown in the bottom left of each panel. Horizontal lines indicate the range (min – max) and mean (red) intake operating depth prior to entrainment by an individual. Data are fitted with a LOESS smoothing function ± SE. Post-entrainment depth is not shown. The x-axis is shown with a fixed width to aid with visualization.

A CONCEPTUAL MODEL OF FISH ENTRAINMENT

Figure 14 shows a conceptual model of fish entrainment. The conceptual model is based on three possible states at which fish may be at a given time: not at risk of entrainment (N; i.e. in the reservoir but outside forebay), at risk (R; i.e. inside forebay) and entrained (E). Fish transit from N to R with rate *r* (the rate at which not-at-risk fish becomes at risk of entrainment), from R to N with rate *n* (the rate at which at-risk fish becomes not-at-risk of entrainment); and from R to E with rate *e* (the rate at which at-risk fish become entrained).

For simplicity, the model assumes that *r* and *n* are simply related to the 2D-location of the fish outside and inside the forebay, respectively. Thus, *r* and *n* are a function of the horizontal movement of the fish. Such movements are influenced by factors operating at different time scales. For example, on a seasonal basis, movements and home ranges may vary with reproductive activity as well as environmental and operational conditions of the reservoir. On a daily basis, movements and home ranges may vary with foraging activities and weather conditions.

In contrast the model assumes that *e* is related to the 3D-location of the fish in the forebay, the fish's swim ability and the intake-induced flow field. The 3D-location of the fish in the forebay is influenced by their foraging behaviour and prey distribution. Water temperature distribution in the forebay varies with season and water withdrawal and therefore is also likely to influence 3D-location of individuals, as fish tend to occupy their preferred thermal ranges. Fish swim ability is known to depend on both the water temperature and their size, and therefore determines their ability to escape or get entrained in strong flows near turbine intakes. Finally, entrainment cannot occur in the absence of an intake-induced flow field. The strength of the flow field is determined by a number of variables. Chiefly among those are the water level and turbine operations (number of turbines, magnitude of flows and duration of operations). These conditions vary markedly with seasons according to predictable variations in water input (rain, snowmelt) and output (meeting of energy and flow demands).

In our conceptual model, E is an absorbing state, meaning that entrained fish cannot leave that state and are permanently lost from the reservoir. However, this may not always be the case, as fish that survive the entrainment event may eventually return to the reservoir if the hydropower facility is equipped with fishways, In addition, the model ignores recruitment of fish from downstream, which may also occur in facilities equipped with fishways.

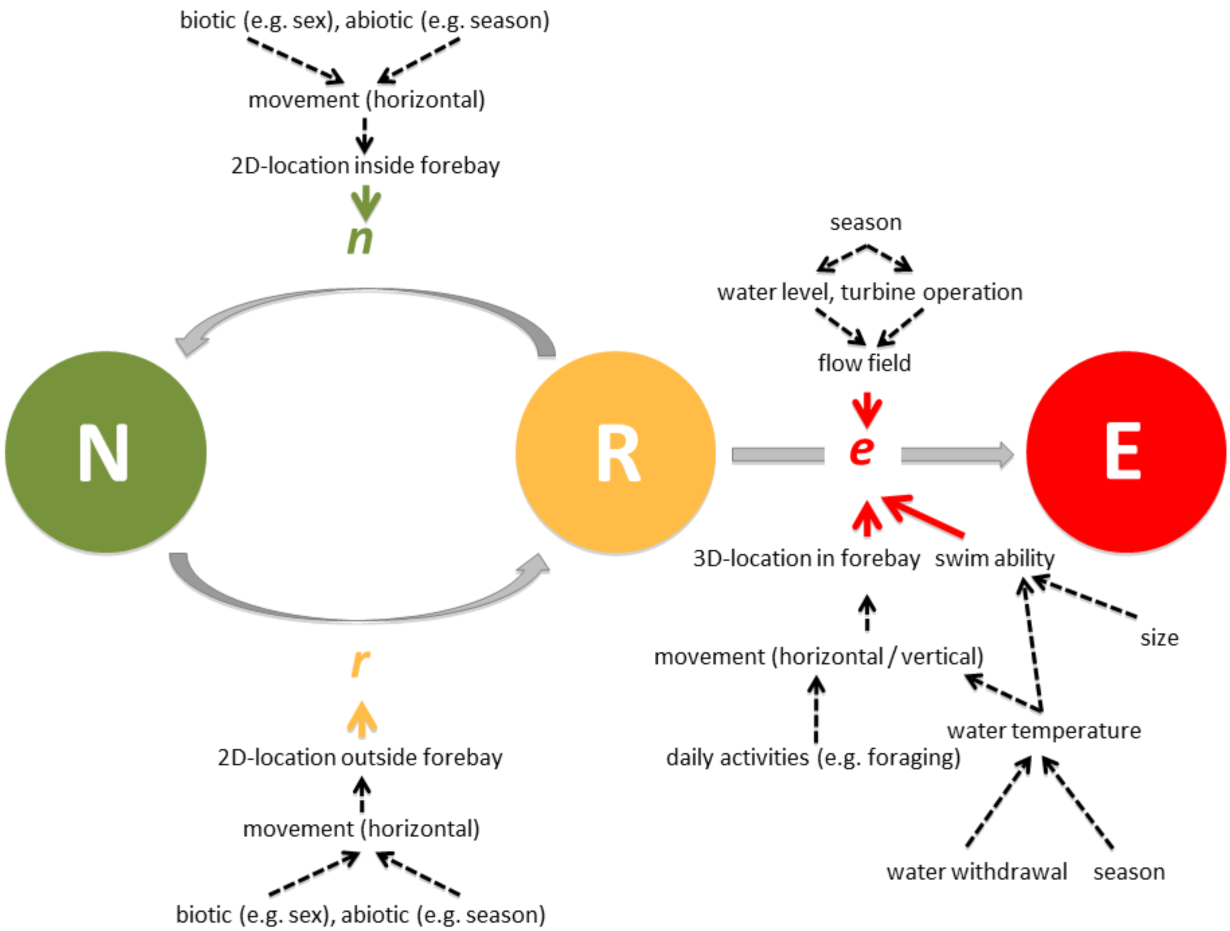

Figure 14: Schematic representation of the conceptual model of adult fish entrainment in hydropower reservoirs.

CHALLENGES AND GENERAL CONSIDERATIONS

Here we synthetize some key points that are needed to be taken into consideration for fish entrainment research:

- It is impossible to understand the factors leading to entrainment without assessing the physical environment in the forebay including flow field dynamics and water temperature in relation to the biology and ecology of the target species. Thus, **entrainment is best evaluated by assembling an interdisciplinary team including engineers and biologists**.
- Spatial ecology explained species-specific entrainment vulnerability estimates as species can exhibit substantially different movement, behaviour, and forebay use. **Entrainment must be considered on a species-specific basis.**
- Overall population level consequences of adult fish entrainment often remain unknown. Assessing these consequences would require population estimates and evaluations of recruitment and early life history (as well as entrainment of early life stages). Future entrainment research should **consider assessments of current and future population status to then estimate the consequences of entrainment in target species**.
- While temperature explains the behavioural ecology during periods of the year when a thermal gradient exists, the isothermal conditions under which all fish were entrained in Kinbasket Reservoir illustrates that for some species, entrainment may occur when temperatures are at their coldest and when the water is not thermally stratified. Temperature is the most important variable controlling fish physiology and behaviour and is likely an important correlate of entrainment for other target species.
- **Methods to assess the biological and hydraulic correlates of entrainment should include a standardized set of collection and analytical tools.** Advancements in biotelemetry, including the development of transmitters designed for small fish, have provided a powerful tool set for making detailed evaluations of species-specific and individual-level spatial ecology. Such tools have proven to be very important for understanding the causes of adult fish entrainment.
- It is difficult to verify lab-based CFD calculations for several reasons. For safety precautions, many dam facilities prohibit working in boats directly above or adjacent to intakes, making it impossible to acquire field based measurements of flow and temperature in this location. Given that small structures can influence flow computed results from CFD modeling (Bhuiyan et al. 2009), detailed 3-D models are a useful alternative to generating realistic estimates for zones of entrainment risk. Such detail would be useful for small fish that can be entrained through lower flow velocities. Where ADCP sampling is permitted in a forebay, for example 15 m from the dam face and where velocity is low (Langford et al. 2012), it is important to eliminate boat drift by securely mooring to at least three on-shore points.
- Large water-level fluctuations and the environmental noise from dam operations both significantly challenge the ability to operate acoustic telemetry systems in reservoirs. This was evident in the forebay of Kinbasket Reservoir where detection efficiency for the 69 kHz course-scale telemetry system tags was typically very low (< 5%) and varied seasonally (Martins et al. 2013). For the 76 kHz fine-scale telemetry tags, positioning efficiency was affected by a dynamic set of variables including transmitter location, season, dam discharge (Martins et al. 2014). Poor detection efficiency restricted the ability to assess the behavioural correlates of entrainment as it occurred. Additionally, new high frequency (200-300 kHz) acoustic systems are less sensitive to mechanical noises. Thus, it is recommended that

multiple transmitter frequencies are tested to ensure the greatest possible detection efficiency is achieved. In addition, beacon tags should be included with hydrophones so that detections efficiency can be calculated and forebay use by fish corrected.

- Entrainment vulnerability depends on spatial and temporal factors. Telemetry is a useful tool for identifying the temporal and spatial correlates of entrainment. Therefore, **telemetry should be used to evaluate the relative entrainment vulnerability of fish that are sample from across reservoir systems.**
- Understanding the apparent attraction to turbine intakes is an important first step toward determining how to best install technologies to help fish avoid or be repelled (e.g., strobe lights) from these structures. **Future research should investigate the mechanisms that draw fish to turbine intakes and subsequent entrainment including potential attraction to noise, vibration, or prey.**
- We were unable to assess any effect of turbine configuration on entrainment for the adult life-stages of the studied species. **Biologists and engineers should work together to identify how turbine configuration influences behaviour and the likelihood of entrainment of target species.**

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