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EPRI Project Manager

P. Jacobson

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Principal Investigator
P. Jacobson

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ABSTRACT

The Electric Power Research Institute (EPRI) established the Eel Passage Research Center (EPRC) in 2013 to address the challenge of providing safe downstream passage for outmigrating adult American eel (*Anguilla rostrata*) on the St. Lawrence River. With funding by OPG, Hydro-Québec (HQ), the Fish Enhancement, Mitigation, and Research Fund (FEMRF) administered by the U.S. Fish and Wildlife Service (Service), and Duke Energy (Duke), the EPRC employs an adaptive, collaborative process to plan and execute a program of research on behavioral guidance of downstream migrating adult eels, as screening and physical guidance have been deemed infeasible. The EPRC's goal is to develop the technology to behaviorally guide the eels to a collection point for capture and transfer around the Moses-Saunders Power Dam and the Beauharnois Generating Station. The EPRC R&D builds upon the very substantial prior investments in eel passage research by EPRC funders and others. R&D is guided by a technical committee comprising representatives of EPRI, EPRC funding organizations, and resource management agencies with regulatory authority over the funders' hydropower activities on the St. Lawrence River. The technical committee collaboratively establishes the research priorities and plan, develops research scopes of work, and reviews R&D proposals and draft project reports. The EPRC has fully funded six major R&D projects and has supported several other projects relevant to the goals and objectives of the EPRC.

Eel escapement from Lake Ontario can be expected to decline in the next several years. This raises the urgency of developing and deploying downstream passage technologies to improve the survival of outmigrating adult eels. Consequently, it will be important to rapidly transition from adaptive, exploratory R&D to adaptive mitigation and management utilizing early stage guidance, collection, and monitoring technologies to support a trap and transport program. This can be accomplished by rapid, iterative design, deployment, and testing of guidance and collection technologies. This approach could be initiated with design and deployment of a subscale, prototype guidance and collection structure or structures utilizing light and perhaps low frequency sound. This adaptive mitigation approach would enhance mitigation effectiveness over the near term, and develop more effective technology over the mid- to long term. Siting and design of a subscale experimental guidance and collection structure can begin in the near-term, utilizing the R&D results produced by the EPRC.

Keywords
American eel
Hydropower
Downstream passage
Behavioral guidance

EXECUTIVE SUMMARY

Virtually all eels migrating from Lake Ontario and its tributaries to the Sargasso Sea currently must pass downstream via the operating turbines at Moses-Saunders Power Dam and Beauharnois Generating Station where they experience an estimated cumulative mortality rate of 39.5%. A decision analysis considering mitigation options and their respective costs and likelihoods of success identified trap and transport as the preferred mitigation method. An ongoing trap and transport program operated by Ontario Power Generation (OPG) passed an annual average of 1,600 eels downstream of the two generating stations over the period 2008-2015. Significant expansion of trap and transport will require a method for capturing adult eels during their downstream migration.

The Eel Passage Research Center (EPRC) was established in 2013 to address the challenge of providing safe downstream passage of outmigrating adult American eel (*Anguilla rostrata*) on the St. Lawrence River. With funding by OPG, Hydro-Québec (HQ), the Fish Enhancement, Mitigation, and Research Fund (FEMRF) administered by the U.S. Fish and Wildlife Service (Service), and Duke Energy (Duke), the EPRC employs an adaptive, collaborative process to plan and execute a program of research on behavioral guidance of downstream migrating adult eels, as screening and physical guidance have been deemed infeasible. The EPRC's goal is to develop the technology to behaviorally guide the eels to a collection point for capture and transfer around the Moses-Saunders Power Dam and the Beauharnois Generating Station. The EPRC R&D builds upon the very substantial prior investments in eel passage research by EPRC funders and others. R&D is guided by a technical committee comprising representatives of EPRI, EPRC funding organizations, and resource management agencies with regulatory authority over the funders' hydropower activities on the St. Lawrence River. The technical committee collaboratively establishes the research priorities and plan, develops research scopes of work, and reviews R&D proposals and draft project reports.

The EPRC has fully funded six major R&D projects and has supported several other projects relevant to the goal and objectives of the EPRC. Each of these projects is summarized below.

Laboratory Studies of Eel Behavior in Response to Various Behavioral Cues examined eel movements when they were exposed to four different stimuli that existing information suggested could be effective in guiding eel movements: electromagnetic field (EMF) and low frequency sound signals in a small[1] flume with water velocity of 0.15 m/s (0.5 ft/s), and an electrical field

[1] The eels were free to move about in an area 2.4 m long by 1.8 m wide by 0.9 m deep (7.9 ft long by 5.9 ft wide by 3.0 ft deep) during the EMF experiments, and an area 4.9 m long by 1.8 m wide by 1.8 m deep (16 ft long by 5.9 ft wide by 5.9 ft deep) during the low frequency sound experiments.

and a flow velocity enhancement plume in a large[2] flume with a water velocity of 0.9 m/s (3.0 ft/s). The EMF experiments yielded no observable response, leading the technical committee to conclude EMF does not merit further R&D by the EPRC. Preliminary tests of eight vibration signals ranging from 5 to 1,000 Hz and pulse durations of 1 to 100 ms identified three signals for more extensive evaluation: (1) 100 ms, 10 Hz tone burst; (2) 100 ms, 50 Hz tone burst; and (3) 10 ms, 50 Hz half-sine impulse. The first two of these three signals produced statistically significant avoidance reactions by movement away from the sound source. These results motivated additional research (see below) on the potential use of sound to guide eels, and highlighted the limitations of working in a small flume. The tests of an electrical field and a flow velocity enhancement plume were conducted individually and in combination. None of the tests yielded consistent avoidance of the two stimuli, either individually or in combination. Despite the unfavorable results, the researchers concluded additional research with these two stimuli was warranted to identify stimuli characteristics that could be effective in guiding eels (e.g. voltage, voltage gradient, and pulse frequency, width, and shape in the case of electricity and nozzle size, and flow volume in the case of the flow velocity enhancement system). Furthermore, eel behaviors observed in the large flume suggested that the flume environment compromised researchers' ability to elicit guidance behavior there.

Recent Research on the Effect of Light on Outmigrating Eels and Recent Advancements in Lighting Technology reviewed the relevant biological literature and technology advances since 2007 when a comprehensive review of these and other topics was conducted for NYPA (Versar 2009). Recent literature indicated that light stimulus is likely to produce effective behavioral eel guidance response in the St. Lawrence River. Two types of light: broad-spectrum white and narrow-spectrum blue, are recommended for testing because of eel-specific sensitivities. Recent advancements in LED lighting make this the preferred technology due to: (1) lower cost and increased reliability and service life, (2) ability to incorporate UV anti-biofouling diodes to reduce cleaning requirements, (3) flexibility of operation, including continuous versus flashing mode, and programmability of stimulus characteristics such as intensity and flash duration and frequency.

CFD Model Development for Iroquois Control Dam and Beauharnois Approach Channel yielded a 3D computational fluid dynamics model for the reach extending approximately 2 km (1.24 miles) upstream and approximately 100 m (328 ft) downstream of Iroquois Water Control Dam (IWCD), and a 2D model for the 25 km (15.5 mile) long Beauharnois Power Canal. These models and their output have been and will continue to be used to understand flow field characteristics and their effects on eel movements, and inform design of guidance, collection, and other structures to be deployed in the water. Model output indicates eel guidance will be needed in water velocities in the range of approximately 0.6 to 1.5 m/s (2.0 to 4.9 ft/s).

Assessment of Three Sonar Technologies to Study Downstream Migrating American Eel Approach and Behavior at Iroquois Dam and Beauharnois Power Canal evaluated a Simrad 120 kHz split-beam echosounder, a Kongsberg Mesotech M3 500 kHz multi-beam imaging sonar, and a Sound Metrics ARIS 1100/1800 kHz multi-beam imaging sonar. Eels could be reliably tracked with all three sonars (especially the 500 kHz multi-beam imaging sonar), but only the ARIS 1100/1800 kHz imaging sonar provided the resolution needed to reliably identify eels. Performance was best when the device was operated in 48-beam mode at 1100 kHz with a 28°

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[2] The testing area of the large flume was approximately 24.3 m long by 5.2 m wide with a depth of 2.4 m (79.7 ft long by 17.1 ft wide with a depth of 7.9 ft).

spreader lens, allowing reliable detection and classification of eels out to a range of 16-20 m (52-66 ft). The study revealed a motion artifact in the ARIS data. The artifact mimicked the anguilliform swimming motion of eels in imagery of inanimate eel-shaped objects (such as sticks). This adds to the difficulty of identifying relatively rare eels among the much more abundant non-eel acoustic targets.

White Paper Investigation of the Potential Use of Sound to Guide Outmigrating American Eels Near Iroquois Dam and Beauharnois Power Canal updated the findings of the comprehensive review conducted for NYPA in 2007 (Versar 2009). The literature review revealed few new publications on sound detection and behavioral responses to sound in eels since 2008, and none of these provide insight into how sound might be used to affect the behavior of outmigrating silver eels. New understanding of sound detection by fishes (including eels) demonstrates that since eels are sensitive to particle motion, and particle motion is especially important to all fishes in enabling them to detect and respond in a directional way to a sound source, it is critical that any sounds presented to eels to guide their movement should generate high levels of particle motion. In shallow water, such as the St. Lawrence River, this may best be achieved through the generation of sound waves through the substrate and at the substrate-water interface. The white paper included research recommendations and concluded that sound alone is unlikely to be a suitable stimulus for affecting the behavior of outmigrating American eels in the St. Lawrence River. Sound (both sound pressure and particle motion) in combination with another stimulus (e.g. light) could be effective.

Behavioral Responses of American and European Silver Eels (Anguilla rostrate and A. anguilla) to Electric Fields Under Both Static and Flowing Water Conditions developed baseline information on eel responses to electricity. The study determined threshold field strengths yielding (1) no response, (2) startle, (3) loss of orientation, and (4) paralysis in silver eels for three different waveform types under static water conditions. The study then applied the threshold field strengths for startle and paralysis to test electricity as a deterrent under two flow regimes and two field strengths. The second set of experiments recorded the same behaviors as the first set and also recorded acceleration, switch in orientation, and rejection (i.e. movement away from the electrical field). While waveform did not affect the threshold for startle or loss of orientation, it did affect the mean field strength threshold for paralysis; The paralysis threshold was lower for the square wave, 10 Hz, 10% duty cycle waveform, compared to the square wave and pulsed 2 Hz, 20% duty cycle waveforms. Behavioral responses were tested at two field strengths under flowing conditions: (1) mean startle field strength under static conditions and (2) mean paralysis field strength under static conditions, and under two flow regimes: 0.5 m/s and 1.0 m/s (1.6 ft/s and 3.3 ft/s). No effect of field strength was observed under flowing water conditions; however, an effect of flow velocity was observed. In the low flow condition, 74% of eels exhibited a response whereas in the high flow condition, only 31.2% responded. Furthermore, the incidence of rejection significantly declined under the high flow condition (4.0%) compared to the low flow condition (32.5%). Upon first encountering the electrical field under high flow conditions, 87.7% of eels either exhibited no response (67.5%) or acceleration (20.2%). Orientation switching behavior was observed in 8.3% of the eels.

Otolith Aging of Eels Captured in the Kamouraska, Québec Eel Fishery was based on a 2014 sample composed exclusively of large maturing females with a mean body length of 870 mm (34.25 inches) that had been utilized in the laboratory study of responses to four behavioral cues (summarized above). Stocked eels comprised 1.8% of the sample. Age determination was successful for 626 of 674 available eels. Ages ranged from 7 to 36 years, with a mean of 12.7 years and a normal distribution slightly skewed toward younger ages. Mean growth rate was 72.2 mm/y (2.84 inches/y). While size at silvering did not change significantly from previous studies, mean age decreased by more than 7 years and growth rate increased by approximately 50%. This trend was confirmed by additional sampling in 2015 and 2016, although the number of eels sampled in the later years was lower.

Acoustic Tracking of Eels Near Iroquois Water Control Dam and in Beauharnois Power Canal over the last several years has provided valuable information regarding the diel and seasonal timing of outmigration, and it provides unique data on eel migration corridors and behavior in the reaches of interest for deployment of guidance and collection technologies. The tracking has revealed that eel tracks are biased toward the United States (right) side of the river upstream of IWCD, and the distribution of eel passage among the 32 dam gates at the IWCD appears to be significantly skewed toward the U.S. shore, with 66% of the eels appearing to pass through 44% of the gates. Preliminary results from acoustic tracking in Beauharnois Canal near Saint-Louis-de-Gonzague Bridge indicate approximately 80% of the eels used the center third of the canal, avoiding the Seaway channel located on the northern shore and the shallower waters of the southern shore.

Research conducted by the EPRC reinforces the conclusion that underwater light should be central to eel guidance systems in the St. Lawrence River. LED technology would reduce both capital and O&M costs, and improve reliability and operational flexibility and control compared to other technologies. While the Flow Velocity Enhancement System was not effective in guiding eels when tested in the laboratory flume, other studies with eels (Piper et al. 2013, Piper et al. 2015, Piper et al. 2017) suggest that flow field manipulation in the near field of a collection device could facilitate entry and capture. Similarly, electricity was not found to be effective for guiding or repelling eels in laboratory flume experiments with water velocities comparable to the St. Lawrence River, but could potentially be effective in reducing or eliminating rejection at the entry to a collection device.

Low frequency sound may prove useful as a secondary guidance or deterrence stimulus, but its use would be highly experimental in the near term. The experiments with sound conducted by the EPRC provide some insight into acoustic stimuli to test in the field.

Much useful information can be gleaned from additional collection and analysis of acoustic telemetry data. Existing acoustic telemetry information suggests that guidance likely will not be needed across the entire river cross-section. Additional data collection and analysis can inform decisions regarding the location and required spatial extent of guidance and collection structures.

Eel escapement from Lake Ontario can be expected to decline in the next several years. This raises the urgency of developing and deploying downstream passage technologies to improve the survival of outmigrating adult eels. Consequently, it will be important to rapidly transition from adaptive, exploratory R&D to adaptive mitigation and management utilizing early stage guidance, collection, and monitoring technologies to support a trap and transport program. This can be accomplished by rapid, iterative design, deployment, and testing of guidance and collection technologies. This approach could be initiated with design and deployment of a subscale, prototype guidance and collection structure or structures utilizing light and perhaps low frequency sound. This adaptive mitigation approach would enhance mitigation effectiveness over the near term, and develop more effective technology over the mid- to long term. Siting and design of a subscale experimental guidance and collection structure can begin in the near-term, utilizing the R&D results produced by the EPRC.

SOMMAIRE

Pratiquement toutes les anguilles en migration du lac Ontario et ses tributaires vers la mer des Sargasses doivent aujourd'hui passe par les turbines des barrages hydro-électriques de Moses-Saunders et de Beauharnois où le taux de mortalité cumulatif associé est estimé à 39,5 %. Une analyse décisionnelle identifiant les options d'atténuation disponibles et prenant en compte leur coût et leur probabilité de succès a identifié le transfert (capture et transport) des anguilles argentées comme l'option privilégiée. Le programme de transfert d'Ontario Power Generation (OPG) a permis entre 2008 et 2015 le transport annuel de 1 600 anguilles en moyenne à l'aval des deux centrales. Une augmentation significative de l'effort de transfert nécessitera une méthode de capture des anguilles adultes durant l'avalaison.

Le centre de recherche sur le passage de l'anguille (CRPA) a été fondé en 2013 pour s'attaquer au défi d'assurer un passage sécuritaire à l'anguille d'Amérique (Anguilla rostrata) adulte en avalaison dans le fleuve Saint-Laurent. Grâce aux fonds d'OPG, d'Hydro-Québec (HQ), de l'U.S. Fish and Wildlife Service qui administre le Fish Enhancement, Mitigation, and Research Fund (FEMRF) et Duke Energy (Duke), le CRPA, de manière adaptative et collaborative, planifie et applique un programme de recherche pour guider par des moyens comportementaux, les anguilles adultes en avalaison; l'utilisation de grillages et autres barrières physiques ayant été jugée irréalisable. Le CRPA a pour objectif de développer une technologie de guidage par modification du comportement des anguilles, vers un site de collecte pour les capturer et les transférer au-delà des centrales hydro-électriques de Moses-Saunders et de Beauharnois. La Recherche et Développment (R et D) au CRPA s'appuie sur d'importants investissements et travaux de recherche précédents sur le passage de l'anguille de la part des membres fondateurs et autres chercheurs. La R et D est menée par un comité technique constitué de représentants de l'EPRI (Electrical Power Research Institute), des fondateurs du CRPA et d'organismes de gestion de la ressource possédant un pouvoir réglementaire sur les activités hydro-électriques des fondateurs sur le fleuve Saint-Laurent. Le comité technique établit de façon collaborative les priorités et la planification de recherche, développe la portée des travaux et révise les soumissions de R et D ainsi que les ébauches de rapports.

Le CRPA a intégralement financé six importants projets de R et D et a financé plusieurs autres projets correspondants à ses objectifs. Chacun de ces projets est résumé ci-dessous.

Une étude en laboratoire (voir *Laboratory Studies of Eel Behavior in Response to Various Behavioral Cues)* a examiné les mouvements d'anguilles exposées à quatre stimuli que la littérature existante suggère être efficace pour en modifier les déplacements : les champs électromagnétiques (CEM) et les signaux acoustiques de basses fréquences, testés dans un petit canal[3] où l'eau circulait à 0,15 m s^{-1} (0,5 pi s^{-1}), tandis qu'un champ électrique et un panache de vitesses d'écoulement augmentées l'ont été dans un grand canal[4] où la vitesse d'écoulement de l'eau était de 0,9 m s^{-1} (3,0 pi s^{-1}).

Les essais avec les champs électromagnétiques n'ont produit aucune réponse observable, ce qui a conduit le comité à conclure que le CRPA ne devrait pas entamer de nouveaux travaux de recherche sur les CEM. Des tests préliminaires de huit signaux vibratoires allant de 5 à 1 000 Hz et des durées d'impulsions de 1 à 100 ms ont permis d'identifier trois signaux méritant une évaluation plus approfondie : (1) signal 10 Hz de 100 ms ; (2) signal de 50 Hz de 100 ms et (3) signal semi-sinusoïdal de 50 Hz de 10 ms. Les deux premiers de ces trois signaux ont produit des réactions d'évitement (éloignement de la source sonore) statistiquement significatives.

Ces résultats ont motivé une étude additionnelle (voir ci-dessous) sur l'utilisation possible du son pour guider les anguilles. Les résultats ont aussi mis en lumière les limites de la recherche dans un petit canal. Les essais impliquant le champ électrique et un panache de vitesses d'écoulement augmentées ont été effectués seuls ou en combinaison des deux. Aucun de ces tests n'a démontré un évitement systématique de ces stimuli, pris individuellement ou en combinaison. Malgré les résultats défavorables, les chercheurs ont conclu que des recherches additionnelles avec ces deux stimuli étaient justifiées afin d'identifier les caractéristiques des stimuli qui pourraient être efficaces pour guider les anguilles (p.ex. tension, gradient de tension et fréquence des impulsions électriques, largeur et forme du champ pour l'électricité et taille de la buse et force du débit volumétrique pour le système de panache de vitesses d'écoulement augmentées). De plus, l'observation du comportement des anguilles dans le grand canal suggère que l'environnement du canal lui-même compromettait la création de guidage.

Des travaux de recherches bibliographiques sur les effets de la lumière sur les anguilles en avalaison et sur les avancées récentes en technologie de l'éclairage (*Recent Research on the Effect of Light on Outmigrating Eels and Recent Advancements in Lighting Technology)* ont revu la littérature biologique pertinente ainsi que les progrès technologiques survenus depuis 2007, année où la New York Power Authority (NYPA) a effectué un examen exhaustif de ces sujets en plus d'autres (Versar, 2009). La consultation de publications récentes indique que les stimuli lumineux sont susceptibles de guider efficacement des anguilles dans le fleuve Saint-Laurent. En raison de la sensibilité spécifique de l'anguille, il est recommandé de tester deux types de lumières : blanche à large spectre et bleue à spectre étroit. Les récents progrès de l'éclairage à la DEL en font la technologie de choix grâce à 1) un coût inférieur, et une augmentation de la fiabilité et de la longévité, 2) la capacité d'incorporer des diodes UV contre le bio-encrassement réduisant les besoins de nettoyage, 3) la souplesse de fonctionnement y compris la présence de modes en continu et en clignotement de même que la capacité de configurer certaines caractéristiques du stimulus telles l'intensité, la durée et la fréquence de l'éclair par exemple.

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[3] Les anguilles étaient libres de se déplacer dans un espace de 2,4 m de longueur, 1,8 m de largeur et 0,9 m de profondeur durant les études de CEM et un espace de 4,9 m de longueur, 1,8 m de largeur et 1,8 m de profondeur durant l'expérimentation avec les sons à basse fréquence.
[4] La zone de tests du grand canal mesurait environ 24,3 m de longueur, 5,2 m de largeur et 2,4 m de profondeur.

Des travaux de modélisation hydrodynamique (*CFD Model Development for Iroquois Control Dam and Beauharnois Approach Channel) ont généré* un modèle de dynamique des fluides numérique 3D de la zone s'étendant sur environ 2 m (1,24 mile) à l'amont et 100 m (328 pi) à l'aval du barrage Iroquois pour le contrôle des eaux (BICE) et un modèle 2D pour les 25 km (15,5 miles) du canal de Beauharnois. Les résultats de ces modèles ont été et seront utilisés pour comprendre les caractéristiques de la circulation de l'eau et son effet sur les déplacements des anguilles de même que pour la conception des structures de guidage, de collecte ou autres structures qui devront être déployées dans l'eau. Les modèles démontrent que les anguilles devront être guidées dans des courants variant entre 0,6 à 1,5 m s^{-1} (2,0 à 4,9 pi s^{-1}).

L'étude suivante a comparé l'efficacité de trois types de sonars à détecter et suivre les déplacements des anguilles (*Assessment of Three Sonar Technologies to Study Downstream Migrating American Eel Approach and Behavior at Iroquois Dam and Beauharnois Power Canal)*. Il s'agissait d'un échosondeur à faisceaux divisés de 120 kHz de Simrad, un sonar M3 à imagerie multifaisceaux de 500 Khz de Kongsberg Mesotech et un sonar Aris à imagerie multifaisceaux de 1 100/1 800 kHz de Sound Metrics. Les déplacements des anguilles ont pu être suivis de façon fiable avec les trois sonars (particulièrement avec le M3), mais seul le Aris avait la résolution nécessaire pour identifier systématiquement les anguilles. Les meilleures performances ont été obtenues lorsque l'appareil fonctionnait en mode 48 faisceaux à 1 100 kHz et une lentille grand-angle additionnelle de 28°. Ceci a permis une identification et classification fiable à une portée entre 16 et 20 m (52-66 pi). L'étude a révélé la présence d'un artefact de mouvement dans les données du ARIS. L'artefact imite la nage en S de l'anguille chez des objets inanimés dont la forme se rapproche de celle de l'anguille (un bâton par exemple). Ceci ajoute à la difficulté d'identifier des anguilles relativement rares parmi les cibles acoustiques beaucoup plus fréquentes qui ne sont pas des anguilles.

Le livre blanc sur l'utilisation du son pour guider les anguilles argentées (*White Paper Investigation of the Potential Use of Sound to Guide Outmigrating American Eels Near Iroquois Dam and Beauharnois Power Canal)* a mis à jour les constats de la revue exhaustive menée par NYPA en 2007 (Versar, 2009). La revue de littérature n'a identifié que quelques nouvelles publications traitant de la détection des sons et les réponses comportementales aux sons chez l'anguille depuis 2008. Aucune de celles-ci n'offre un aperçu de la manière dont le son pourrait être utilisé pour influencer le comportement des anguilles argentées en avalaison. La nouvelle conception de la détection du son chez le poisson (y compris les anguilles) veut que le mouvement des particules soit particulièrement important pour tous les poissons en leur permettant de détecter la direction de la source sonore et d'y répondre en conséquence. Puisque l'anguille est sensible aux mouvements des particules, il est essentiel que celui-ci génère de forts mouvements de particules, quel que soit le son auquel on exposera l'anguille afin d'en modifier le déplacement.

Dans les eaux peu profondes comme celles du fleuve Saint-Laurent, la meilleure façon d'obtenir ce résultat est de générer des ondes sonores dans le substrat ainsi qu'à l'interface substrat-eau. Le livre blanc comprend des recommandations pour la recherche et conclut qu'il est peu probable que le son seul soit un stimulus capable de modifier le comportement de l'anguille d'Amérique en avalaison dans le Saint-Laurent. Le son (pression sonore et mouvements de particules) en combinaison avec un autre stimulus (p. ex. la lumière) pourrait être efficace.

L'étude sur l'utilisation de l'électricité pour guider les anguilles en avalaison (*Investigation of the Use of Electricity to Guide Outmigrating Eels*) a développé les données de référence quant à la réponse de l'anguille à l'électricité. L'étude a déterminé, en eau stagnante, les valeurs seuils d'intensité du champ électrique qui provoque 1) aucune réponse, 2) un sursaut, 3) la perte d'orientation et 4) la paralysie chez l'anguille argentée soumise à trois types de formes d'onde. À partir de seuils d'intensité provoquant le sursaut et la paralysie, l'étude a alors cherché à déterminer l'effet dissuasif de l'électricité sous deux régimes d'écoulement et deux intensités de champs électriques. La seconde série d'expériences a suivi les mêmes comportements que durant la première, mais a de plus décrit l'accélération, le changement d'orientation et le rejet (c.-à-d. l'éloignement du champ électrique). Tandis que la forme de l'onde n'a pas eu d'effet sur le seuil pour le sursaut ou la perte d'orientation, elle a eu un effet sur la valeur moyenne du seuil d'intensité du champ provoquant la paralysie; celui-ci était plus bas pour l'onde carrée de10 Hz de fréquence avec un facteur d'utilisation de 10 % que le seuil obtenu pour l'onde carrée pulsée de 2 Hz de fréquence avec un facteur d'utilisation de 20 %. Les réponses comportementales ont été observées en eau courante, sous deux intensités de champ électrique : 1) intensité moyenne du champ causant un sursaut en eau stagnante et 2) l'intensité moyenne du champ en eau stagnante et en eau courante à deux débits différents : 0,5 m s^{-1} et 1,0 m s^{-1} (1,6 pi s^{-1} et 3,3 pi s^{-1}). L'intensité du champ n'avait aucun effet durant les essais en eau courante, on a toutefois observé un effet de la vélocité de l'eau. En condition de faible vélocité, 74 % des anguilles ont montré une réponse tandis qu'en condition de forte vélocité, seulement 31,2 % montrèrent une réponse. De plus, la fréquence des rejets a diminué significativement en condition de forte vélocité (4,0 %) comparativement ce qui a été observé à faible vélocité (32,5 %). En présence de forte vélocité au moment du contact avec le champ électrique 87,7 % des anguilles n'ont montré aucune réponse (67,5 %) ou une accélération (20,2 %). Un changement d'orientation a été observé chez 8,3 % des anguilles.

La détermination de l'âge des anguilles capturées dans la pêcherie de Kamouraska, Québec grâce à leurs otolithes (*Otolith Aging of Eels Captured in the Kamouraska, Québec Eel Fishery*) a été basé sur un échantillonnage de 2014 et composé exclusivement de grosses femelles matures ou sur le point de le devenir d'une longueur moyenne de 870 mm (34,25 po). Ces spécimens provenaient de l'étude en laboratoire sur les réponses des anguilles à quatre stimuli (résumée plus haut). L'échantillon comprenait aussi 1,8 % d'anguilles ensemencées. Six cent vingt-six des six cent soixante-quatorze anguilles disponibles ont été âgées avec succès. L'âge variait entre 7 et 36 ans, avec une moyenne de 12,7 ans et formait une distribution normale légèrement décalée vers les âges les plus jeunes. Le taux de croissance moyen était de 72,2 mm an^{-1} (2,84 po an^{-1}). Même si l'âge d'argenture n'était pas significativement différent de celui rapporté dans des études antérieures, l'âge moyen a diminué de plus de 7 ans et le taux de croissance a augmenté d'environ 50 %. Cette tendance a été confirmée lors d'échantillonnages additionnels en 2015 et 2016. Le nombre d'anguilles échantillonnées était toutefois plus faible dans ces dernières années.

Le suivi acoustique des anguilles à proximité du barrage Iroquois et dans le canal de Beauharnois (*Acoustic Tracking of Eels Near Iroquois Water Control Dam and in Beauharnois Power Canal*) ces dernières années a fourni de précieux renseignements sur le moment de la dévalaison, tant au plan quotidien que saisonnier et fournit une source unique de données sur les couloirs de migrations et le comportement des anguilles dans les zones d'intérêts pour le déploiement de technologies de guidage et de collecte. Le suivi a aussi révélé que les déplacements des anguilles à l'amont du BICE étaient plutôt orientés vers la rive états-unienne (rive droite) du fleuve. La distribution des passages des anguilles par les 32 vannes du BICE paraît être significativement biaisée vers la rive américaine et 66 % des anguilles semblent utiliser 44 % des vannes. Les résultats préliminaires du suivi acoustique dans le canal de Beauharnois au niveau du pont de Saint-Louis-de-Gonzague indiquent qu'approximativement 80 % des anguilles utilisent le tiers central du canal, évitant ainsi le chenal de la Voie maritime situé en rive nord et les eaux peu profondes de la rive sud.

La recherche menée par le CRPA renforce la conclusion que de la lumière sous l'eau devrait constituer la pierre angulaire d'un système de guidage de l'anguille dans le fleuve Saint-Laurent. Par rapport aux autres technologies, l'utilisation de DEL réduirait les coûts d'achat, de fonctionnement et d'entretien et fournirait une meilleure fiabilité, contrôle et flexibilité opérationnelle. Bien que le système de panache de vitesses d'écoulement augmentées n'ait pas été efficace pour guider les anguilles lors des essais en canal de laboratoire, d'autres études avec des anguilles (Piper et col. 2013, Piper et col. 2015, Piper et col. 2017) suggèrent que la manipulation du champ de vitesses à proximité d'un dispositif de collecte pourrait faciliter l'entrée de l'anguille et sa capture. Pareillement, l'électricité n'a pas montré de capacité de guidage ou de répulsion des anguilles dans des essais en canaux de laboratoires à des vitesses d'écoulement comparables à celles du fleuve Saint-Laurent; elle pourrait toutefois être efficace à réduire ou éliminer le rejet à l'entrée d'un dispositif de collecte.

Les sons de basses fréquences peuvent s'avérer utiles comme système de guidage secondaire ou comme stimulus dissuasif, mais leur utilisation serait, à court terme, hautement expérimentale. Les expériences menées par le CRPA sur le son fournissent un aperçu des stimuli acoustiques à expérimenter sur le terrain.

Des renseignements pertinents peuvent être tirés de la collecte et de l'analyse supplémentaire de données de télémétries acoustiques. L'information existante provenant de la télémétrie acoustique suggère que le guidage ne sera probablement pas nécessaire sur toute la largeur du Fleuve. La collecte et l'analyse de données supplémentaires peuvent aider à la prise de décision quant à la localisation et à la portée spatiale nécessaire aux structures de guidage et de collecte.

Selon toute attente, l'échappement des anguilles du lac Ontario devrait décroître durant les prochaines années. Ceci met en lumière l'urgence de développer et de déployer des technologies d'aide à la dévalaison afin d'améliorer la survie de l'anguille adulte en avalaison. Par conséquent, il sera important de rapidement passer d'une R et D adaptative et exploratoire à une gestion adaptative d'atténuation en utilisant les technologies de guidage, de collecte et de suivi identifiées durant les étapes préliminaires afin de soutenir un programme de capture et de transfert. Ceci peut s'accomplir par le déploiement et la réalisation à court terme d'essais itératifs des technologies de collecte et de guidage. Cette approche pourrait commencer avec la planification et le déploiement d'un prototype à échelle réduite d'une structure ou structures de guidage et de collecte utilisant la lumière et peut-être des sons de basses fréquences. Cette approche adaptative améliorerait à court terme l'efficacité de la mesure d'atténuation et développerait des technologies plus efficaces à moyen ou long terme. La conceptualisation et la localisation d'une structure de guidage et de collecte expérimentale à échelle réduite peuvent démarrer rapidement grâce aux résultats de R et D produits par le CRPA.

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1 INTRODUCTION AND BACKGROUND

Downstream passage of eels at hydroelectric projects is a concern in several regions of the world, including the Atlantic Coasts of North America, Europe, Scandinavia, and the British Isles; as well as Australia, New Zealand, and New Guinea. The concern is perhaps greatest for the closely-related species of the North Atlantic – the American eel (*Anguilla rostrata*) and the European eel (*Anguilla anguilla*). The European eel is listed as critically endangered by the European Union and Norway, and the American eel faces possible listing under the Canadian Species at Risk Act. Currently the American eel is listed as endangered by the Ontario Provincial Government. In late 2014, the International Union for the Conservation of Nature (IUCN, “Red List”) classified the American eel as endangered. The U.S. Fish and Wildlife Service (Service) announced on October 7, 2015, in a decision known as a 12-month finding, that listing of American eel as threatened under the U.S. Endangered Species Act was not warranted; however, the Agency did recommend continued efforts to improve river passage for migrating eels. Thus, hydropower projects distributed over the portions of North America, Europe, Scandinavia, and the British Isles draining to the Atlantic Ocean face mandates to provide safe downstream passage for eels.

Upstream passage for juvenile eels at hydroelectric projects is relatively straightforward, with established design and operational parameters for eel ladders (Haro 2013). Downstream passage of adults at hydroelectric projects, however, has proven to be problematic, especially at larger facilities with deep and wide intake structures (Greig *et al.* 2006). Behavioral characteristics of eels during downstream migration make turbine passage protection and guidance to alternative passage routes challenging (Baran and Basilico 2012). Cumulative turbine mortality for eels migrating from Lake Ontario to the Atlantic Ocean has been estimated to be 39.5% (Normandeau and Skalski 2000, ESSA 2005). As part of the relicensing of the St. Lawrence FDR Project (Federal Energy Regulatory Commission [FERC] Project No. 2000), the New York Power Authority (NYPA) conducted extensive field studies investigating means of guiding and collecting migrating adult eels for transport around the Robert Moses Power Dam (see Versar 2009). Following relicensing, NYPA commissioned a review of technologies for guiding, capturing, holding, transporting, and monitoring outmigrating eels (Versar 2009) that constituted a comprehensive assessment of the state of science and technology related to downstream passage of anguillid eels. Coincident with and following NYPA’s relicensing-related research, Hydro-Québec (HQ) and Ontario Power Generation (OPG) also conducted substantial research projects related to mitigation of turbine mortality at their generating facilities on the St. Lawrence River.

Currently, other than trap and transport around generating stations, no effective method exists to safely pass eels downstream around large, operating hydroelectric facilities. Measures mandated at some smaller facilities are also problematic for plant operators due to the protracted, episodic nature of outmigration in the St. Lawrence River watershed and the lack of effective protection and passage technologies. As regulators and fisheries managers effectively press for upstream eel passage, there is the expectation that downstream passage measures will be implemented in the future when the eels passed upstream mature and migrate downstream to the sea.

Purpose and Formation of the Eel Passage Research Center

The OPG Action Plan for the St. Lawrence River contains a mandate from the Ontario Ministry of Natural Resources and Forestry to address the challenge of downstream eel passage through targeted research to reduce turbine mortality at Ontario Power Generation's (OPG) R.H. Saunders Generating Station. Likewise, Hydro-Québec (HQ) seeks to address this challenge at its Beauharnois Generating Station through targeted research as a matter of corporate principle. The settlement agreement reached as part of the relicensing of NYPA's St. Lawrence-FDR project established the $24 million Fish Enhancement, Research, and Mitigation Fund (FEMRF), $8 million of which was dedicated to eels. The OPG Action Plan, HQ's corporate principle, and the FEMRF purpose to fund eel passage research on the St. Lawrence River provided the impetus to organize a collaborative research center to coordinate these discrete but aligned interests.

The bi-national, EPRI-led Eel Passage Research Center (EPRC) was established in 2013 to meet the need for coordinated, collaboratively-funded research to address the challenge of safe downstream passage of American eel at hydropower projects on the St. Lawrence River (EPRI 2013). This initiative is a direct outgrowth of long-standing collaboration among members of the Canadian Eel Working Group[5]. Initial funding commitments to the EPRC extend through 2018 with Tier 1 funding from Hydro-Québec, Ontario Power Generation, and the U.S. Fish & Wildlife Service-administered FEMRF. Duke Energy participates in the EPRC as a Tier 2 funder.

Overview of Prior Activities

OPG, HQ, and NYPA have funded a substantial research effort directed toward American eel passage on the St. Lawrence River over an extended period of time, both individually and collectively through the Canadian Eel Working Group. The EPRC effort builds upon the extensive body of research conducted by OPG, HQ, and NYPA, and draws upon the history of collaborative engagement among members of the Canadian Eel Working Group.

FERC Relicensing

The original 50-year license for NYPA's St. Lawrence-FDR project (FERC Project 2000) was issued in 1953 by the Federal Power Commission, the predecessor to the FERC. During the eight-year period from 1996 when NYPA officially began its relicensing effort to October 2003 when FERC issued a new 50-year license, NYPA conducted numerous studies addressing both upstream and downstream eel passage on the St. Lawrence River. A settlement agreement reached between NYPA and the United States Fish and Wildlife Service (Service) established the $24-million FEMRF which has the express purpose of benefiting fisheries resources in the

[5] Members of the Canadian Eel Working Group included: Fisheries and Oceans Canada (DFO), Ontario Ministry of Natural Resources (OMNR), Minsitètre des Ressources Naturelles et de Faune du Québec (MRNF), HQ, OPG, USFWS, Great Lakes Fishery Commission, NYSDEC, and NYPA.

Lake Ontario – St. Lawrence River Basin and to continue research on the American eel and other species that may be affected by the St. Lawrence-FDR Project (USFWS 2009).

The most significant studies undertaken by NYPA during relicensing include:

- Surface and midwater trawling for American eels in the St. Lawrence River
- Differentiating downstream migrating American eels from resident eels in the St. Lawrence River
- Development of acoustic telemetry technologies suitable for tracking American eel movements in the vicinity of a large hydroelectric project
- American eel light avoidance study.

These studies are described in greater detail below (page 2-12)

Related to the FERC order approving settlement agreements and issuing a new license, NYPA commissioned a review of technologies for guiding, capturing, holding, transporting, and monitoring outmigrating eels (Versar 2009). This report, in conjunction with the decision analysis (described immediately below), was the point of departure for the Eel Passage Research Center.

Table 1-1
Short-term and long-term priorities for mitigating downstream passage mortality in the USLR-LO system

Short Term	Long Term
• Stocking of American eels into the USLR-LO system. Feasibility: High. Uncertainty: Medium.	• Trap and transport of American eel downstream of the hydroelectric generating stations. Feasibility: High. Uncertainty: Medium
• Reduction of commercial fishing for American eel in the St. Lawrence River. Feasibility: High. Uncertainty: Low.	• Research to develop means to “eliminate the problem of downstream passage mortality at the source (e.g. through effective means for diversion to bypass systems)”.
• Basic research into the life history and population dynamics of American eel in the USLR-LO system	
• Research into diversion of migrating silver eels, initially for diversion to traps or other collection systems for transport downstream of the hydroelectric stations	

HQ Activities to Mitigate Eel Turbine Mortality

Hydro-Québec’s activities to mitigate turbine mortality have included:

- Initiation of and research and monitoring related to a stocking program
- Research of methods to guide downstream migrating eels away from turbine intakes.
- Buyout of commercial fishermen operating in the lower St. Lawrence River

These activities are described in greater detail beginning on page 2-20.

OPG Activities to Mitigate Eel Turbine Mortality

OPG activities conducted under the two Action Plans to mitigate turbine mortality included:

- Initiation of and research and monitoring related to a "bootlace" eel stocking program
- Initiation of and research and monitoring related to a yellow eel commercial fishery trap and transport program (first Action Plan)
- Initiation of and research and monitoring related to a silver eel trap and transport program (first Action Plan)
- Incorporation of a trap and transport program in the second Action Plan, due to success observed during the first Action Plan.

These activities are described in greater detail beginning on page 2-21.

These programs and related monitoring activities continue to the present time, with the exception of eel stocking which was only conducted from 2006 to 2010.

2
DOWNSTREAM PASSAGE ON THE ST. LAWRENCE RIVER

Characteristics of the St. Lawrence River and the utilization of the River as a migration corridor present several stark challenges for providing safe downstream passage of adult American eels at the hydropower projects.

The St. Lawrence River System

The St. Lawrence River stretches 870 miles (1,400 km) from the outlet of Lake Ontario to the Gulf of St. Lawrence (Figure 2-1; NYPA 1996). Excluding the estuary, the river (freshwater) extends 310 miles (500 km) to the eastern end of Ile d'Orleans just downstream of Quebec City. Average discharge is 262,000 cfs (7,410 m^3/s) at the outflow of Lake Ontario and 427,399 cfs (12,101 m^3/s) at Quebec City (Benke and Cushing 2005). As a consequence of the large drainage area of the Great Lakes, outflows from Lake Ontario are remarkably stable. U.S. Geological Survey daily flow data range from 139,000 cfs to 378,000 cfs (3,936 m^3/s to 10,704 m^3/s) during the period 1900 through 1998 at the International St. Lawrence Power Project (FERC 2003a). Average monthly flow for the St. Lawrence River is shown in Table 2-1.

Figure 2-1
The St. Lawrence River. Map courtesy of New York Power Authority.

Table 2-1
Average monthly flow for the St. Lawrence River (1900-1998) (FERC 2003a)

Month	Average Flow*	
	cfs	m^3/s
January	221,000	6,258
February	233,000	6,598
March	241,700	6,844
April	248,800	7,045
May	259,100	7,337
June	263,800	7,470
July	264,400	7,487
August	263,600	7,464
September	259,700	7,354
October	253,100	7,167
November	246,700	6,986
December	237,500	6,725

*Data for 1900-1959 from U.S. Army Corps of Engineers simulation of IJC Plan of Regulation 1958-D; data for 1960-1998 from St. Lawrence International Power Project records.

The Upper St. Lawrence River

The Upper St. Lawrence River extends from the outlet of Lake Ontario to the mouth of the Ottawa River, upstream of Montreal. This reach serves as a migration corridor for catadromous eels as far inland as Lake Ontario and its tributaries, and as growth habitat along its length. Historically, hundreds of thousands of juvenile, early yellow stage eels (mean ages 5-8 years) were observed passing upriver annually at the eel ladder that became operational in 1974 at the Robert H. Saunders Generating Station in Cornwall, Ontario (Liew 1982, Zhu et al. 2013). Since the peak ladder estimate in 1983[6], the number of recruits has declined sharply. Abundance across the entire population has declined significantly as well; however, declines in other areas are not nearly as severe as those observed in the St. Lawrence River watershed (MacGregor *et al.* 2013, ASMFC 2017). Outmigrating adults from the watershed are uniformly large females (Verreault *et al.* 2003). Given the historic abundance of these large females, the upper St. Lawrence River is presumed to have made a significant contribution to the spawning stock biomass; however, this has never been documented.

Virtually all flow in the Upper St. Lawrence River passes through the hydropower turbines at Moses-Saunders Power Dam, and on average 80% or more flows through the Beauharnois

[6] Methods for estimating upstream passage at the dam have evolved during the period of record (see Casselman et al. 1997); furthermore, significant fallback and re-ascent inflated the total passage counts until 2009 when an exit tube was installed to displace the eel ladder outlet 300m upstream from the dam.

Generating Station, exposing outmigrating eels to turbine mortality risk. Nearly all of the water not passed at Beauharnois Generating Station passes through the turbines at Les Cèdres. Turbine mortality at Moses-Saunders has been estimated to be 26.5% and 18.0% at Beauharnois, resulting in an estimated 39.5% cumulative mortality among eels passing both power dams (Normandeau Associates and Skalski 2000, ESSA 2005); however, mortality rates may vary over time with varying size of outmigrants.

The Hydropower Facilities

Moses-Saunders Power Dam

The Robert Moses-Robert H. Saunders Power Dam (Moses-Saunders), the heart of the St. Lawrence International Power Project, was cooperatively constructed by the New York Power Authority and Ontario Hydro (now OPG) and began operations in 1958. The dam has 32 turbine-generators, equally divided between NYPA and OPG by the U.S.-Canada border. The Power Dam has a total generating capacity of 1,957 MW. The dam is 195.5 ft (60m) tall and 3212 ft (979m) long (Parham 2009). Hydraulic head is 81 ft (25m) (NYPA 1996).

The Project operates essentially as a run-of-river project. Approximately 99% of the flow at Moses-Saunders is outflow from Lake Ontario (NYPA 1996). Lake Ontario water levels are managed at the Project, with Moses-Saunders outflows determined by the International Joint Commission's (IJC) International Lake Ontario – St. Lawrence River Board. The hydraulic capacity of the power dam is well matched to this stable river discharge, and as a result the project is capable of achieving a remarkably high capacity factor (e.g. 81% for NYPA's Moses Power Dam) while rarely spilling water (FERC 2003a). Limited peaking and ponding[7] occurs within limits established by the International Joint Commission. Typically, peaking occurs during daylight hours when there is more demand for power. Peaking is allowed throughout the year, with within-day variation of ±30,000 cfs (850 m^3/s) allowed when mean weekly flow is 250,000 cfs (7,079 m^3/s) or less, decreasing linearly to zero for weekly average flow of 280,000 cfs (7,929 m^3/s) or greater (NYPA 1996). During the period 1962-1990, full or partial peaking occurred on 51% of the days during the navigation season and 54% of the days during the non-navigation season (Carson and Metcalfe 1994). Ponding is only allowed during the winter, non-navigation season. Maximum daily flow deviation is 20,000 cfs (566 m^3/s) below the daily mean flow during the two weekend days when water is stored and 8,000 cfs (227 m^3/s) above the daily mean flow on the five days when the water stored water is released. These ponding allowances decrease linearly when mean weekly flow is greater than 272,000 cfs to 280,000 cfs (7,702 to 7,929 m^3/s), above which no ponding is allowed. Ice conditions may further constrain ponding operations (NYPA 1996). Ponding occurred on only 35% of the days when it was allowed during the period 1962 to 1990 (Carson and Metcalfe 1994). The maximum flow discharged at Moses-Saunders is approximately 378,000 cfs (10,704 m^3/s) (NYPA 1996).

Long Sault Dam, located 3.5 miles (6 km) upstream of Moses-Saunders serves as the spillway for the Project (Figure 2-2). Spill there is rare, having occurred on just 5% of the days and

[7] ***Peaking*** refers to within-day variation in generation (and therefore discharge) to match diel variation in electricity demand. ***Ponding*** refers to within-week variation in daily generation, such as storing water on the weekend and releasing it during the week when daily electricity demand is greater.

accounting for less than 0.3% of the total river flow from the early 1960s, when all 32 turbines first became operational, to 1995 (NYPA 1996).

The Wiley-Dondero Canal and Eisenhower and Snell locks (part of the St. Lawrence Seaway; Figure 2-2) allow ships to bypass Moses-Saunders. An insignificant amount of water bypasses the project by this route, averaging 180 to 500 cfs (5 to 14 m^3/s) (NYPA 1996).

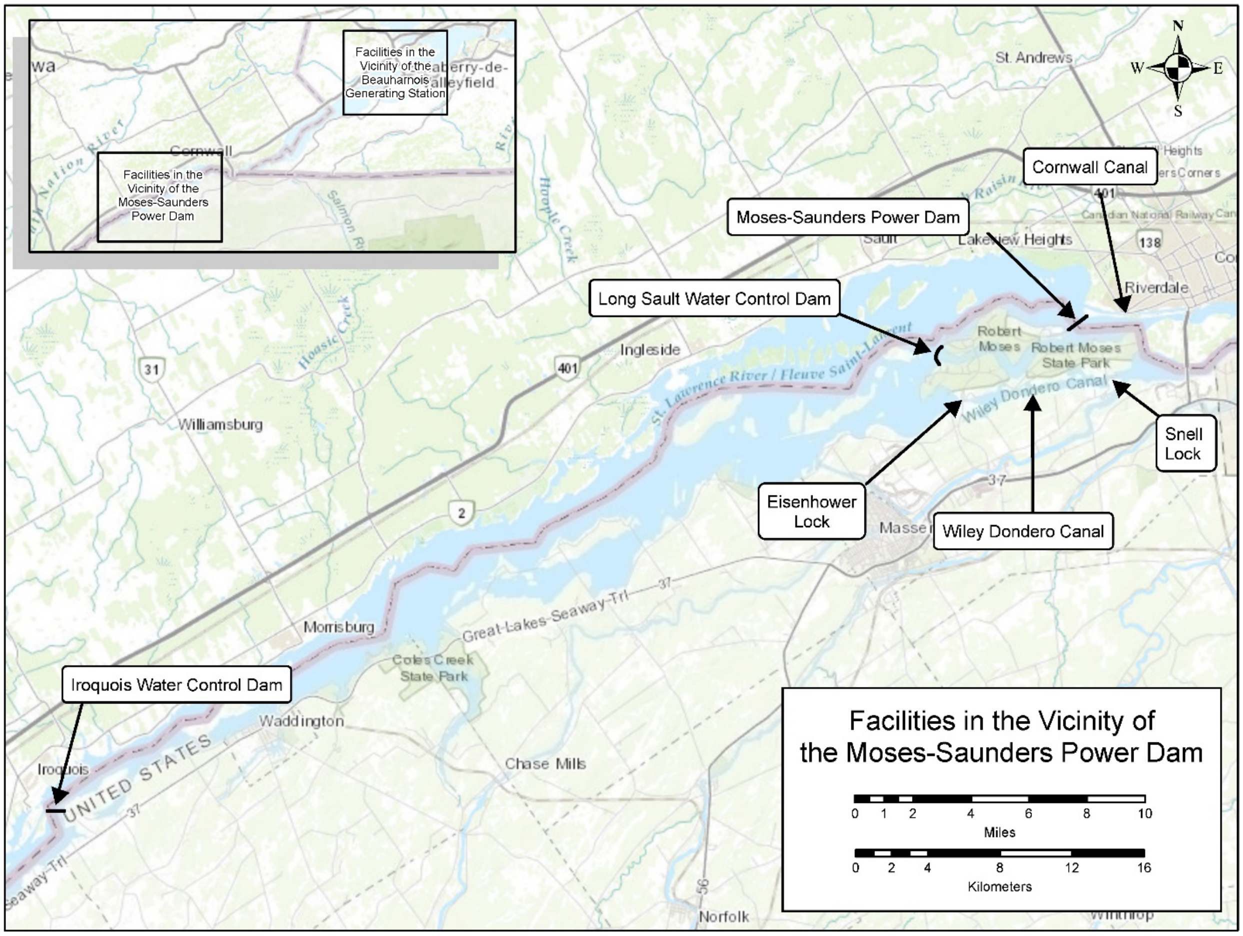

Figure 2-2
Major facilities associated with the Moses-Saunders Power Dam

Beauharnois Generating Station

Hydro-Québec's Beauharnois Generating Station (BGS) is located 51 miles (82 km) downstream of Moses-Saunders, 25 miles (40 km) west of Montreal (NYPA 1996). Water is conveyed from Lake St. Francis to the generating station by the 15.1-mile long (25 km) Beauharnois Canal, bypassing the original river channel. The canal is approximately 1 km wide with an average depth of 33 ft. (10 m) (Figure 2-3).

The Beauharnois power station and the Beauharnois canal were built in three phases. The first phase began in 1929 and ended in 1948. Twelve Francis units and two auxiliary units were installed without any spillway. From 1948 to 1953 an additional twelve new Francis units and the spillway were constructed. From 1956 to 1961 ten propeller type units were added. Also, during the third phase, Hydro-Québec widened the canal to accommodate the additional flow and the new Seaway locks. Beauharnois Lock, part of the St. Lawrence Seaway, provides ship and, to some extent, fish passage around BGS.

Beauharnois Generating Station's 36 units have a combined installed capacity of 1,900 MW. Hydraulic head is 80 ft (24.5 m) (Hydro-Québec 2018). Maximum operational flow at the project is 290,000 cfs (8,200 m^3/s). It was at one point in its history one of the largest hydropower generating stations in the world. BGS operates as a run-of-river facility with the incoming flows largely controlled by Moses-Saunders since tributary inflows to the St. Lawrence River and Lake St. Francis are relatively minor.

The water from Lake St. Francis is diverted to the Beauharnois Canal by two series of gates – Coteau 1 and Coteau 3 – controlled by the Beauharnois Generating Station.

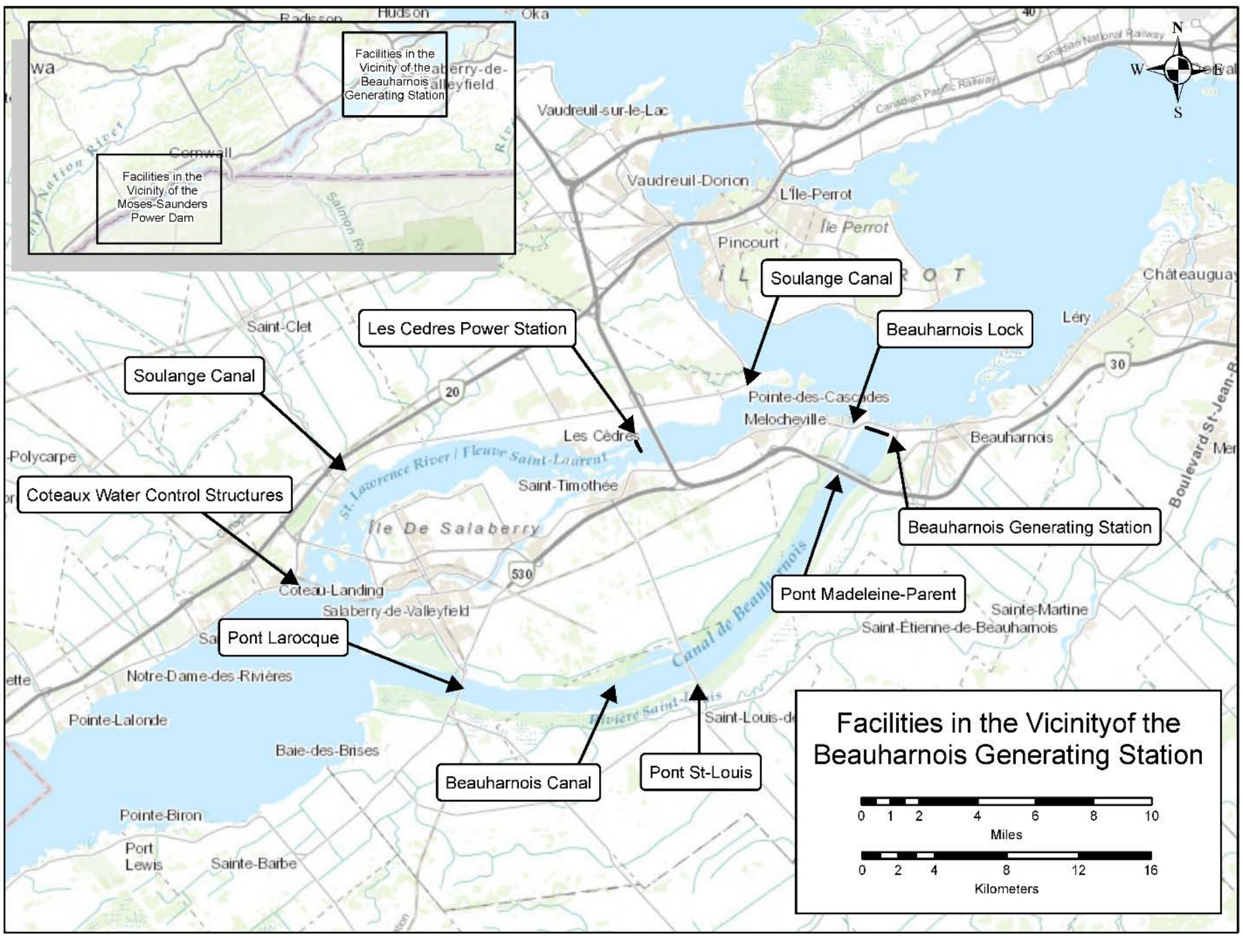

Figure 2-3
Facilities near the Beauharnois Generating Station

Les Cèdres

Les Cèdres Generating Station, owned and operated by Hydro-Québec, is located 30 miles west of Montreal on the original St. Lawrence River channel (Figure 2-3). The facility was built between 1912 and 1924. Originally 18 Francis unites were installed. In 1924, it was the largest generating station in Quebec and the first one, with its 162 MW, that was constructed to export electricity outside of Quebec to ALCOA (Aluminum Company of America) in Massena, NY.

Now, BGS has 12 units running with a combined capacity of 113 MW with a hydraulic head of 30 ft (9.14 m) (Hydro-Québec 2018). This reach of the river has a series of rapids – Coteau, Les Cèdres, and Cascades – with a combined drop of 82 ft (25 m) over 15 miles (25 km). The generating station extends only partway across the river channel; a dike running parallel to shore directs water through the station while leaving a channel open for navigation (Hydro-Québec 2015). The Les Cèdres generating station and its spillway can accommodate the water not passing though the Beauharnois Canal.

Upper St. Lawrence River Eels

Eels in the Upper St. Lawrence river are near the northern-most extent of the species' range; they are also among the eels farthest from the Sargasso Sea spawning ground (Figure 2-4). Early stage yellow eels are typically 325 – 390 mm in length and 4 to 5 years old when they reach Beauharnois and 350 to 450 mm in length and 5 to 8 years old when they ascend the two eel ladders at Moses-Saunders (Marcogliese, and Casselman 2009, Zhu et al. 2013). Naturally recruited outmigrating eels are exclusively large (typically >800 mm in length) females (Verreault *et al.* 2003). Mean age of naturally recruited outmigrants has declined, from 16.8 (±2.9) years in 1970 (Verreault et al. 2017) to 12.5 (±2.6) years in 2017 (Verreault and Dussureault 2018). Given the size and fecundity of these fish, the Upper St. Lawrence River is presumed to have been an important, if not crucial, contributor to the spawning stock of this panmictic species (Caron et al. 2003, Verreault and Dumont 2003); however, since the species is panmictic and the spawning site has not been located, the parentage of recruits has not been geographically distinguishable and the contribution of Upper St. Lawrence River eels to recruitment remains undocumented.

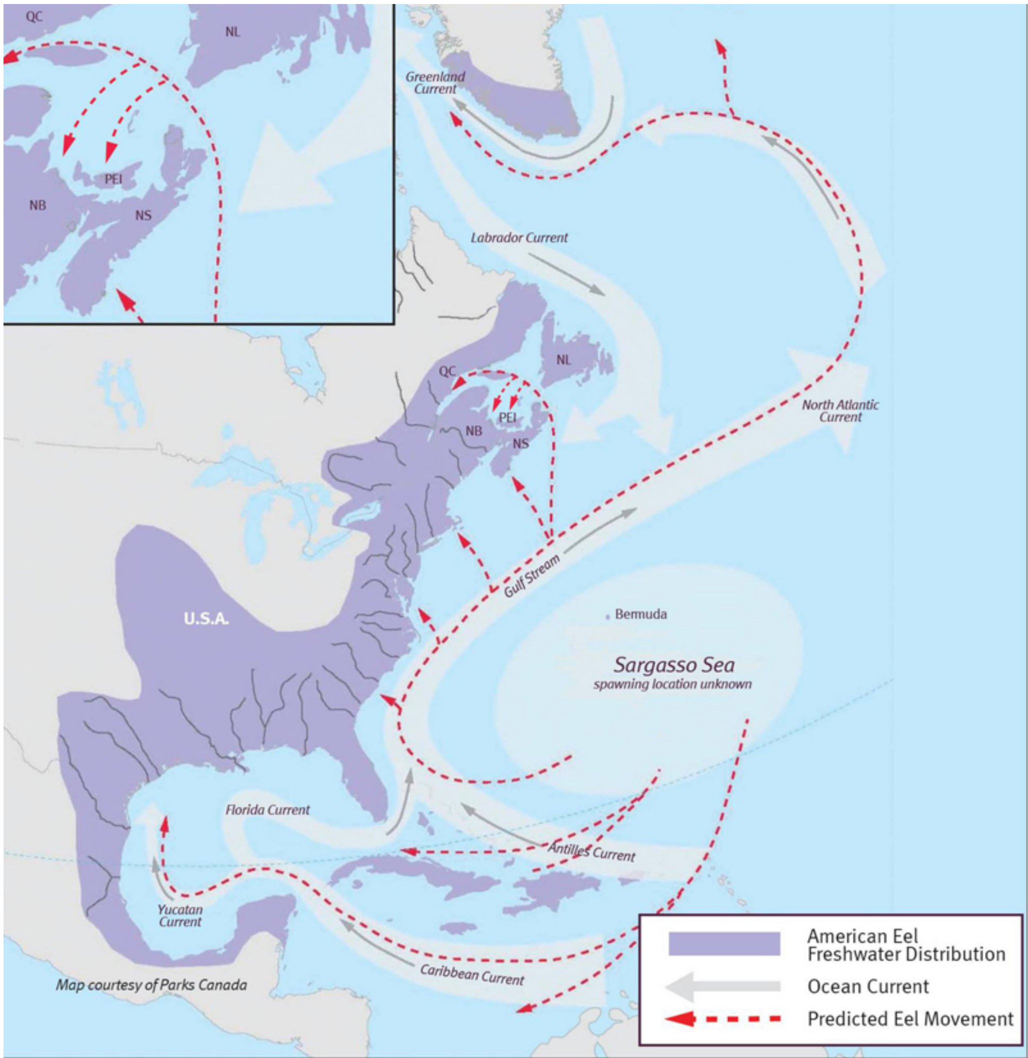

Figure 2-4
Predicted movement of juvenile American eels from the Sargasso Sea spawning area, and their freshwater distribution.

Upstream Passage Facilities and Trends

Prior to construction of the St. Lawrence Seaway and completion of the Beauharnois and Moses-Saunders hydroelectric projects in the late 1950s to early 1960s, eels were able to pass up the St. Lawrence River to Lake Ontario. Upstream eel migration was impeded but not blocked by the powerhouse and associated hydraulic works at Les Cèdres which was first constructed in 1912, commissioned in 1914, and expanded until 1924 (Hydro-Québec 2015). Additional hydraulic infrastructure associated with hydropower and Seaway development in the early 1960s largely blocked upstream passage above Beauharnois, except for via the Seaway Beauharnois Lock. There were no provisions for eel passage at Moses-Saunders Power Dam until the eel ladder at Saunders was completed in 1974. The first eel ladder at Beauharnois was completed on the west side of the facility in 2002. A second ladder was completed on the east side of Beauharnois in 2004 (Milieu 2018).

Ladder counts quantify upstream passage at Moses-Saunders, beginning in 1974 (Figure 2-5) and at Beauharnois beginning in 2002. An eel trap placed in Unit 37 (that was never outfitted) of Beauharnois provides additional data between 1994 and 2001 (Figure 2-6). NYPA completed the second Moses-Saunders eel ladder in 2006. Initially, the majority of eels ascending the ladders at Moses-Saunders ascended the NYPA ladder; however, in more recent years the distribution has generally been relatively even (Figure 2-5).

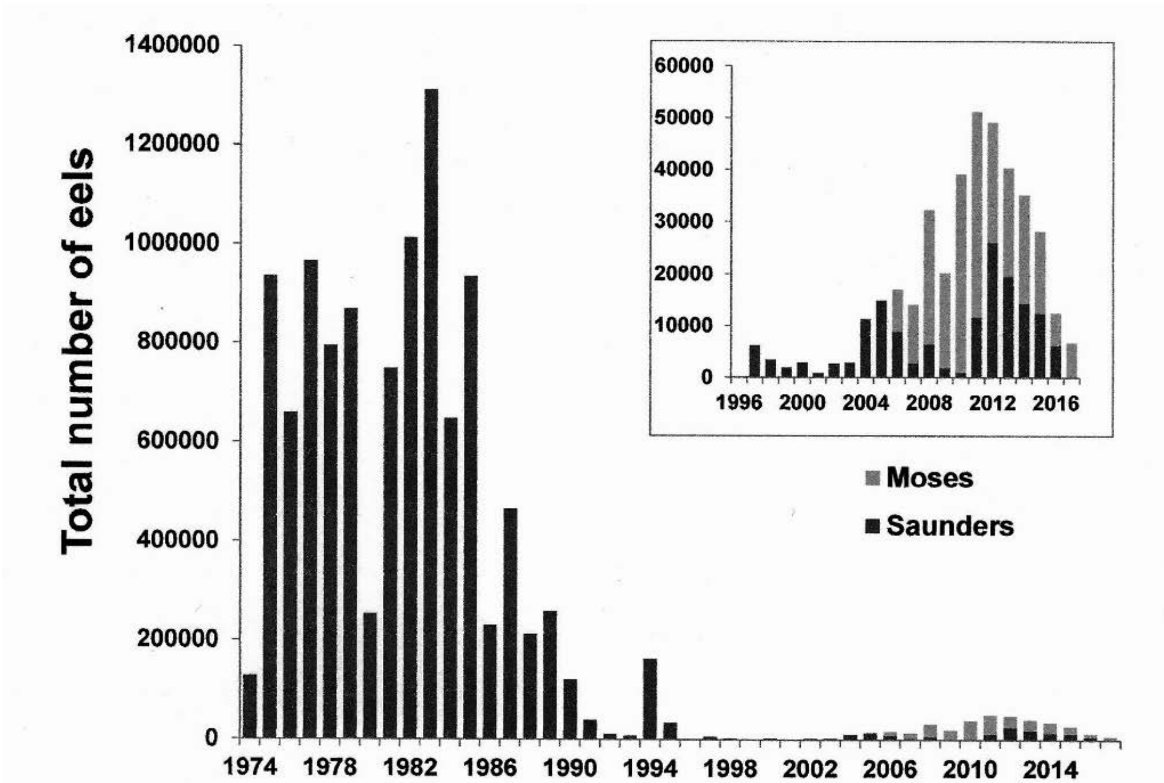

Figure 2-5
Total number of eels ascending the eel ladders at the Moses-Saunders Dam, Cornwall, Ontario from 1974 to 2017. During 1996, the ladder operated; however, no counts were made. Source: Ontario Ministry of Natural Resources and Forestry (OMNRF 2018).

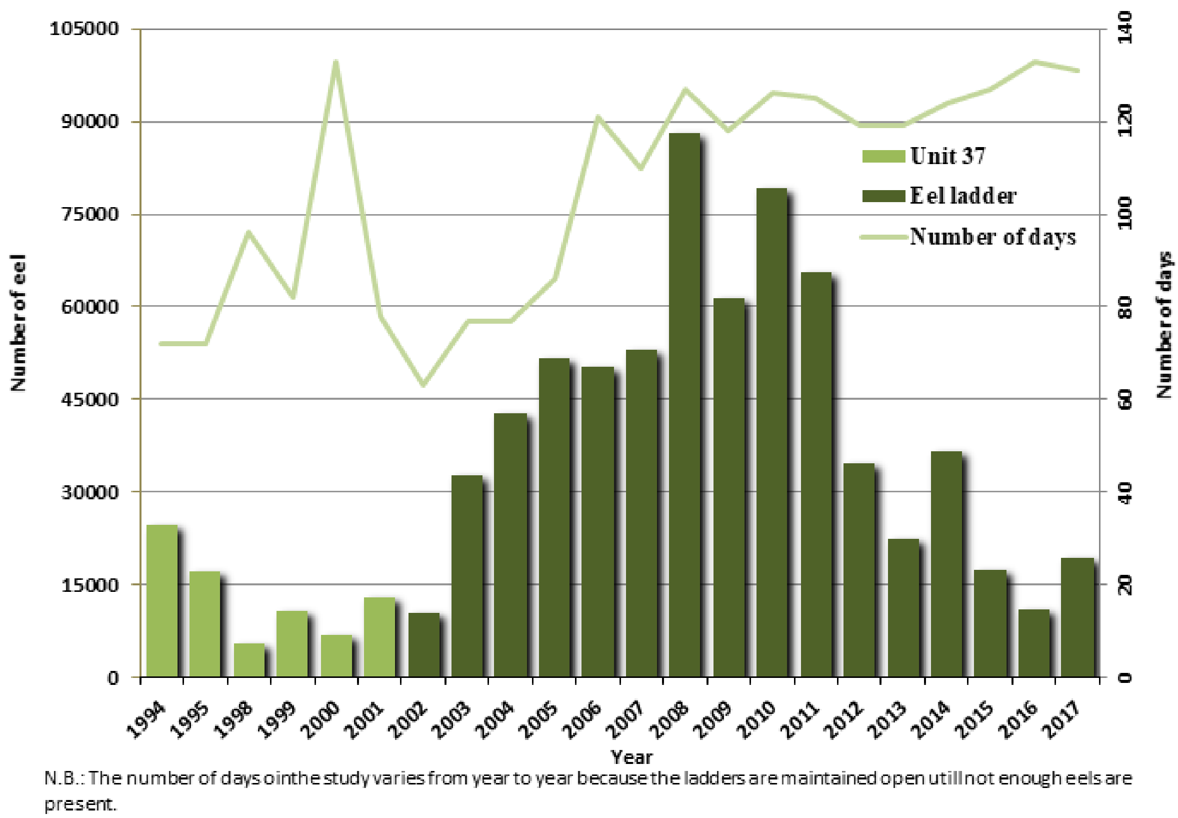

Figure 2-6
Total number of eels collected in Unit 37 (1994-2001) and ascending the eel ladder(s) (2002-2017) at Beauharnois. Source: Guillemette, S., A. Guindon, and D. Desrochers (2017).

It is estimated that more than one million eels ascended the Saunders ladder annually at the peak in 1982 and 1983. Since that time, the number of eels ascending the ladders has sharply declined. The numbers at Beauharnois parallel the numbers at Moses-Saunders. Marcogliese and Casselman (2009) assessed long-term trends in size and abundance of juvenile eels ascending the St. Lawrence River at Moses-Saunders. They concluded that the number of eels ascending the Saunders ladder had declined by more than three orders of magnitude from 1982 to 2001 and that recruitment of small, young eels had essentially ceased. The numbers of up migrating small eels at both facilities trended upward for several years beginning in the early 2000s, reaching 88,000 in 2008; however, the numbers have been declining since 2012.

Downstream Passage Facilities and Trends

Currently, there are no passage facilities to protect downstream migrating American eels on the St. Lawrence River. Turbine passage is essentially the only route available to outmigrants because virtually all (>99%) of flow at Moses-Saunders passes through the turbines. Likewise, below Lake St. Francis nearly all the flow passes through the turbines at Les Cèdres and Beauharnois, with most of that flow passing via the Beauharnois Canal and Generating Station. Of 26 adult eels observed with acoustic telemetry passing downstream of the Beauharnois-Les Cèdres complex, all 26 passed via the generating station (Verdon and Desrochers 2005). A 2012 telemetry study (Hatin et al. 2014), however, showed that up to 25% of tagged eels detected upstream of the locks entrance and the BGS used the locks and avoided the GS to continue their downstream migration unharmed.

Data on the potential and actual number of outmigrants is limited; however, available data are consistent with the long-term decline that would be expected based on the number of recruiting eels ascending the ladder at Saunders and, more recently, Beauharnois and Moses ladders. The yellow eel commercial fishery in Lake Ontario and the St. Lawrence River above Moses-Saunders was relatively stable from 1984 to 1993 but declined precipitously thereafter (Mathers and Stewart 2009). Those data series ended when the commercial fishery in Ontario permanently closed in 2004 and the recreational fishery closed in 2005. Two fishery-independent surveys targeting older yellow eel also exist. A trawling survey in the Bay of Quinte and an electrofishing survey in eastern Lake Ontario both show very substantial declines in abundance from the 1980s to the 2000s (Mathers and Pratt 2011; Figure 2-7). Both indices are strongly correlated with upstream eel passage at Moses-Saunders lagged 4 years (Bay of Quinte trawling survey; r=0.78) or 5 years (eastern Lake Ontario electrofishing survey; r=0.89) (Casselman *et al.* 1997).

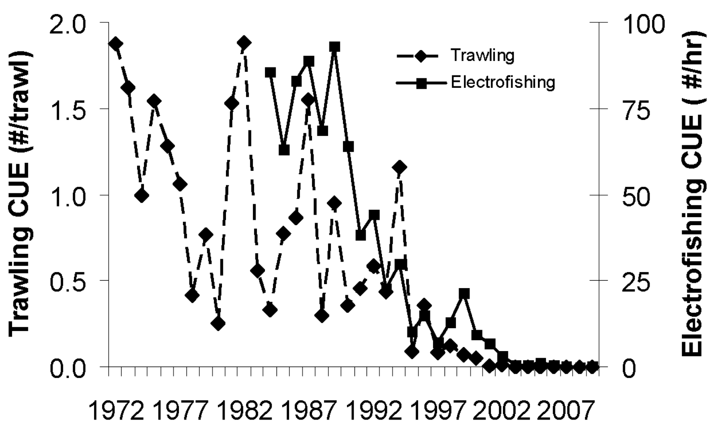

Figure 2-7
Resident American eel abundance indices for trawling in the Bay of Quinte and electrofishing in eastern Lake Ontario. Source: Mathers and Pratt (2011).

Standardized counts of outmigrating eel carcasses below Moses-Saunders provide an index of the abundance of outmigrants (NYPA 2010). The counts decreased by more than 90% over the period 2000 to 2008 (Figure 2-8).

The American eel commercial fishery in the St. Lawrence River estuary declined from 300 metric tons in 1990 to 72 metric tons in 2000 and less than 50 metric tons in 2012 (Verreault *et al.* 2003, 2017).

Based on relationships among ladder counts at Moses-Saunders, numbers of eels stocked, the abundance indices of older yellow eels, and tailwater eel carcass surveys, the decline in the number of outmigrants in recent decades is expected to accelerate within the next several years.

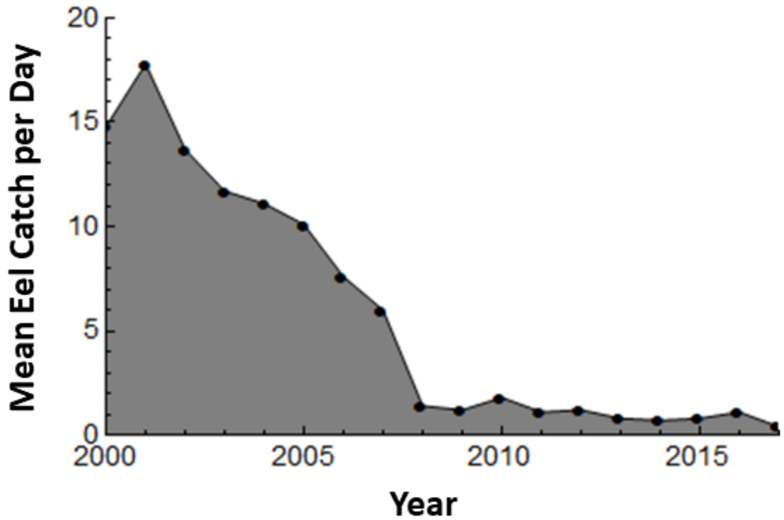

Figure 2-8
Mean daily standardized collection of outmigrating American eel carcasses downstream of the Moses-Saunders Power Dam. Data source: Riveredge (2018).

Based on relationships among ladder counts at Moses-Saunders, numbers of eels stocked, the abundance indices of older yellow eels, and tailwater eel carcass surveys, the decline in the number of outmigrants in recent decades is expected to accelerate within the next several years.

NYPA Relicensing Activities

NYPA formally commenced relicensing of its St. Lawrence-FDR Project (FERC Project No. 2000) by initiating the Cooperative Consultation Process (CCP) and submitting the Initial Consultation Package (NYPA 1996) to FERC on April 25, 1996. Relicensing concluded with FERC's order approving settlement agreements and issuing a new license on October 23, 2003. Over the intervening seven-and-a-half-year period, NYPA engaged with numerous stakeholders through the CCP identifying and addressing numerous issues in its license application to FERC. Passage of American eel was the most significant fisheries-related issue identified by the CCP. NYPA conducted several significant studies during relicensing to address eel-related questions critically important to the CCP, especially provision of downstream eel passage. The settlement agreement and new license resulting from the CCP required construction of an eel ladder at the Robert Moses Power Dam to address the issue of upstream eel passage, along with establishment of the FEMRF to continue downstream eel passage research.

Major eel-related studies conducted during relicensing and related to downstream passage included:

- Differentiating downstream migrating eels from resident eels in the St. Lawrence River (McGrath *et al.* 2003c)
- Methods for capturing outmigrating eels in Lake St. Lawrence (McGrath *et al.* 2003d)
- Acoustic tracking of large eels in Lake St. Lawrence (McGrath *et al.* 2003a, McGrath 2005)

- An in-river evaluation of the effectiveness of light for guiding outmigrating eels (McGrath *et al.* 2003b)

The study to identify methods for differentiating resident from migrating American eels in the St. Lawrence River successfully demonstrated that external morphological characteristics can be used to for this purpose (McGrath *et al.* 2003c). The study correctly classified 87% of mature migrants and 83% of immature residents. Discriminant functions for the two developmental categories included length, weight, girth, and ocular index variables. The classification was conservative in the sense that the method tended to categorize a portion of maturing eels as immature. These results have been useful for identifying specimens for subsequent studies of outmigration behavior.

Capture methods for outmigrating eels in Lake St. Lawrence were investigated to support behavioral studies (McGrath *et al.* 2003d). Trawling, especially paired vessel, mid-water trawling, was successful in collecting downstream migrating adult eels in good condition; however, only 34 eels were captured in 254 tows. The most productive trawling site yielded 0.353 eels/10-minute tow. These low capture rates occurred when eel densities were much higher (approximately 20 times) than what currently exists in the river.

NYPA developed 200 kHz acoustic telemetry technology in collaboration with Vemco, Inc. for tracking American eel movements near the Moses-Saunders Power Dam (McGrath *et al.* 2003a). The technology was used to successfully track eels near the dam. Three-dimensional tracking data revealed a random pattern of approach to and passage through the dam, with a diversity of passage behaviors ranging from immediate approach and passage to brief or extensive exploration across the face of the dam, to rejection and re-approach. Approach and passage occurred across the entire width and depth of the dam. Travel at the acoustic array was primarily (52%) within the top 5 m, 75% in the top 10 m, and 25% 10 m or deeper (McGrath 2005).

NYPA conducted two studies investigating the feasibility of using light to guide downstream migrating adult eels. The first study was conducted in an underwater net pen with captive eels in an ice sluice of the Moses-Saunders Power Dam. The study was unsuccessful in moving eels away from a light source. The observed results (lack of response) may have been caused by the experimental conditions in the ice sluice, including loud, broadband underwater sound. Despite the lack of response during the ice sluice experiment, NYPA undertook a larger-scale light study in the St. Lawrence River upstream of Iroquois Water Control Dam (IWCD) with wild, naturally migrating eels (McGrath *et al.* 2003b; Figure 2-9). The study deployed an array of halogen lights from a floating platform anchored in the river (Figure 2-10) to create a wall of light 90 m long from the water surface to the bottom and extending approximately 52m from the platform. Migrating eels avoided the 90m-long wall of light set 30º to flow of approximately 0.6 m/s. Netting results indicated 77% of the eels avoided the light field, and visual observations indicated 85% were able to modify their trajectory thereby avoiding the light field. Unanswered by the study was the feasibility and effectiveness of scaling up a light array to cover a sufficiently large cross-section of the river. Some nighttime guidance occurred with the lights off, perhaps due to sound generated by water flowing around submerged parts of the platform and mooring lines.

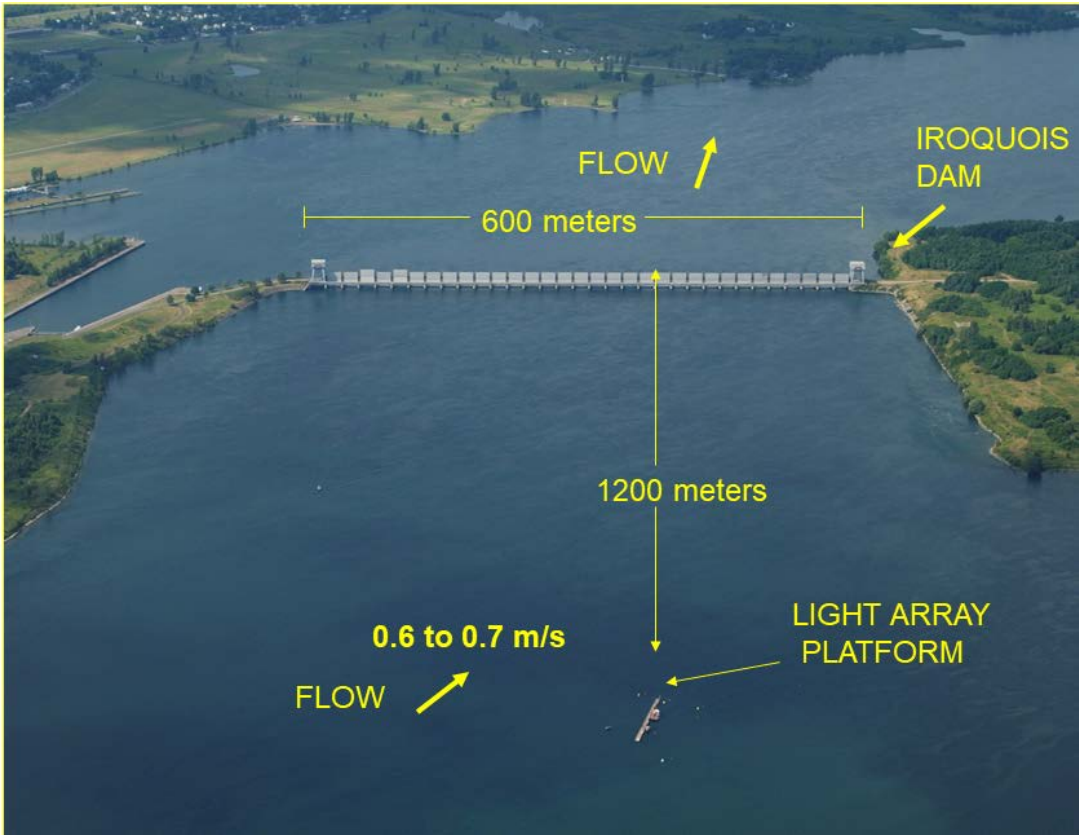

Figure 2-9
Location of the light array platform in the St. Lawrence River for the NYPA light study.

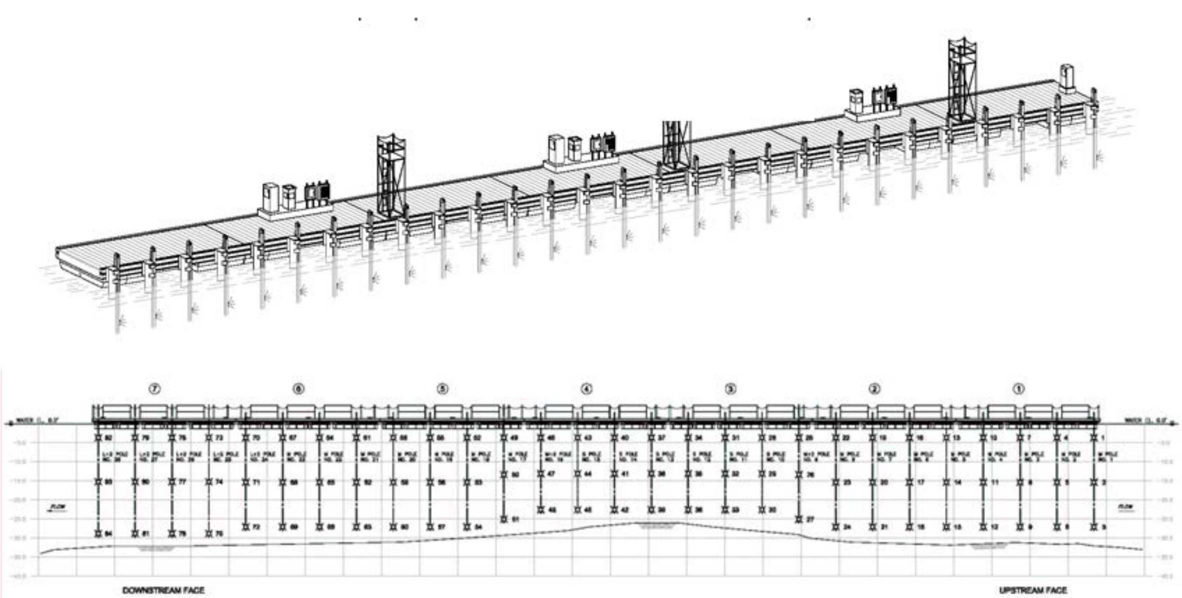

Figure 2-10
Drawings of the light array platform for the NYPA light study (McGrath et al. 2003).

Decision Analysis

A "decision analysis" comprising three workshops and associated reports was undertaken starting in 2005 to identify and evaluate alternatives for reducing mortality of American eels caused by the Moses-Saunders and Beauharnois hydroelectric generating stations (Greig *et al.* 2006). The decision analysis was undertaken on behalf of the interagency Canadian Eel Working Group. The process commenced with a scoping workshop held in Cornwall, Ontario, February 15-18, 2005 (Parnell *et al.* 2005a). The scoping workshop was followed by a workshop to identify alternatives that was held in Ottawa, Ontario, July 13-14, 2005 (Parnell *et al.* 2005b). A third workshop was held in Ottawa, September 22-23, 2005 to evaluate alternatives and select a set of alternatives for implementation (Parnell and Greig 2005).

The scoping workshop placed the focus of the decision analysis on (Parnell *et al.* 2005a):

- Exploration of options to increase eel survival related to upstream and downstream migration and other habitat effects in the St. Lawrence River and Lake Ontario,
- Developing clear understanding of how this contributes to overall eel conservation goals relative to other mortality sources, including the major tributaries (i.e. Ottawa River and Richelieu River), and
- Aiding decision-makers in determining the best mitigation measure(s) in the face of uncertainty about eel ecology and the likely effectiveness of potential mitigation measures.

Important issues identified during the scoping workshop included:

- Precipitous decline of eel abundance in the St. Lawrence River and Lake Ontario is coincident with declines across the Atlantic Coast of North America.
- Continuation of the current population trajectories would likely lead to listing of American eel as threatened or endangered under the Species at Risk Act (Canada) and the Endangered Species Act (United States).
- Moses-Saunders and Beauharnois hydroelectric projects exert a cumulative 40% mortality rate on eels migrating downstream from Lake Ontario.
- The large scale of the river and hydropower facilities, combined with the complex and uncertain nature of eel ecology, result in technical uncertainties and potentially high costs for reducing eel mortality at the hydropower facilities.
- Cost-effective mitigation measures will require considerable advancement in understanding of eel behavior and considerable pilot testing of proposed approaches.
- Experiments in smaller systems (e.g. flumes and smaller rivers and hydropower facilities) will not necessarily be transferable to the St. Lawrence River.
- Decreasing numbers of eels in Lake Ontario make it difficult, costly, and potentially damaging to capture and utilize these animals as test organisms for mitigation prototypes.

Workshop participants identified increased escapement and reduced passage mortality rates as primary means objectives. A list of preliminary alternatives and options generated by the scoping workshop is reproduced as Appendix A.

The second workshop explicitly specified a set of alternatives for reducing anthropogenic eel mortality and increasing recruitment, and established a set of performance measures to be applied during the evaluation of alternatives in the third workshop (Parnell *et al.* 2005b). Alternatives, specified in greater number and detail in the workshop report, were:

- Replacement of the turbines at R.H. Saunders and Beauharnois Generating Stations with Alden fish friendly design runners
- Physical diversion of eels to station bypasses
- Behavioral diversion of eels to station bypasses
- Operational shut-down with spill to pass eels
- Trap eels above R.H. Saunders and Beauharnois stations and transport below Beauharnois
- Increase access to upstream rearing habitat
- Implement fishery controls to reduce fishing mortality
- Stock eels into available rearing habitat
- Habitat enhancement

Objectives for the third and final workshop were to:

- Review the alternatives carried forward from the second workshop and further developed by the technical workgroups
- Review the performance measures and assigned values for each alternative
- Iteratively evaluate alternatives
- Specify actions for the first year.

Short-term and long-term priorities identified by participants in the third workshop are listed in Table 1-1, above. As discussion and evaluation of alternatives progressed during the third workshop, it became clear that additional work would be needed before a set of recommendations for implementation could be finalized. At a follow-up meeting in October in Quebec City, the workshop participants reached consensus that a multiparty implementation group should be formed "to design and implement a program that will combine short-term mitigation actions with research initiatives aimed at increasing the understanding of how to directly mitigate downstream passage mortality in the long-term" (Parnell and Greig 2005). Proposed participants in the program were federal, provincial, and state fishery management agencies (i.e. DFO, OMNRF, MFFP, NYSDEC, USFWS), hydropower companies (i.e., HQ, OPG, NYPA), and academics and consultants with relevant experience. This group was known as the Canadian Eel Working Group. A memorandum of understanding among the Canadian parties was to have established a governance structure and documented commitments to a mitigation program.

Other Management and Research Activities Related to Downstream Passage

Numerous additional studies related to downstream passage of American eel on the St. Lawrence River have been conducted since NYPA's St. Lawrence-FDR project was relicensed and the Canadian Eel Work Group (CEWG) conducted its decision analysis. Many of these studies address issues and questions identified by the NYPA relicensing and CEWG decision analysis efforts.

Fish Enhancement, Mitigation, and Research Fund

The FERC order approving settlement agreements and issuing a new license for NYPA's St. Lawrence-FDR project (FERC 2003b) contained a provision for establishment of a Fish Enhancement, Mitigation, and Research Fund (FEMRF; USFWS 2009). The license required NYPA to deposit $24 million into an escrow account for the National Fish and Wildlife Foundation (NFWF) to establish the Fund, with disbursements to be made by the U.S. Fish and Wildlife Service to benefit fisheries resources in the Lake Ontario – St. Lawrence River basin and to continue research on the American eel and other species that may be affected by the Project. The FEMRF agreement established a Fisheries Advisory Committee (FAC) comprising representatives of:

- U.S. Fish and Wildlife Service
- U.S. Bureau of Indian Affairs
- U.S. Geological Survey
- N.Y. State Department of Environmental Conservation
- Ontario Ministry of Natural Resources
- New York Power Authority
- St. Regis Mohawk tribe

A subcommittee of the FAC, the Eel Study Group (ESG), is charged with providing advice to the FAC related to studies needed to address downstream passage of American eel at hydropower projects on the St. Lawrence River. The USFWS consults with the FAC and the ESG to identify needed fish enhancement, mitigation, and research projects and prior to funding external project proposals.

2009 Versar Study

The FEMRF ESG and FAC identified five topics for white paper investigation, related to protection of downstream migrating American eels on the St. Lawrence River:

- Techniques and feasibility to collect, hold, and transport downstream migrating eels with particular emphasis on the area of IWCD
- The potential effects of telemetry on outmigration behavior in eels and use of telemetry or other technologies near IWCD to determine the effectiveness of various guidance or concentration devices

- The use of light in guidance (or avoidance) of eels as a component of a system/facility to collect eels at IWCD
- The use of infrasound as a guidance/avoidance stimulus, and
- The use of other attractants/repellants as a guidance/avoidance stimulus

NYPA funded a desktop project encompassing all of these topics that produced a white paper known as the Versar report (Versar 2009). The document constitutes a comprehensive review of the state of knowledge related to technologies for guiding, capturing, holding, transporting, and monitoring outmigrating eels through 2008, and assesses the potential applicability of the compiled information for use in developing a trap and transport program for outmigrating eels at IWCD.

Selected conclusions from Versar (2009) are listed below:

<u>Guidance Technologies</u>

- Physical Barriers
    - Eels respond to physical barriers differently than most other species of fish, tending to make contact with barriers and often attempting to pass through them rather than avoiding them
    - The literature provided no examples of attempts to use physical barriers to direct the movements of outmigrating eels in a system as large as the St. Lawrence River. Most applications were at intakes of steam electric generating facilities or relatively small hydroelectric facilities
    - A physical barrier across the width and depth of the river would be subject to extensive debris loading, reducing its effectiveness and requiring extensive maintenance
    - Conceptual estimates of the cost to construct and operate a 1,000m physical barrier at a 30^{o} angle to the current are \$155 million and \$3.2 million (± 50%) annually, respectively (2007 U.S. dollars)
- Attractants and Repellents other than Light and Sound
    - Little is known about the effectiveness of stimuli other than light and sound that could serve as attractants or repellents for use in concentrating fish in general, and virtually no information specific to eels is available.
- Infrasound
    - Only one study provided information on the potential of using infrasound to control eel movement, and that was for a small river in Europe. The results of that study suggested scaling the technology for application in the St. Lawrence River would be difficult
    - Technology for using infrasound to guide eels is in very early stages of development. Considerable basic research would be required to evaluate its feasibility for application in the St. Lawrence River.
    - Effects of infrasound on non-target species is unknown

  - Use of infrasound would be expensive because the field of effect appears to be limited to 2-3m from the source
- Light
  - Avoidance of light by eels in darkness is well documented at many sites; however, some reports indicate little or no response
  - Information about stimulus characteristics required to elicit a response is limited
  - Using light to guide outmigrating eels at IWCD would require substantial infrastructure that would be difficult to construct and maintain. Conceptual estimates of cost for a light barrier at IWCD (30° to the current) are $132 million and $5.6 million (± 50%), respectively (2007 U.S. dollars)
  - Outmigrating eels at IWCD would be exposed to a light array for up to nine minutes. Information on potential habituation over that length of time is lacking
  - A simple conceptual model based on data and observations from the NYPA light study at IWCD (McGrath *et al.* 2003b) estimated that diversion efficiencies could range from 13% (accounting for some habituation) to 58.5% (assuming no habituation).[8]

<u>Collection, Holding, and Transportation Technologies</u>

- Many of the methods for capturing, holding, and transporting eels reported in the literature were applied in smaller waterbodies and have little applicability to the St. Lawrence River at IWCD
- Several techniques were identified that could be feasible for use if scaled to the larger size that would be required at IWCD
- Large collection facilities on rivers in Oregon and Washington effectively concentrate and collect salmon smolts; however, those facilities only operate near the surface, and collection at IWCD would likely need to span the entire water column. No techniques or equipment have been developed to accomplish this in a system as large as the St. Lawrence River
- An inclined-screen trap seems to offer the best potential for collecting outmigrating eels at one or more gates at IWCD; however, the large water discharge through the gates and the expected substantial loading of debris could be problematic
- Conceptual estimates of the cost to construct and operate a modular, inclined-screen trap at IWCD are $12.6 million and $220,000 (± 50%) annually, respectively (2007 U.S. dollars). Operating costs do not include transportation of eels downstream to release points.

<u>Monitoring Technologies</u>

- Acoustic telemetry studies could utilize smaller transmitters than those used in previous studies, providing the spatial resolution and detail about the behavior and movement patterns of eels needed to evaluate effectiveness of a concentration/guidance structure and the collection device

[8] Author note: these calculations assume, based on the NYPA telemetry study (McGrath 2005), that 25% of migrating eels move during daylight, and that the light array would be ineffective during the day.

- Some concerns remain regarding the effects of tagging and handling on the behavior of eels, regardless of the size of the tag. Evaluations based solely on acoustically-tagged fish will be subject to questions of bias induced by tagging and handling
- Multi-beam imaging sonar, such as DIDSON, and other active hydroacoustic monitoring systems could supplement information gathered from telemetry; however, those tools alone cannot provide the spatial coverage to assess the effectiveness of a guidance and collection facility
- The best available methods for collecting test specimens are difficult and expensive. Declining numbers of outmigrating eels exacerbates this challenge
- Researchers noted that collecting fish from downstream locations for use in studies at IWCD could bias study results.

Hydro-Québec

Hydro-Québec has conducted numerous studies related to protection of downstream migrating eels in the St. Lawrence River. In 2000, when NYPA tagged 167 adult eels with acoustic tags and released them 20km upstream of Moses-Saunders, Hydro-Québec monitored their passage downstream of the Beauharnois-Les Cèdres Complex with acoustic receiver arrays at Les Cèdres Power Dam, St. Timothee Dam, and Beauharnois Power Dam forebays (Verdon and Desrochers 2005). None of the eels were detected at Les Cèdres or St. Timothee; however, 26 eels (15.6% of the tagged fish) were detected in the Beauharnois forebay. Most (85%) of the eels approached the dam between 8:00 p.m. and 5:00 a.m. Slightly more than half of the eels (14/26) moved downstream in a corridor less than 250m wide.

Hydro-Québec investigated light avoidance by silver eels in the headrace of Les Cèdres in the fall of 2004 (Desrochers and Fleury 2005, Verdon *et al.* 2005). A green laser (40 watts, 532 nm) was directed across the intake canal to examine the potential to guide eels over long distances. The light was scattered over a short distance by particulate matter entering the canal from Lake St. Francis. Two 12,000W incandescent lights were then mounted above the water surface at a 32° angle to the water. Eels (N=210) were tagged and released 1.6km upstream of the light array. Observations were made in a 400m x 225m by 2m deep (1,312 ft x 738 ft x 6.6 ft) study area over 30 days. Lights were on half of the days; 136 (64.8%) of the tagged eels were detected with 40 passages recorded in the light zone. Partial avoidance (33.3%) was observed above 100 lux.

In 2010, Hydro-Québec examined the response of silver eels to infrasound in a large experimental cage placed in the St. Lawrence River. The system failed at depths greater than 5m (16 ft) at 16 Hz. When working, the device did not elicit any notable responses by eels. To ensure the validity of these results, HQ teamed with Electricity Supply Board, Ireland (ESB); Dr. McCarthy, Galway University, Ireland; and the Belgium-based company ProFish in 2011. A site 4.7km (2.9 mi.) into the headrace canal of the Ardnacrusha hydropower station on the River Shannon, Ireland, was selected for the trial. When Ardnacrusha hydropower station is operating at full capacity (4 turbines), discharge at Clonlara is 400 m^3/s (14,000 cfs), and the depth is about 7m (23 ft). When fewer turbines are in operation, the depth increases to about 8.5m (28 ft). The width of the canal at this point is 38m (125 ft). Two infrasound units, attached to one-ton concrete weights, were deployed at the site and a Dual Frequency Identification Sonar (DIDSON), which was mounted on the specially constructed shore platform was used to evaluate the potential response to infrasound. DIDSON can be operated in either low frequency (1.1 MHz) or high frequency (1.8 MHz) modes, with a maximum range of 15m and 40m (49 ft and 131 ft), respectively. However, after overcoming many technical difficulties, it was concluded that the infrasound in this experiment also did not elicit any notable avoidance response by eels (McCarthy et al 2012).

Between 2000 and 2008, HQ collaborated with commercial eel fishers in Quebec in a series of initiatives that stocked eels into Lake Champlain; however, MFFP declined to allow this stocking to continue during the period 2009-2013. As part of its 2009-2013 Action Plan, HQ implemented a voluntary buy-out program for commercial eel permits and fishing gear on the Ottawa River and from Lake St. Francis to the lower St. Lawrence River. Fishery closures (Ontario) and license buy-backs (Québec) achieved the 50% reduction in commercial fishing mortality goal (DFO 2010, Talbot et al. 2011, Daigle et al 2012).

Ontario Power Generation

Ontario Power Generation's activities related to downstream passage of American eels on the St. Lawrence River leading up to and coincident with the first term of the Eel Passage Research Center have been in fulfillment of OPG's Action Plans. Two projects summarized here are the Lake Ontario eel stocking program and the trap and transport program.

Lake Ontario Eel Stocking Program

A total of 3.8 million glass eels and elvers were collected from commercial fisheries on the Atlantic Coast of Canada and stocked into the upper St. Lawrence River and Lake Ontario between 2006 and 2010 (Pratt and Threader 2011). Stocking was intended to supplement recruitment of eels to the Upper St. Lawrence – Lake Ontario system and to provide eels for future studies (Mathers and Pratt 2011). The eels were stocked as glass eels/elvers and were smaller and younger than naturally recruited eels; additionally, approximately 50% of the stocked eels were male (Stacey *et al.* 2014), which also distinguishes stocked eels from naturally recruited eels which are female (Castonguay *et al.* 1994). Boat electrofishing surveys have incidentally collected stocked eels hundreds of kilometers from the stocking sites; those data indicate rapid growth, survival, and dispersal (Pratt and Threader 2011, Stacey *et al.* 2014).

A portion of the female stocked eels exhibited significantly higher growth rates and length-at-age than their naturally-recruited counterparts, more comparable to growth rates observed in their source waterbody (Stacey *et al.* 2014). Their growth rates were comparable with rates observed in coastal brackish and saltwater habitats; however, size and age of stocked silver eels captured in the St. Lawrence River estuary were markedly lower than that of naturally recruited silver eels (Stacey *et al.* 2014). Concerns regarding the ability of the stocked fish to reach the spawning ground in the Sargasso Sea and in a timely manner highlight a need to source eels appropriately if conservation stocking is to be resumed in the St. Lawrence River basin (Couillard *et al.* 2014, Stacey *et al.* 2014). The same observation was made with regard to HQ and MFFP's stocking efforts in Lake Champlain.

Prior to the stocking program, *Anguillicoloides crassus* surveillance in both upstream migrating juvenile and outmigrating silver eels found no incidence of infection. Stocked eels were screened for parasites and other pathogens and marked with oxytetracycline prior to release. A number of recaptured, stocked eels were infected with *A. crassus*, suggesting stocked eels introduced *A. crassus* to the Lake Ontario-St. Lawrence River system.

The remaining stocked eels are all female, and they are outmigrating at sizes more similar to naturally recruiting eels. These larger stocked females currently constitute an estimated 33.5% of the eels migrating downstream in the St. Lawrence River. The number of large stocked eels migrating downstream has been increasing, but is expected to decline sharply within the next several years.

Trap and Transport Program

OPG initiated a trap and transport program using large yellow eels in 2008 as part of its 2006-2011 Action Plan (Mathers and Pratt 2011). Eels >800 mm collected as by-catch in commercial fisheries in Lake Ontario and Lake St. Francis are purchased, biologically assessed, tagged, and transported around the generating stations or released back into Lake St. Francis as a control. The trap and transport program continues to the present time, having transported just over 20,000 eels through 2017 (Stanley 2017). Follow-up studies have confirmed that trapped and transported eels are physically and physiologically indistinguishable from naturally migrating silver eels (Stanley and Pope 2009, 2010; Stanley 2017) and successfully migrate out of the St. Lawrence River (Béguer-Pon *et al.* 2018).

3
EEL PASSAGE RESEARCH CENTER

Purpose and Scope

The EPRI-led Eel Passage Research Center (EPRC) was established to meet the need for coordinated, collaboratively funded research to address the challenge of safe downstream passage of American eels at hydropower projects on the St. Lawrence River (EPRI 2013). This bi-national effort builds upon the substantial previous research conducted on the St. Lawrence River by current funders of the EPRC and resource agencies with regulatory and management responsibilities for American eel in the Lake Ontario - Upper St. Lawrence River Basin. Preceding activities, such as the decision analysis initiated by the Canadian Eel Work Group (Greig *et al.* 2006) and the review of technologies for protecting outmigrating eels initiated by the FEMRF and NYPA (Versar 2009) clearly articulated the need for a coordinated program of research and development to address this problem. The recovery strategy for the American eel in Ontario (MacGregor *et al.* 2013) acknowledges that immediate, near-term, and long-term mitigation measures are all needed to attain the recovery goals. Research and development of means to reduce turbine mortality at the St. Lawrence River hydropower projects is critically important to successful recovery over the mid- to long term.

Problem Definition

The EPRC's R&D activities address the following long-term goal:

> *Maximize the survival rate of eels that would otherwise pass through turbines at Moses-Saunders Power Dam and Beauharnois Generating Station without significantly reducing power production.*

Research and development to attain this goal support three management objectives:

- Concentrate adult eels for collection above Moses-Saunders Power Dam and Beauharnois Generating Station
- Collect and transfer adult eels downstream around turbines at Moses-Saunders Power Dam and Beauharnois Generating Station
- Demonstrate effectiveness of the selected methods

Physical screening of intakes had been deemed infeasible; thus, research to address the first objective investigates and develops one or more technologies to guide eels to a collection or bypass location using the eels' innate behavioral response to sensory stimulation (i.e., taxis). Stimuli to be investigated included (individually or in combination):

- light
- sound

- electricity
- electro-magnetic field
- water velocity, turbulence, or shear
- chemicals
- others not yet identified

Research is needed to identify means of collecting and transferring eels from an area of concentration around the Moses-Saunders and Beauharnois generating stations. Depending upon the distance involved, this could include capture and transport (e.g. trucking, barging) or bypass via a conduit.

Effectiveness of various stimuli, technologies, and devices must be demonstrated during research, development, demonstration, and full-scale deployment. Thus, research is needed to develop tools and techniques to assess effectiveness of guidance and collection technologies.

The scope of Eel Passage Research Center R&D encompasses and is limited to that which is necessary to achieve the three management objectives described above. While other R&D may support recovery and sound management of eels in the Upper St. Lawrence River, it is outside of the current scope of activities for the Eel Passage Research Center.

Location

The primary venue for field-based research and development is the St. Lawrence River, upstream of Montreal (Figure 2-1). Field-based research may be conducted at other locations, if doing so advances the purpose of providing safe downstream passage on the St. Lawrence River. Such research may be conducted on a smaller system to facilitate deployment and investigation of a sub-scale, prototype device; or in another location because of greater availability of migrating eels for study. Laboratory studies have also been conducted to advance the R&D goal and objectives of the EPRC.

Center Structure, Funding, and Administration

The Eel Passage Research Center is organized and managed by the Electric Power Research Institute (EPRI). The Eel Passage Research Center is a virtual center. It has no facilities, equipment, or staff of its own; rather, it is an administrative structure for collaboratively funding and conducting eel passage research. It encompasses multiple funding types and multiple research projects from 2013 to the present time. Currently, all funding is directed toward a single program of research and all funders have access to the entire portfolio of research. In the future, however, the EPRC may encompass multiple programs of research with differing suites of funders.

Funding Structure

Current funders of the Eel Passage Research Center (EPRC) are hydroelectric generators in Canada (OPG and HQ) and the United States (Duke Energy) concerned with mitigating turbine passage mortality at their facilities and the FEMRF which is administered by the Service. The EPRC currently comprises three classes of funding. Tier 2 funders (currently Duke Energy) participate in all activities of the EPRC and have immediate access to all EPRC products. Tier 1 funders (OPG, HQ and FEMRF) have these privileges and also provide direct input to the overall theme and specific content of the research portfolio. Current Tier 1 funders have specific interest in eel passage on the St. Lawrence River. Tier 1 and Tier 2 funding is for a term of five years.

Ad hoc funding provides an as yet unutilized mechanism for a funder (other than a Tier 1 or Tier 2 funder) to collaboratively fund and participate in a defined subset of the EPRC research portfolio. Participation and access to research products would be limited to that subset of the research portfolio. The amount and term of ad hoc funding is case-specific. If the level of interest and funding warrants it, a parallel structure will be developed specifically to address eel passage challenges for facilities other than those on the St. Lawrence River.

Administrative Structure

The Eel Passage Research Center draws upon contributions from a Management Committee, a Technical Committee, a technical support consultant, and R&D consultants. The respective roles of these entities are described below. Additionally, Technical Committee members and affiliated organizations provide in-kind services from time to time to facilitate execution of the EPRC research program.

EPRI Scope of Services

EPRI provides overall technical leadership and management of the Eel Passage Research Center. This includes recruitment of funders; Center planning; reporting, selection and management of R&D consultants; meeting facilitation and management; and implementation of the terms of reference as defined in the funding agreement between EPRI and Center funders. EPRI has acquired the services of a technical consultant to assist with these tasks.

Management Committee

Final recommendations to EPRI regarding research scope and funding decisions are developed by consensus of a Management Committee comprising the EPRI Project Manager and a single representative of each Tier 1 funding organization.

Technical Committee

The technical deliberations of the Eel Passage Research Center take place among a Technical Committee comprising:

- Technical representatives from each of the Tier 1 funding organizations
- Technical representatives of the member organizations of the Eel Working Group of the Service-administered Fish Enhancement, Mitigation, and Research Fund
- Regulatory and resource management agency personnel individually selected by Tier 1 funders because of their engagement with Tier 1 funders' eel protection and mitigation activities.

Tier 1 funders are not limited in the number of representatives they may assign to the Technical Committee. Representatives of Tier 2 funding organizations may participate as observers of all Technical Committee activities.

Technical Committee members are listed in Table 3-1.

Technical Committee activities include:

- Deliberation on the development of the Adaptive R&D Plan
- Preliminary specification of R&D priorities
- Deliberation on the development of R&D scopes of services
- Review and preliminary selection of R&D proposals
- Review of consultant deliverables and EPRI reports

From time to time the Technical Committee is polled to gain a sense of interests, concerns, and priorities; however, final decisions are informed by consensus among the members of the Management Committee.

Table 3-1
Members of the Eel Passage Research Center Technical Committee

Name	Affiliation
Scott Ault	Kleinschmidt Associates
Jean Caumartin	Hydro-Québec
Jeff Gerlach	New York Power Authority
Daniel Hatin	Ministère des Forêts, de la Faune et des Parcs
Paul Jacobson	Electric Power Research Institute
Steve LaPan	New York State Department of Environmental Conservation
Jake La Rose	Ontario Ministry of Natural Resources and Forestry
Ben Lenz	New York Power Authority
Alastair Mathers	Ontario Ministry of Natural Resources and Forestry
Tracy Maynard	Kleinschmidt Associates
Stephen Patch	U.S. Fish and Wildlife Service
Tom Pratt	Fisheries and Oceans Canada
John Sanna	Ontario Power Generation
Scott Schlueter	U.S. Fish and Wildlife Service
David Stanley	Ontario Power Generation
Ron Threader	Ontario Power Generation
Andrew Weinstock	New York Power Authority

R&D Contracting

All contracting in support of the EPRC is by EPRI. This includes:

- Contracted technical and administrative support to the EPRI project manager
- Contracted R&D to advance the goal and management objectives of the EPRC

Contracts may be either sole sourced or competitively bid depending on which selection method is deemed by EPRI to best meet technical requirements in a cost-effective and timely manner. The Technical Committee provides input to EPRI's decisions regarding sole source versus competitively bid contracting.

Reporting

Abstracts and reports of EPRC R&D activities are published as EPRI technical reports and posted to EPRI's website. These and other documents, such as the Supplemental Project Notice and annual updates on EPRC activities are freely downloadable by the public. Financial reports are provided directly to EPRC funders by the program manager.

Adaptive R&D Planning

The R&D planning over the initial funding term has employed a structured approach to program design that is adapted from a framework for formulating complex ecological assessment (Figure 3-1). Intensive discussions among Technical Committee members synthesizes understanding of conceptual models, technical methods, and existing information leading to specification of R&D questions that are the basis for the R&D plan and specific scopes of work. The R&D plan is revisited by the Technical Committee and adapted as new information accrues from EPRC research and other sources.

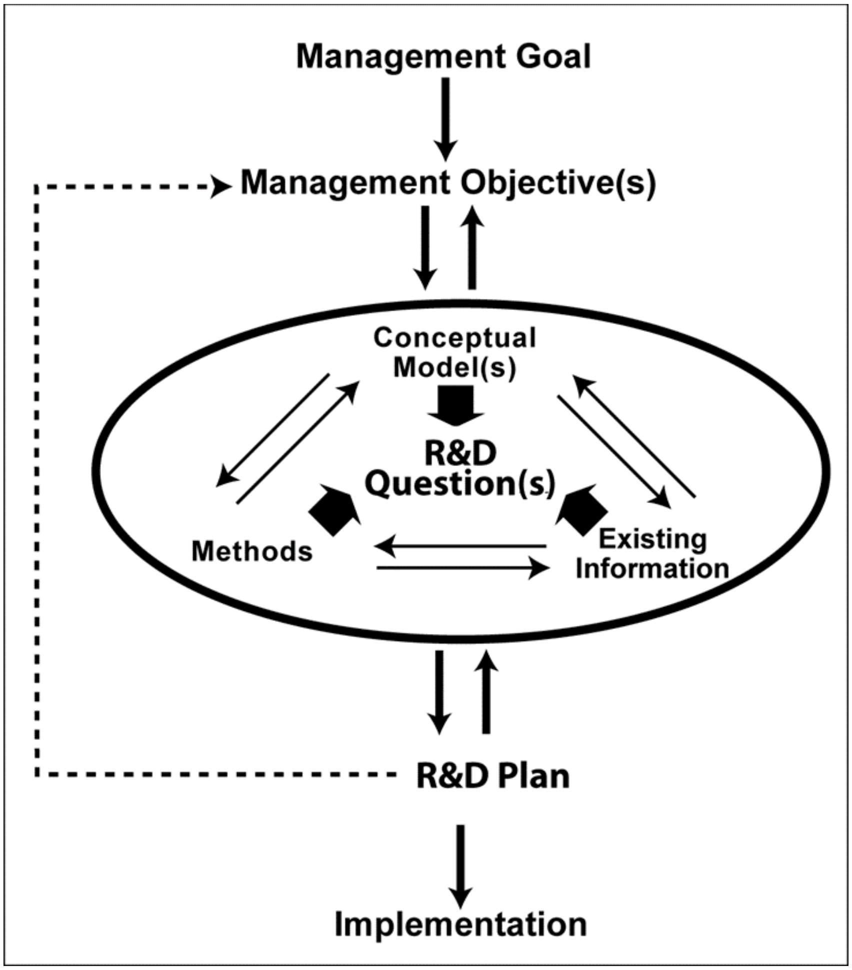

Figure 3-1
Framework for formulating the Adaptive R&D Plan. The dotted line indicates Management Committee review of the R&D Plan to ensure conformity to management goals and objectives.

Conceptual Model for Downstream Eel Passage

Figure 3-2 depicts the conceptual model for eel migration on the Upper St. Lawrence River. The light blue ellipses indicate waterbodies separated from one another by water control structures indicated by gray ovals. The differing sizes of the blue ellipses are intended to highlight the differing quantities of habitat encompassed by each, including tributaries; however, the ellipses are not drawn to scale. The gray ovals depict possible pathways for upstream and downstream movement by eels, whether they are actually used by eels or not. Text on the left-hand side indicates sources of data on eel abundance and movement. The dotted lines with arrowheads on the right-hand side of the picture (labeled B1 through B4) indicate possible bypass routes for eels.

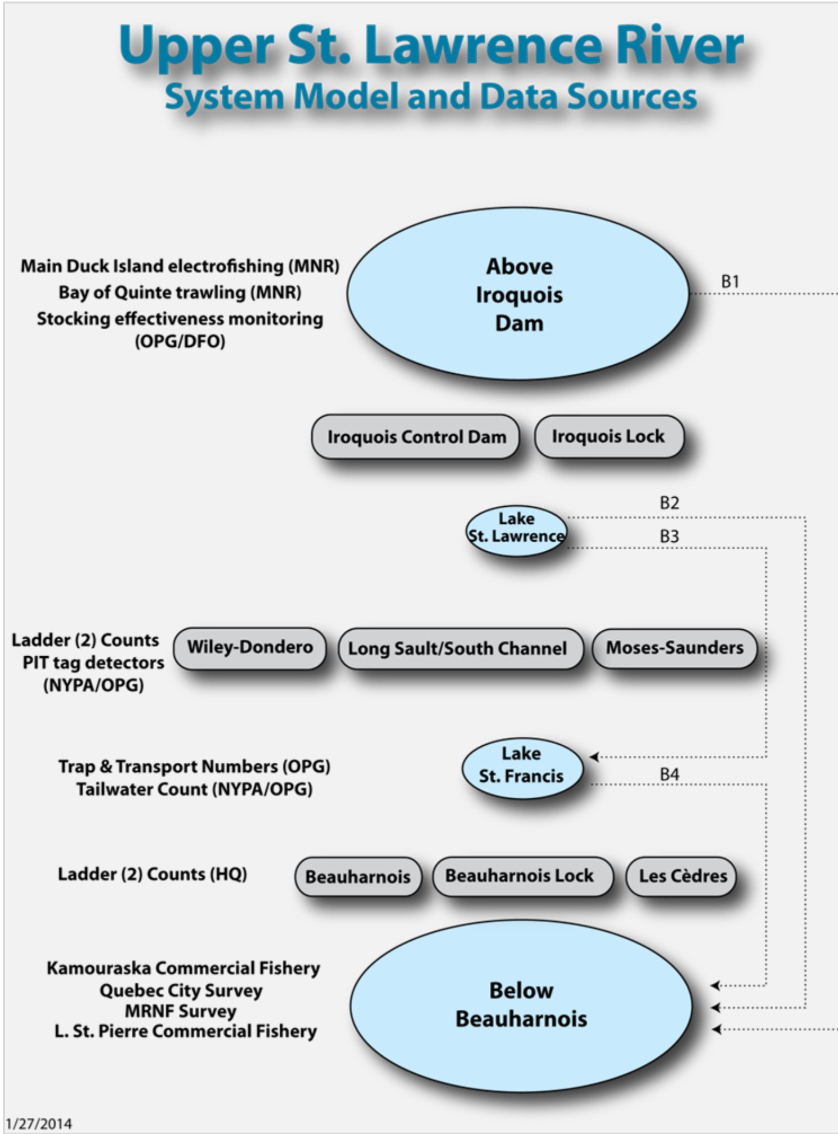

Figure 3-2
Conceptual model of the Upper St. Lawrence River system and data sources.

The highly dispersed nature of movements through Lake St. Lawrence and at the Moses-Saunders Power Dam (McGrath et al. 2003a) elicited the conclusion that guidance and collection of eels needed to occur upstream of Lake St. Lawrence in a constricted reach such as at IWCD (B1). Likewise, the BGS forebay is considered an unsuitable location for guidance and collection; guidance and collection devices likely will be placed in Beauharnois Power Canal, more than 1,500 m upstream of the dam (B4).

Information Gaps and Research Needs

Research conducted prior to establishment of the EPRC determined that light can be effective in guiding outmigrating American eels in the St. Lawrence River at night (McGrath *et al.* 2003b, McGrath *et al.* 2005). That study; however, did not address several important questions including:

- How far can eels be guided before habituation causes them to pass through a light guidance array?
- Will a light array be effective in guiding eels that pass the array during daylight hours?
- Are there light characteristics (e.g. pulse frequency and width, wavelength) that are potentially more effective in guiding outmigrating eels?
- Are there other stimuli that individually or in combination with light could more effectively guide eels, especially during daylight hours?

The results of the acoustic tracking studies in Lake St. Lawrence (McGrath *et al.* 2003b, McGrath *et al.* 2005) raised the following questions:

- What technologies can be used to monitor the behavior of outmigrating eels that don't require capture and insertion of telemetry tags?
- To what degree, if any, is the behavior of outmigrants affected by the acoustic tags used?
- What is the temporal and spatial distribution of eels passing through IWCD and the reach immediately upstream?

Hydro-Québec also deemed it undesirable to deploy an eel guidance structure immediately upstream of its Beauharnois power dam. Rather, one or more guidance structures would be deployed within Beauharnois Power Canal at least several hundred meters upstream of the generating station, such as at the Saint-Louis-de-Gonzague Bridge. Limited acoustic tracking data suggest that eel migration down the canal may be biased toward the south shore in at least one location (Hatin et al. 2014); however, this study left unanswered:

- What is the temporal and spatial distribution of eels passing near potential guidance locations within Beauharnois Power Canal?

Several studies of eel migration have noted silver eels' preference for travelling in the fastest moving water (Versar 2009). More recent studies have documented various behavioral responses by silver European eels to complex flow fields (Piper *et al.* 2013, Piper *et al.* 2015, Piper *et al.* 2017). Bulk flow and flow field structure likely influence route selection in the river and at anthropic structures; thus, information on flow field characteristics is needed at multiple scales. Key questions are:

- What are the detailed flow field characteristics in the guidance and collection reaches?
- How do eel movements and trajectories relate to the flow field?
- What effects do experimental and proposed demonstration guidance and collection devices have on the flow field and thereby on eel movement behavior and the effectiveness of guidance and collection?

These questions drove the research agenda during the initial term of the EPRC.

Research Agenda

Prior research indicated underwater light showed great promise for guiding outmigrating eels; however, the Technical Committee determined that it would not be appropriate to immediately pursue further development of light prior to exploring other stimuli that could be used individually or in combination with light to achieve an acceptable level of effectiveness.

It was recognized that collection of eels was a related, essential component of the broader R&D problem. Collection and guidance are interdependent, with the degree of guidance required influenced by the maximum spatial extent of the collection structure(s), and the characteristics of the collection structure potentially affecting the effectiveness of guidance into the collection structures. An explicit decision was made to defer the collection issue.

To address these outstanding questions, the EPRC undertook a series of research projects. Consensus was reached among the Technical Committee members that consultant teams for each of the projects should be selected through an open, competitive RFP process to meet three objectives:

- Reveal individuals and organizations, including those who may not have been known to us, who could provide expert consulting services for the near-term and future R&D projects
- Obtain independently developed proposals that could reveal novel ideas, approaches, and methods to the Technical Committee that we otherwise might not have been aware of
- Obtain competitive cost proposals, potentially resulting in lower R&D project costs.

A downside of competitive selection was the time, effort, and arm's-length relationship required to ensure a fair and effective RFP process. Preparation of RFPs and review of proposals by EPRI and the Technical Committee on one side and competitive proposal preparation by the R&D consultants on the other side consumed time and effort that might otherwise have been spent on collaborative development of project scopes of work.

4
RESEARCH AND DEVELOPMENT

The EPRC employed an RFP selection process and hired consultants to conduct six R&D projects. In addition, the EPRC supported two R&D projects initiated by other EPRC members. The EPRC developed scopes of work and reviewed draft documents prior to publication as EPRI technical reports. Each of these projects and their key results are summarized below. Project-specific research reports, annual program updates, and other selected documents are listed in Table 4-1.

Table 4-1
EPRC technical reports and other documents

Title/Citation	EPRI Product ID
Eel Passage Research Center: Supplemental Project Notice	1026884
Eel Passage Research Center – 2014 Year-End Update	3002003707
Eel Passage Research Center – 2015 Year-End Update	3002009376
Laboratory Studies of Eel Behavior in Response to Various Behavioral Cues	3002009405
Assessment of Three Sonar Technologies to Study Downstream Migrating American Eel Approach and Behavior at Iroquois Dam and Beauharnois Power Canal	3002009406
Recent Research on the Effect of Light on Outmigrating Eels and Recent Advancements in Lighting Technology	3002009407
CFD Model Development for Iroquois Control Dam and Beauharnois Approach Channel	3002009408
Collaborating to Address Downstream Passage of American Eel at Hydro Plants. Hydro Review: 64-70. July 2016	N/A
Eel Passage Research Center – 2016 Update	3002009864
White Paper Investigation of the Potential Use of Sound to Guide Outmigrating American Eels Near Iroquois Dam and in the Beauharnois Power Canal on the St. Lawrence River	3002014636
Eel Passage Research Center – 2017 Update	3002014637
Behavioral Responses of American and European Silver Eels (*Anguilla rostrata and A. anguilla*) to Electric Fields Under Both Static and Flowing Water Conditions	3002014638

Laboratory Studies of Eel Behavior in Response to Various Behavioral Cues

The laboratory evaluation of silver eel responses to behavioral cues was divided into two components: (1) large flume guidance testing with an electric guidance system (EGS) and a flow velocity enhancement system (FVES); and (2) small flume behavioral response testing with low frequency sound and an electromagnetic field (EMF). The objective of large flume testing with the EGS and FVES was to determine the ability of each stimulus to guide silver eels towards a designated "bypass" collection area. The objective of small flume testing with sound and EMF was to determine their ability to elicit behavioral responses from test eels. The study utilized a total of 800 migratory silver eels that were procured from a commercial fisherman in Rivière-Ouelle, Quebec.

EGS and FVES Evaluation

Methods

Large flume testing with the EGS and FVES was designed to evaluate eel movement and response during trials with each stimulus tested alone and in combination, as well as behavior during control trials. The testing area of the flume used for this evaluation was approximately 24.3 m (79.7 ft) long by 5.2 m (17.1 ft) wide with a water depth of about 2.4 m (7.9 ft) and velocity of 0.9 m/s (3.0 ft/s). The test facility design included a fish acclimation and release pen, the EGS electrode array, the FVES, and three collection "bins" at the downstream end of the channel. The EGS electrodes and the FVES were configured to create stimulus fields that were approximately 30 degrees to the flow (Figure 4-1 and Figure 4-2). Based on this configuration, the middle and left collection bins were expected to receive eels that passed through the behavioral stimulus fields and the right (bypass) bin was expected to receive eels that were guided by the stimuli. Individual eels were also tracked in three dimensions using an HTI Acoustic Tag Tracking System with 15 hydrophones deployed along the two flume walls at multiple depths.

Figure 4-1
Downstream view of three electrode arrays used for evaluation of eel responses to behavioral cues. In the first (upstream) array of electrodes, the ninth electrode (at far right) was added for Block 4 and 5 trials. The FVES eductor nozzle can be seen on lower part of the left hand wall near the first electrode in the second array. One set of surface and bottom hydrophones can be seen on right hand wall just upstream of the bypass collection bin entrance and surface hydrophone can be seen protruding from the temporary (left) wall in the upper left corner of the photo.

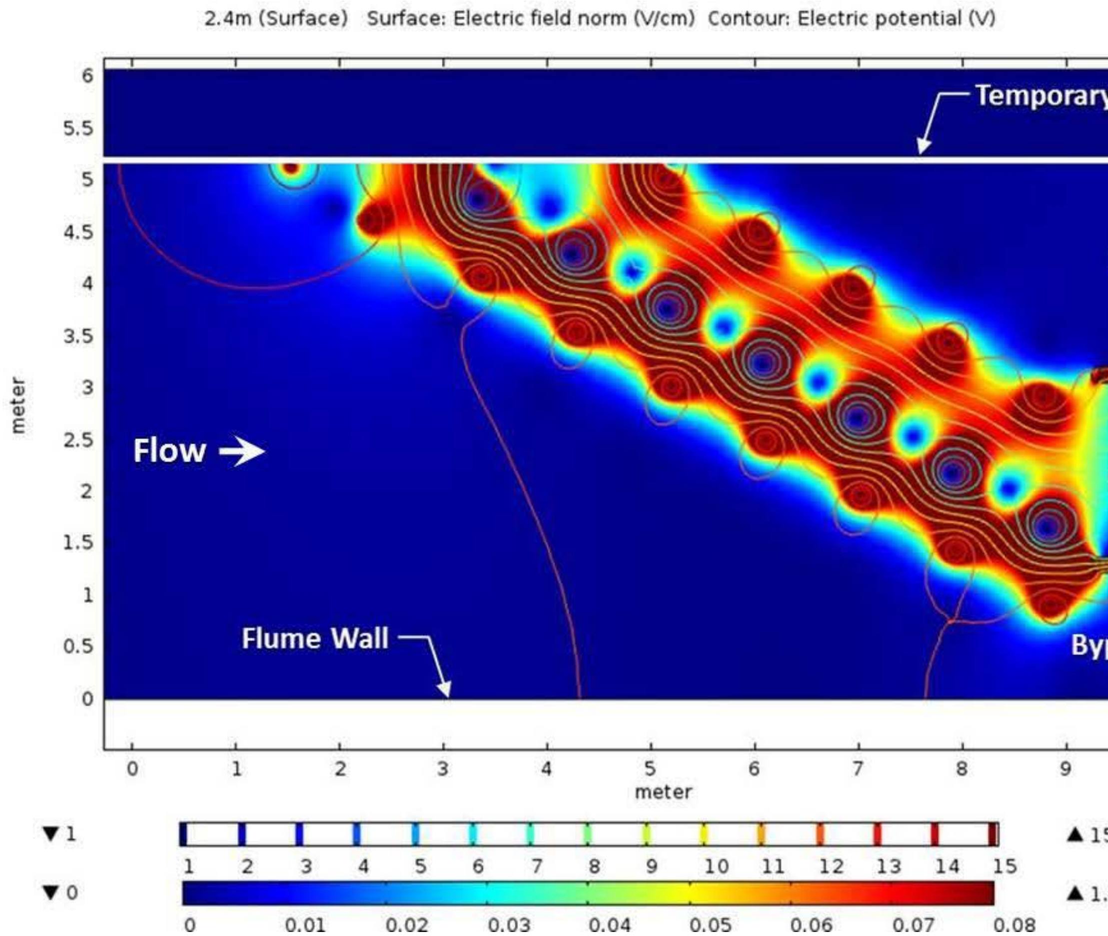

Figure 4-2
COMSOL model of electric field for silver eel behavioral cue guidance trials. Water flow direction is from left to right. Contours (top scale) indicate electric potential (V) referenced to the cathodes (center line of electrodes). The color gradient (bottom scale) represents the electric field gradient in V/cm at the surface.

Eel responses to the EGS and FVES were evaluated during five blocks of trials that included the two stimuli operated alone and in combination and a control (i.e., four trials per block). For each trial, 30 eels with internally-implanted 3D telemetry tags were released and tracked for 2 hours. The number of eels recollected from each of the three downstream bins and from the flume upstream of the bins was also recorded. For the first two blocks of trials, the acclimation/release pen was attached to the left channel wall (looking downstream) at about the mid length of the flume upstream of the stimulus fields. This location was selected to increase the probability that eels would encounter the stimulus fields before entering the bypass collection bin at the downstream end of the flume on the opposite side.

After the completion of the second block of trials, a preliminary analysis of eel movement data indicated that the acclimation pen was likely producing hydraulic conditions (lower velocities, back eddies, and redirection of flow) immediately downstream of the pen that appeared to be influencing eel behavior and movements. Consequently, the acclimation pen was relocated to the center of the flume at the upstream end prior to conducting Block 3-5 trials. Two additional control trials (Block 6) were also conducted to investigate whether the physical presence of the vertically-suspended electrodes was affecting eel behavior. The electrodes remained in the water but not charged for these added controls, whereas the electrodes were removed from the water during Block 1-5 control trials. All trials were conducted at night under dark conditions (i.e., no artificial lighting) with a flume channel velocity of 0.9 m/s (3.0 ft/s). The target sample size for each trial was 30 naïve eels (150 total per test condition for five blocks of trials plus 60 eels for the two additional Block 6 control trials). Actual sample sizes for each trial ranged from 28 to 31).

Initially, it was anticipated the bin counts would provide data to estimate rates of entrainment through the stimulus fields and guidance to the bypass bin. It became evident, however, that eels were capable of moving in and out of bins over the course of a trial, making it difficult to accurately determine the number of eels that were repelled, guided, or entrained through the stimulus fields simply by using the recovery location data. Despite this observation, statistical analysis of the bin collection data was performed to determine if there were any differences in the distribution of eels recovered from the four locations (three bins and main flume channel) among the four test conditions (three stimulus treatments and control) that might indicate some type of behavioral effect by the two stimuli.

The 3D telemetry data were used to plot the movement of each eel evaluated and to develop density plots of eel locations. The density plots show the distribution of occurrence of eels throughout the test channel during each trial and depict the percentage of eels in each trial that passed through specified cells (4 ft x 4 ft x 4 ft; 1.2m x 1.2m x 1.2m) to help define zones of movement in the flume. These plots were developed for the entire 2-hr duration of each trial (Figure 4-3) and for a time period extending from 30 seconds prior to an eel's first encounter with a stimulus field to 10 minutes after entering the field. The density plots were used to compare the test conditions for differences in eel distributions throughout the test flume, particularly near the stimulus fields.

A statistical evaluation of the 3D eel tracks was also conducted to compare temporal and spatial aspects of eel behavior following the first encounter with the estimated stimulus field of coverage during treatment and control trial. The spatial data for each eel (the x, y, and z coordinates) were converted into a time series of vector information. For each point of observation, the distance and direction traveled since the last observation was computed assuming straight-line travel. The distance divided by elapsed time quantified the speed of travel. Using methods for circular data, summary statistics were computed for the time series of vectors immediately following first interaction with a guidance device. The mean vector for each selected time period was defined to determine whether eels that are exposed to the stimulus fields were more likely to move toward the bypass than eels in the control trials. Variability of the movement vectors in the period following first contact with a guidance stimulus was quantified by the directedness of an eel's initial response. The statistical analyses were used to examine differences in eel movements among the treatments and control conditions at selected time intervals.

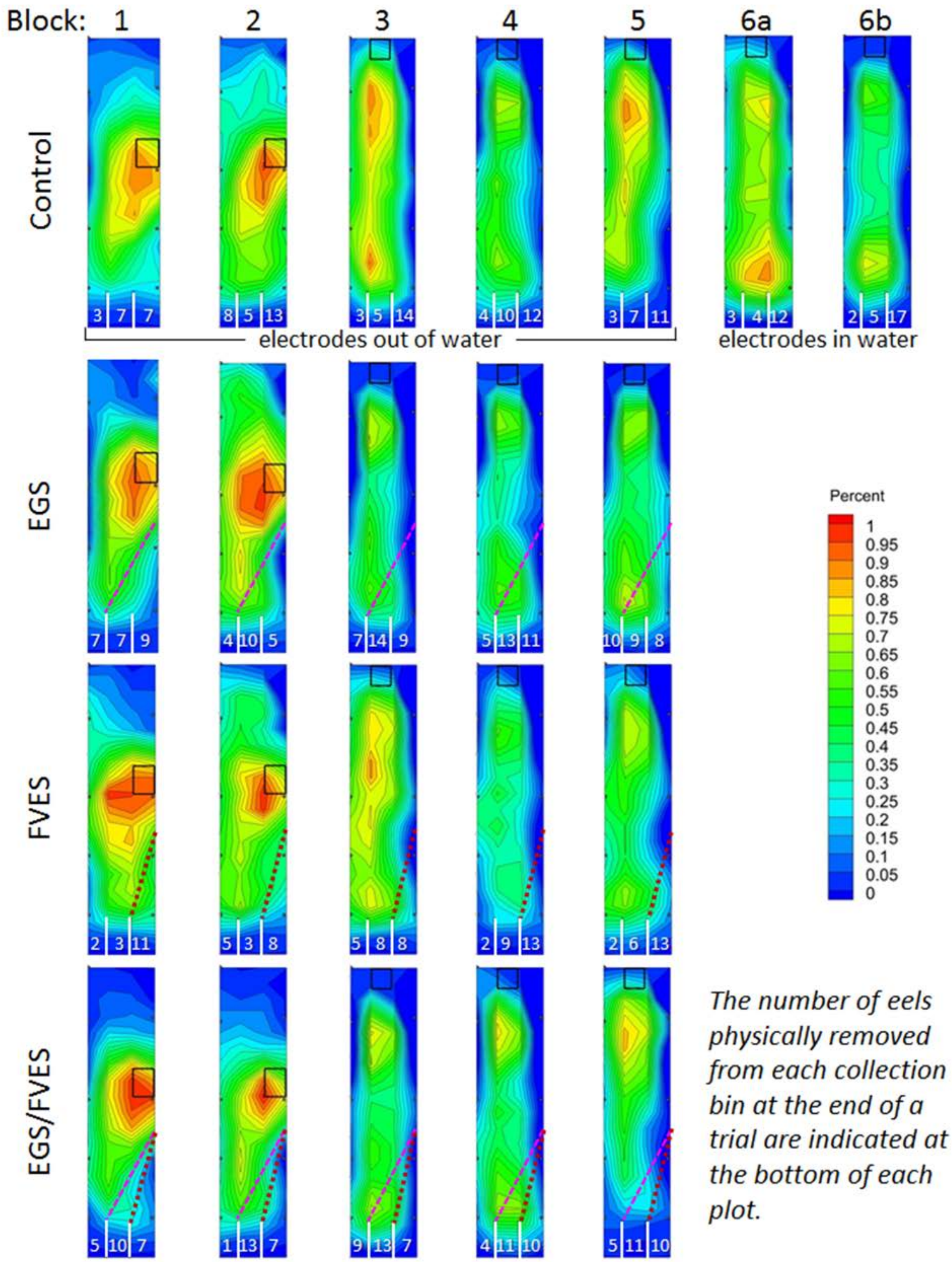

Figure 4-3
Density plots developed from eel tracking data by test condition and trial block. Color contours indicate the proportion of eels that were detected in each cell of a horizontal grid over the entire two-hour duration of each trial.

Results and Conclusions

The following are the primary conclusions from the evaluation of the EGS and FVES with silver eels:

- Although the collection bin counts could not be used to reliably estimate guidance efficiency, they demonstrated that a large proportion of eels passed through the stimulus fields at some point during each trial. Also, there were no major or consistent differences in the proportions recollected from each location between stimulus and control trials.
- The 2-hour density plots of eel distributions did not indicate any strong or consistent avoidance to any of the three stimulus treatments evaluated (EGS, FVES, EGS+FVES), regardless of acclimation pen location.
- Density plots developed for a period extending from 30 seconds prior to and 10 minutes after eels encountered a stimulus field also did not demonstrate any strong or consistent avoidance or guidance responses for the three stimulus conditions.
- The analysis of eel movements following initial encounters with the area of coverage estimated for the stimulus fields did not detect any consistent differences between stimulus and control trials for any of the time intervals evaluated (ranging from 5 to 600 seconds).
- The analysis of eel movements following initial encounters with the area covered by the electrode array during control trials with and without the electrodes in the water indicated the physical presence of the unenergized electrodes influenced eel behavior. However, this effect was not detectable after 60 seconds.
- Because the ADCP velocity data were not sufficient to characterize the hydraulic conditions throughout the flume and to effectively identify the FVES plume, a CFD model of the test flume would allow for a more thorough analysis of eel movements relative to hydraulic conditions throughout the flume with and without the FVES operating. This model would also provide some indication of the effect of the electrodes on hydraulic conditions and how such an effect may have influenced eel behavior.
- With respect to the EGS, the electrical field parameters selected for the flume evaluation were based on observed physical and behavioral responses to a variety of signal characteristics that several silver eels were exposed to in a small tank. Additional testing of electrical field parameters (e.g., voltage, voltage gradient, and pulse frequency, width, and shape) could be conducted to determine if alternative settings may elicit stronger avoidance reactions without leading to narcosis of exposed fish. Additional investigation could also be conducted to determine how the electrode configuration could be further optimized to increase deterrence and guidance effectiveness (e.g., electrode size, shape, polarity, and orientation).
- Alternative configurations of the FVES (e.g., nozzle size and flow volume) could be considered for improving eel responses to this stimulus. Such changes could be evaluated with a CFD model to determine the extent of any improvements to the FVES plume that may lead to better guidance.

The results of the experiments with EGS and FVES need to be considered in context of the flume environment in which the experiments were conducted. For example, there was evidence of a slight bias in eel distributions towards the right-side wall (looking downstream) for both stimulus and control trials. Despite this observation, a large proportion of eels were recollected from the middle and left collection bins at the end of each trial (counter to a reasonable presumption that a right-wall bias would lead to more eels being collected in the bypass bin located on this side of the flume). This indicates that eels may have been avoiding the entrance of the bypass bin (which was narrower than the middle and left bins) and/or were more likely to leave this bin and enter and remain in one of the other two bins.

Sound and EMF Evaluation

The primary objective of low frequency sound and EMF testing was to determine if either stimulus could elicit behavioral responses from silver eels, including startle and/or directional avoidance. Both stimuli were evaluated in test enclosures constructed in Alden's small flume test facility. These enclosures included the positioning of stimulus sources at either end so that directional movement away from a source could be assessed.

Alden's small flume fish testing facility is a closed-loop system that is about 24 m long by 1.8 m wide by 2.1 m deep (79 ft long by 5.9 ft wide by 6.9 ft deep). An external bow thruster powered by an electric motor is used to circulate water through the flume at flow rates up to 2.8 m^3/s (100 cfs) and velocities up to 0.9 m/s (3.0 ft/s) at full depth and width. Separate test facilities for the evaluations of sound and EMF were installed in this flume and are described in more detail below.

Sound Test Methods

The test enclosure used for the evaluation of eel responses to sound signals was constructed in the test flume by installing isolation screens about 4.9 m (16 ft) apart. The width of the enclosure was the full width of the flume (1.8 m; 5.9 ft) and a water depth of about 1.8 m (5.9 ft) and flow velocity of 0.15 m/s (0.5 ft/s) was maintained during testing. The test enclosure was divided into equally-sized quadrants for the purposes of tracking fish locations and analyzing movements and responses based on changes in eel spatial distribution through time. A flow velocity of about 0.15 m/s (0.5 ft/s) was maintained during all acclimation and test periods. A vibration generator (shaker) was located at each end of the test enclosure.

The sound signals were generated with two 250-pound force electrodynamic shakers (vibratory exciters) located on the outside of the isolation screens at each end of the test enclosure. Testing with sound focused on short and frequently repeated signals at frequencies within the known sensory range of eels. Preliminary tests were conducted with eight signals with frequencies ranging from 5 to 1,000 Hz and pulse durations of 1 to 100 ms. Based on the type and strength of observed responses to each of these signals, which were ranked from 1 (weak or no response) to 10 (strong response and directional movement away from source), the three signals that elicited the strongest responses during preliminary trials were selected for a more extensive evaluation of eel responses to sound. These signals included: (1) 100 ms, 10 Hz tone burst; (2) 100 ms, 50 Hz tone burst; and (3) 10 ms, 50 Hz half-sine impulse (Figure 4-4).

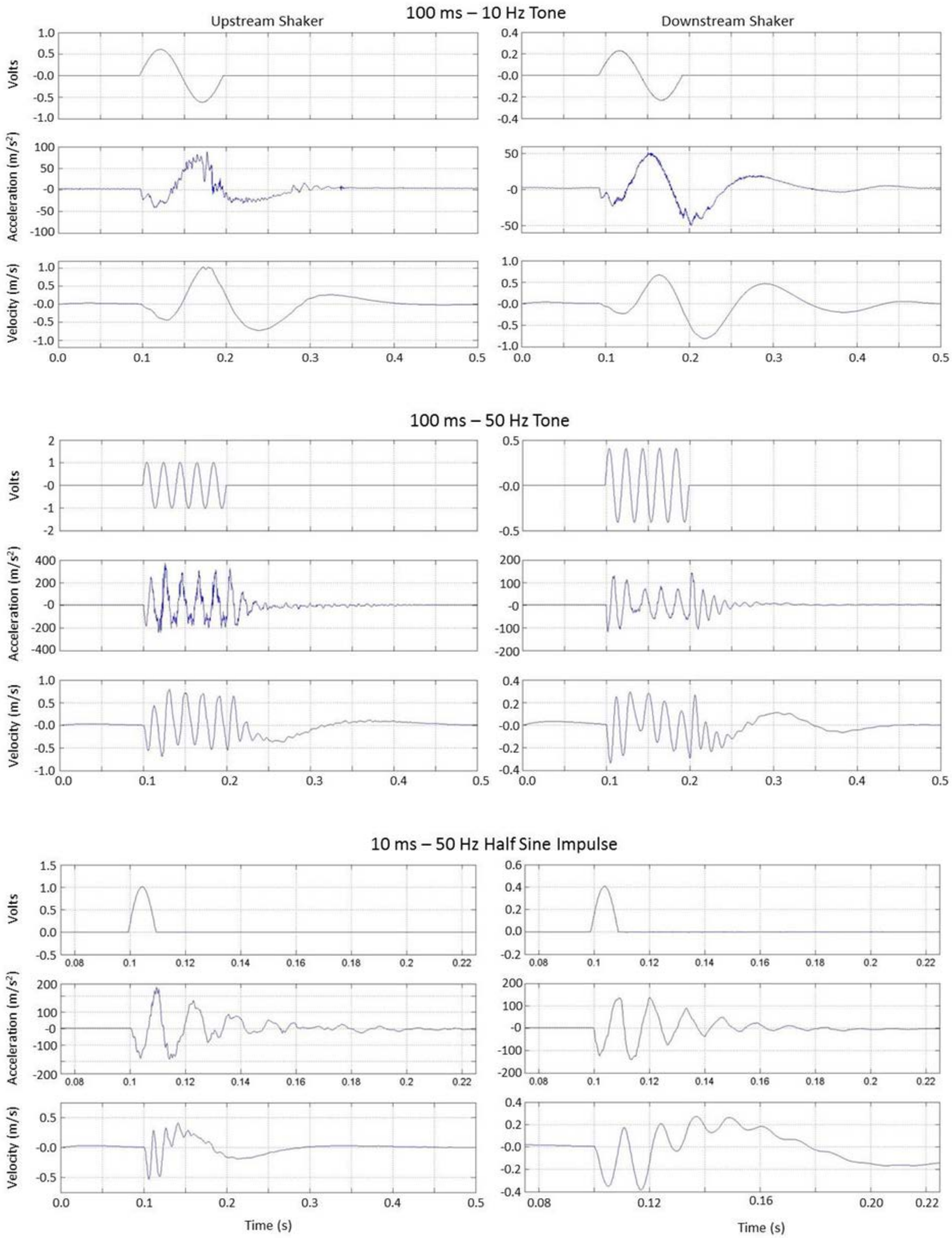

Figure 4-4
Accelerometer data recorded for the upstream (left) and downstream (right) shakers. The upstream shaker had twice the displacement of the downstream shaker, resulting in higher output (i.e., greater particle velocity and acceleration) at frequencies less than 100 Hz. The difference in output between the two shakers was frequency dependent.

To track eel movements within the test enclosure under the dark test conditions (i.e., at night with no artificial lights), all eels were tagged with glow sticks attached to Floy tags inserted into the dorsal musculature. This allowed testing staff to visually monitor eel movement and location within the test enclosures from above the flume. The detailed evaluation of the three selected signals included three blocks of trials conducted with each signal and a control resulting in a total of 12 trials. The order of testing with the three signals and the control was randomized within each block. Fifteen eels, with no previous exposure to sound stimuli, were used per trial. A complete trial consisted of three consecutive 20-minute periods classified as pre-exposure, exposure, and post-exposure periods. With the exception of control trials, each test group was exposed to a sound signal during the exposure period. Control trials were conducted exactly the same as stimulus trials but without any stimulus being presented to the test fish during the exposure period. The number of fish located in each quadrant was recorded by testing staff at 1-minute intervals during each of the three 20-minute periods constituting a trial beginning at the first minute after a trial was commenced and ending at the sixtieth minute. For stimulus trials, the sound source at the end of the enclosure to which more than half the eels were nearest was activated at the beginning of each exposure period. At the completion of the exposure period, the sound signal was terminated and the 20-minute post-exposure period was initiated.

EMF Test Methods

The test enclosure constructed for the evaluation of eel responses to EMF was 1.2 m wide by 2.4 m long with a water depth of about 0.9 m (3.9 ft wide by 7.9 ft long by 3.0 ft deep). The enclosure was constructed of non-conductive PVC and supported by a fiberglass frame so as not to affect or distort the EMF field. The upstream and downstream ends of the enclosure had 1.9-cm (0.75 inch) mesh screens at each end to allow flowing water to pass through. Flow velocity was maintained at about 0.15 m/s (0.5 ft/s) for all trials. A single EMF source (electromagnet) was installed at each end of the test tank. The electromagnets were designed to produce a detectable EMF field approximately 0.6 m (2.0 ft) in all directions.

Similar to vibration testing, the evaluation of eel response to EMF was conducted during nighttime hours (after dusk) in complete darkness and eel movement and positions in the test enclosure were tracked with light sticks attached to each eel with Floy tags. Three blocks of trials were conducted with a full strength EMF field and a control resulting in a total of 6 trials. Due to the smaller size of the EMF test enclosure, the target sample size was 10 eels per trial. Similar to vibration tests, each EMF trial consisted of 20-minute long pre-exposure, exposure, and post-exposure periods for a total trial time of one hour. Due to the smaller size of the EMF test enclosure, it was delineated into upstream and downstream halves for recording the distribution of eels at an interval of two minutes. The electromagnet in the half of the test enclosure where most eels were located at the end of a pre-exposure period was activated at the beginning of the exposure period.

Data Analysis

The response of eels to sound and EMF stimuli was determined by analyzing fish distributions (i.e., number of eels in each quadrant of the test enclosure for vibration testing and each half for EMF testing) through time during the pre-exposure, exposure, and post-exposure periods constituting each trial. For each trial, the distribution of eels was characterized by calculating the "center-of-school" through time (i.e., one-minute intervals for vibration testing and two-minute intervals for EMF testing) for each of the three observation periods constituting a complete trial. Center-of-school estimates provide a quantitative measure of fish distribution along the length of the test enclosures relative to a stimulus source. For sound response data, the center-of-school measurements were averaged over all observations within an observation period to obtain one response for each period of each condition within each block. These observations were analyzed by a repeated measure analysis of variance (rmANOVA) where the three observation periods were a within-subjects factor applied to the same eels over time and the two conditions, control and stimulus exposure, are a between-subjects factor applied to separate groups of eels.

The statistical analysis of the EMF test data included an examination of the mean number of eels in the downstream half of the test enclosure where the mean was computed over the repeated observations for each block of trials, test condition, and observation period. A second analysis examined the mean center-of-school. A third analysis examined the individual frequencies of eels in each half of the EMF test enclosure for every observation. The first two analyses use repeated measures analysis of variance (rmANOVA) to assess the significance of condition (stimulus trials vs. control trials), period (pre-exposure, exposure, and post-exposure), as well as the interaction of these factors. The third analysis used a generalized linear mixed model (GLMM), which is a generalized linear model that includes random factors.

Results and Conclusions

The evaluation of silver eel responses to sound signals produced statistically significant avoidance reactions to 100 ms-10 Hz (Figure 4-5) and 100 ms-50 Hz (Figure 4-6) tone bursts characterized by movement away from the sound source. The responses to these signals indicate low frequency sound may have potential to repel and guide eels and should be considered for future investigations under conditions more similar to a field application (i.e., in a more open environment with flowing water). Because the physical size of the small flume test facility precluded acoustic pressure as a stimulus for the signals that were tested, the observed avoidance responses were most likely due to particle motion. Evaluation of alternative signal characteristics could lead to additional optimization of acoustic stimuli to produce stronger avoidance responses from silver eels. If additional research is conducted with sound, it is recommended that a method be developed to map the particle motion field inside the test enclosure. This likely would involve the use of an accelerometer and computational fluid dynamics modeling to identify the signal field parameters eels are experiencing when they exhibit avoidance (i.e., determine particle acceleration, velocity, and pressure thresholds that are required to elicit avoidance responses).

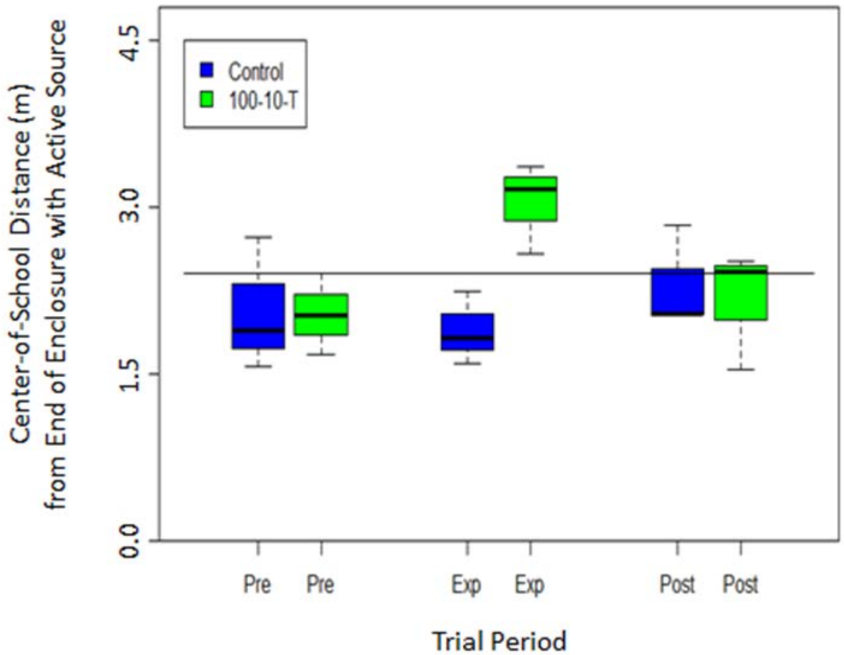

Figure 4-5
Comparison of displacement of the center-of-school measure for the three experimental periods (pre-exposure, exposure, and post-exposure) of trials conducted with the 100 ms-10-Hz tone sound signal and the control condition.

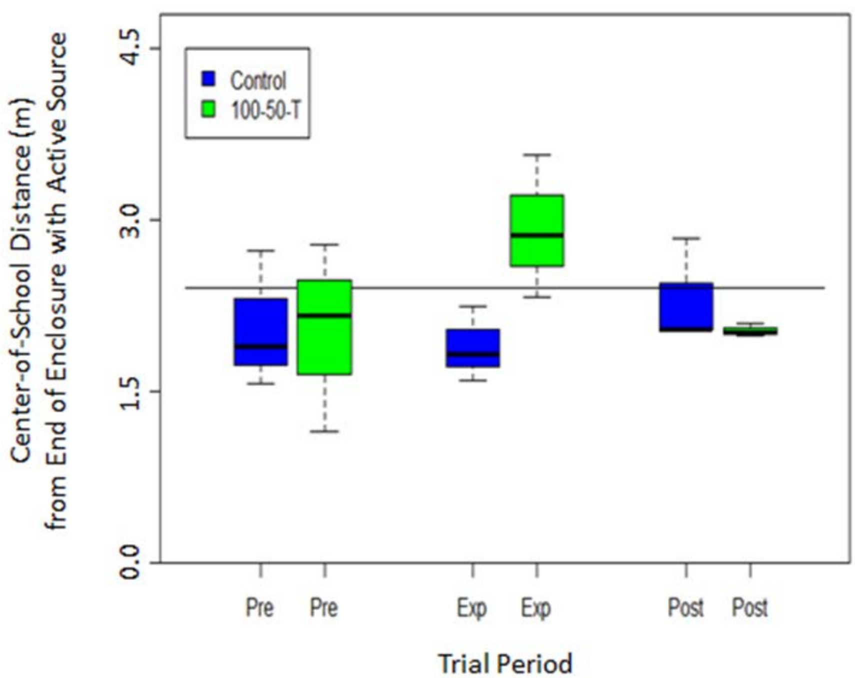

Figure 4-6
Comparison of displacement of the center-of-school measure for the three experimental periods (pre-exposure, exposure, and post-exposure) of trials conducted with the 100 ms-50 Hz tone sound signal and the control condition.

The experiments exposing eels to an EMF source did not demonstrate any discernible responses that would suggest this type of stimulus could be used as a method to repel or guide silver during their outmigration (Figure 4-7). The strength of the EMF generated in the test tank was as strong, or stronger, than levels for which eel responses have been reported in previous studies. The lack of any type of directional movement away from the EMF in this study indicates that EMFs are unlikely to be useful in altering silver eel behavior to the extent that this type of stimulus would provide an effective means to guide eels.

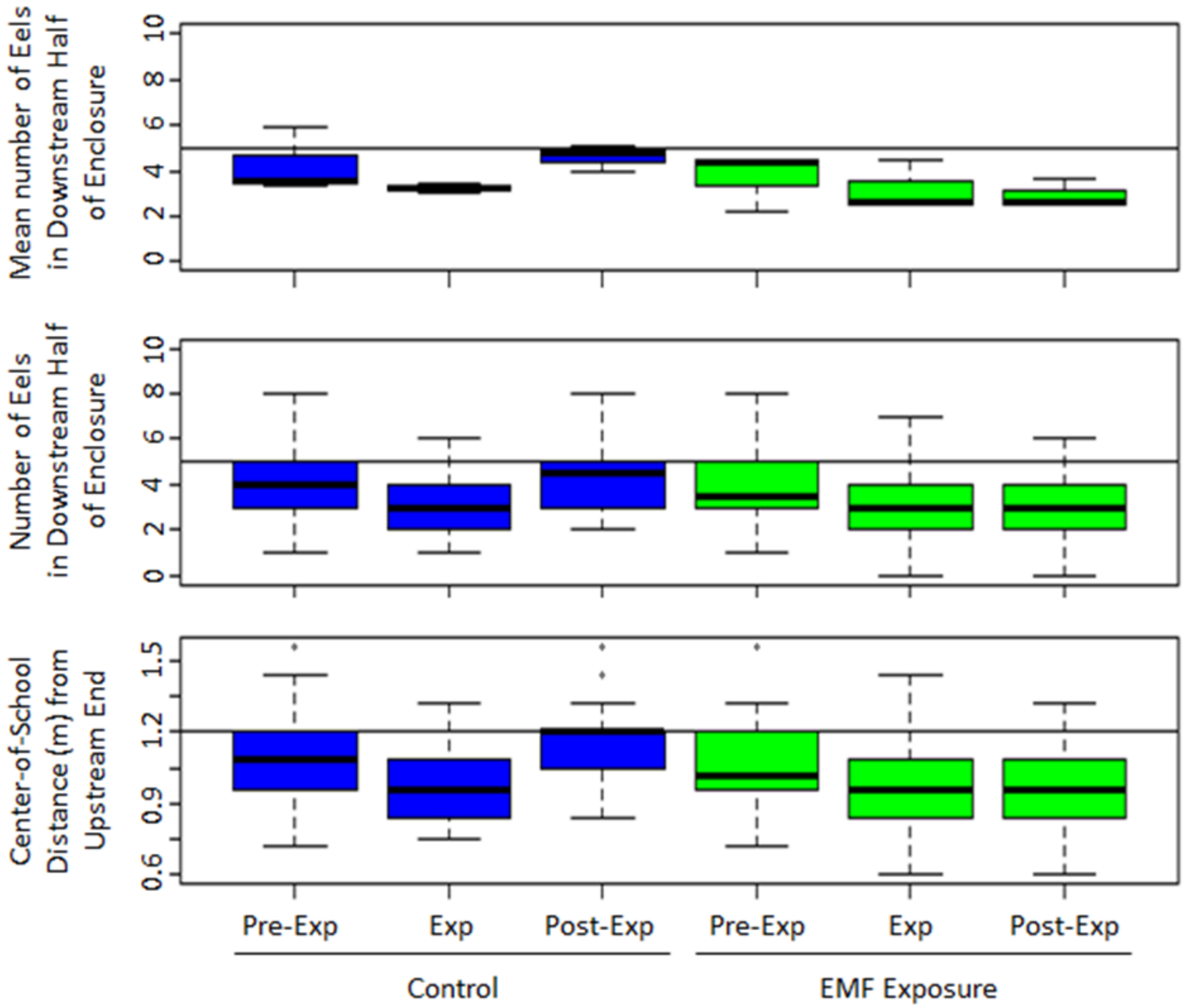

Figure 4-7
Box and whisker plots comparing EMF exposure and control center-of-school data by observation period for the three blocks of trials.

Recent Research on the Effect of Light on Outmigrating Eels and Recent Advancements in Lighting Technology

This project reviewed the world's primary and gray literature to evaluate one stimulus (light) and its potential for use in a downstream eel passage structure. The report describes results of experiments that evaluate the effectiveness of light in deterring and guiding eels. Versar (2009) summarized all works in this field up to 2007. The current report summarizes all known work between 2007 and 2015. In addition, an effort was made to canvas all the world's known eel research participants to learn of unpublished information. Unpublished information from these sources is included in the review.

Since 2007, three relevant studies have been completed with mixed results, two of which show that LED strobe lights can be used as an effective silver eel guidance stimulus in field situations. Bowen (2014) tested a LED strobe light in a small river (15 m (49 ft) width), the River Test (UK), that emitted white broad-spectrum light that ranged in frequency from 425 to 725 nm. Bowen (2014) found significant silver eel guidance, but interpretation was limited by small sample size. In a second field test, Kruitwagen (2014) worked in the IJmuiden lock complex (North Sea Canal, Netherlands) where the river width was 800 m (0.5 mi.). LED strobe lights (FishFlow Innovations (Medemblik, Netherlands)) that emitted white broad-spectrum light considerably reduced the number of eels approaching the trash rack (50 m (164 ft) width). Eels chose other routes, navigation locks or spillway sluices, rather than passing through the strobe light array and the pumps. Dual-frequency Identification Sonar (DIDSON™) data obtained with the strobe lights on showed that 0.8 eels/h presented near the trash rack compared to 11.9 silver eels/h observed near the trash rack when the strobe lights were off. In the third study, Bruijis and Vriese (2013) showed that LED strobe lights can fail to guide silver eels. In the River Meuse (Linne Hydropower Plant, The Netherlands), FishFlow Innovations LED strobe lights (the same as those used at IJmuiden by Kruitwagen (2014)) were placed too close to the inlet of the bypass and 0.0% guidance was observed. This is less than would be expected by a random process. Bruijis and Vriese (2013) concluded that turbulence immediately in front of the intake masked the inlet to the bypass and that turbidity may have also contributed to the light array's failure. The designer of the Linne LED strobe light array also noted that the sound of the turbines resonating in the inlets may have significantly contributed to the failure of the system to guide silver eels.

These studies showed that LED strobe lights can be effective in a field situation in guiding eels. However, the exact placement of the lights, bypass location and the deployment configuration can reduce or even preclude effectiveness of an eel guidance structure.

The most important findings of the report are:

- Multiple reports have indicated that light stimulus is likely to produce effective behavioral eel guidance response in the St. Lawrence River.
- Two types of lights, broad-spectrum white and narrow-spectrum blue, are recommended for testing because of eel specific sensitivities.
- LED lights are recommended for further testing because they:
    a. would be less expensive than the more traditional xenon or other types of strobe lights,
    b. can incorporate UV anti-biofouling diodes to reduce cleaning requirements,
    c. can be operated in continuous or flashing mode, and
    d. their flash characteristics are highly flexible and could be programed to vary within a 24-h period or by season to improve visibility, reduce habituation, and reduce effects on other fish species.

CFD Model Development for Iroquois Control Dam and Beauharnois Approach Channel

The objective of this project was to provide detailed 2D and 3D simulations of the velocities and depths of flow upstream of the Beauharnois Generating Station and upstream of Iroquois Water Control Dam on the St. Lawrence River. These simulations, as well as future simulations utilizing the tools and input files developed by this project, will support research and development of behavioral guidance technologies to safely pass outmigrating eels around Beauharnois Generating Station and Moses-Saunders Power Dam. The study relied upon existing data, supplemented with Acoustic Doppler Current Profiler (ADCP) and bathymetric surveys collected by Ontario Power Generation for this project.

Beauharnois Canal

The 25 km (15.5 mile) long by 1 km (0.6 mile) wide Beauharnois Power Canal was modeled in two dimensions (depth averaged) utilizing the TELEMAC-2D computational fluid dynamics modeling software (Version 6.3) and Blue Kenue pre- and post-processor. The model was calibrated based upon water levels measured September 10, 2014 at a flow of 7,300 m^3/s (257,800 cfs). Two simulations were conducted at a flow rate of 8,200 m^3/s (289,600 cfs), a flow considered representative of conditions during eel outmigration. One simulation represented conditions without operation of the Seaway Lock 4, and a second simulation represented conditions with operation of the lock (Figures 4-8 and 4-9, respectively).

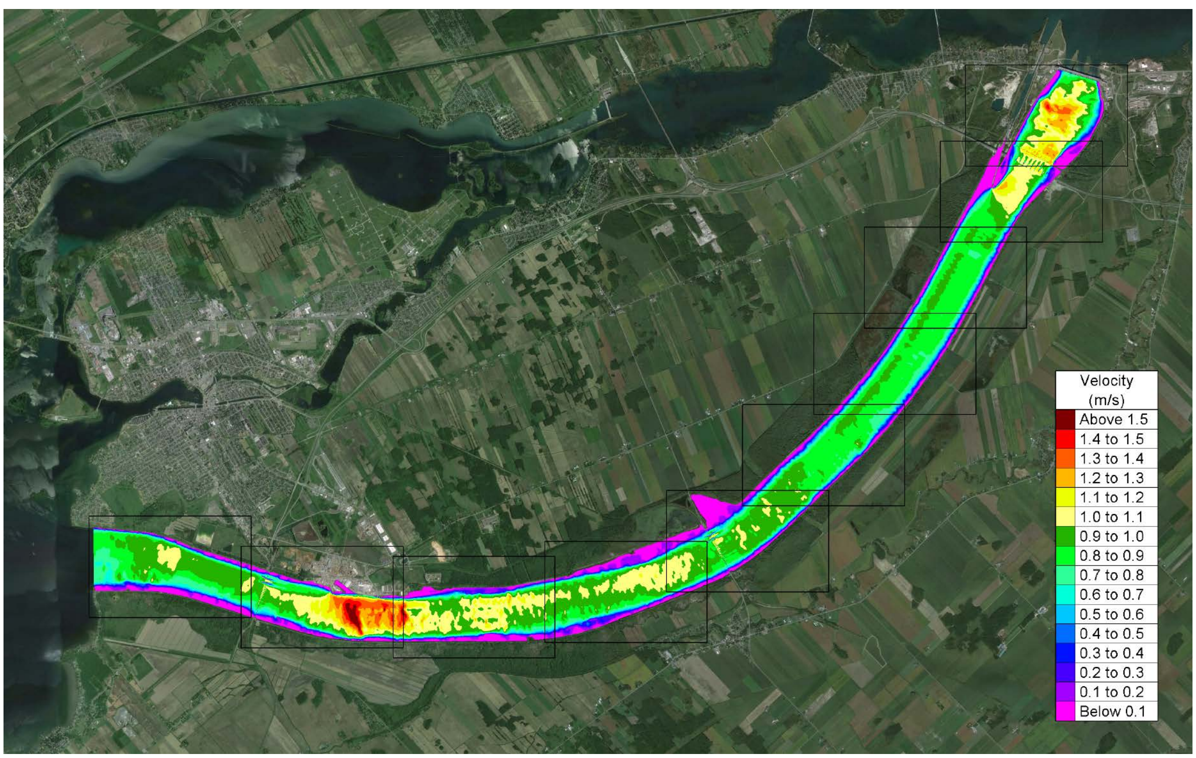

Figure 4-8
Depth averaged velocity in Beauharnois Power Canal from TELEMAC-2D with a flow rate of 8,200 m^3/s (289,600 cfs).

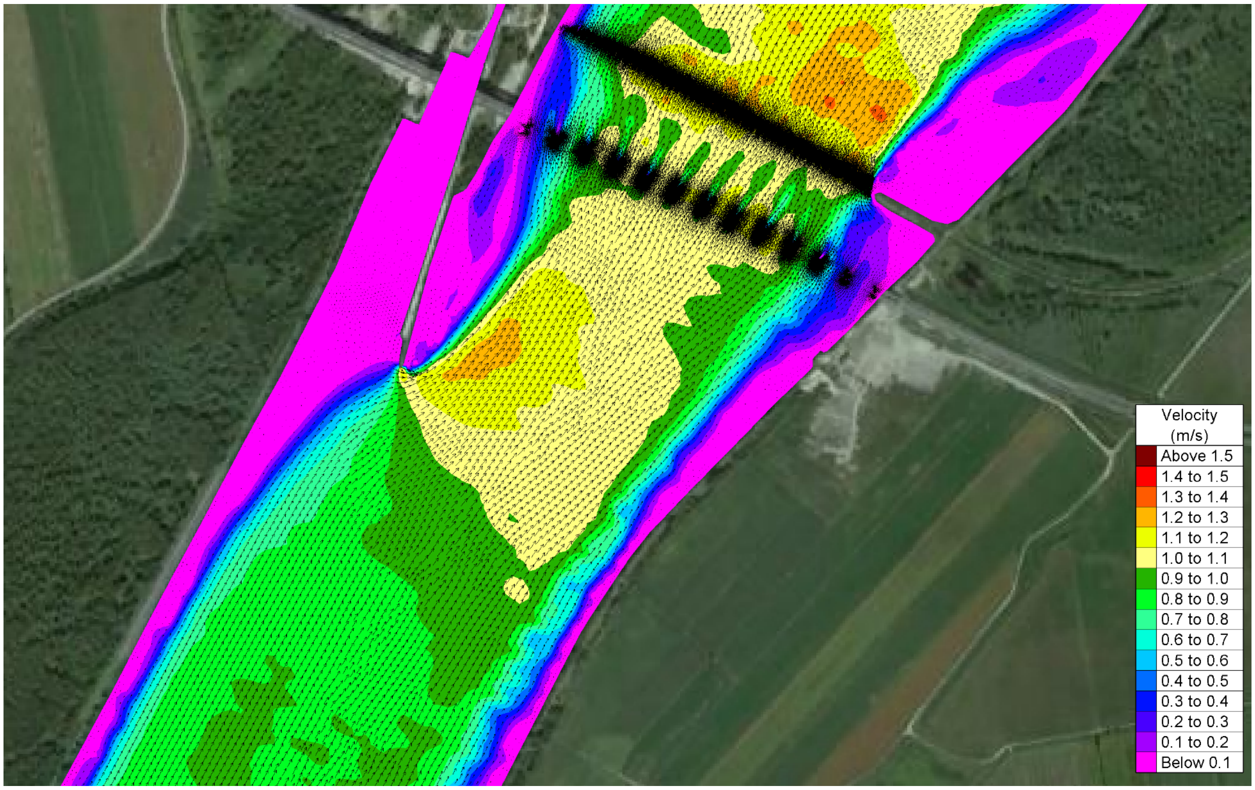

Figure 4-9
Velocity direction in the Beauharnois Canal with a flowrate of 8.200 m^3/s (289,600 cfs) and lock operation.

Iroquois Water Control Dam

The IWCD and the river reach extending approximately 2 km (1.24 miles) upstream and approximately 100 m (328 ft.) downstream was modeled in three-dimensions using ANSYS FLUENT. The same spatial domain was modeled using TELEMAC 3D software. The mesh resolution varied from 3 m (9.8 ft.) to 0.5 m (1.6 ft.) near the structures. Further mesh refinements were required during model calibration to track the water surface elevation and to refine the flow distribution across the entire boundary at the model domain inlet. The FLUENT model was calibrated against the Ontario Power Generation survey on September 9th, 2014, during which the measured average flow was 7,992.6 m^3/s (282,250 cfs). The velocity profiles for both models were validated against the ADCP measurements for each transect (Figure 4-10 and Figure 4-11).

Model output for both Beauharnois Power Canal and the IWCD reach indicates eel guidance will be needed in water velocities in the range of approximately 0.6 to 1.5 m/s (2.0 to 4.9 ft/s).

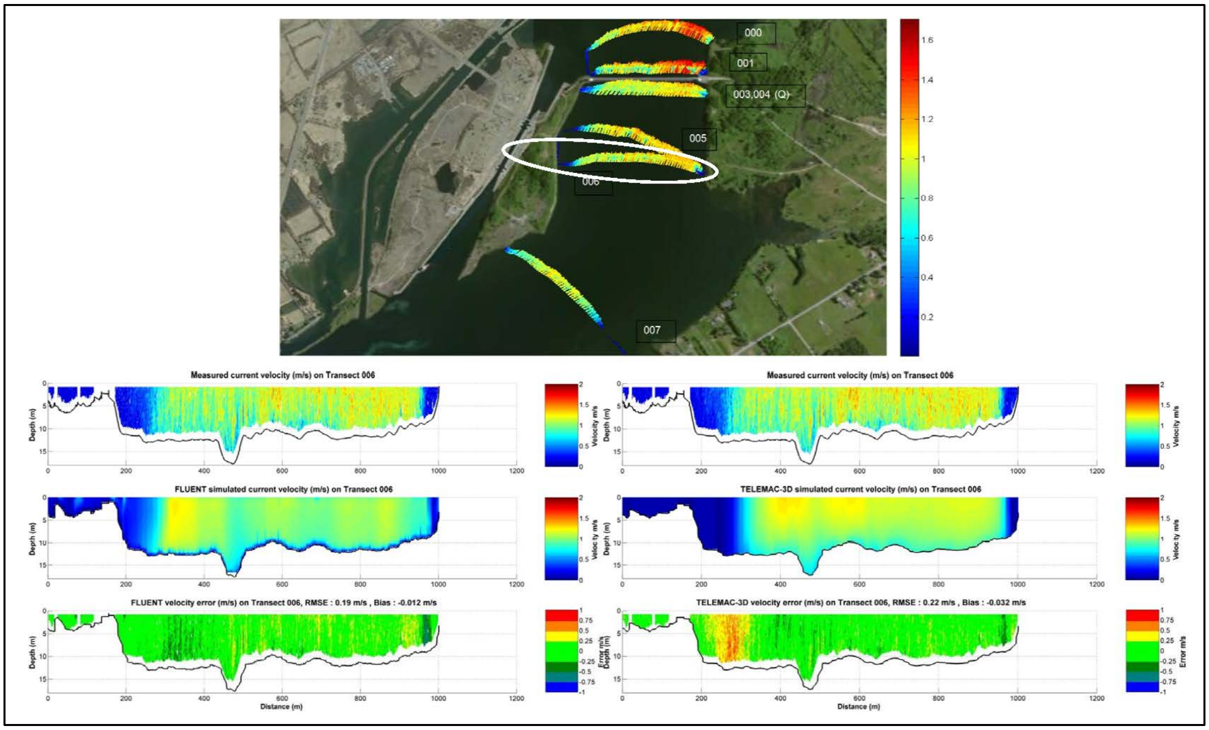

Figure 4-10
Top: Satellite image showing locations and results of ADCP transects. Circled transect is depicted in the bottom panel. Bottom: Measured (top row), simulated (middle row) and difference (bottom row) for FLUENT simulations (left column) and TELEMAC-3D simulations (right column). Velocity color scales are 0-2 m/s (0-6.6 ft/s.), except bottom row (error map) which is -1 to +1 m/s (-3.3 to +3.3 ft/s.).

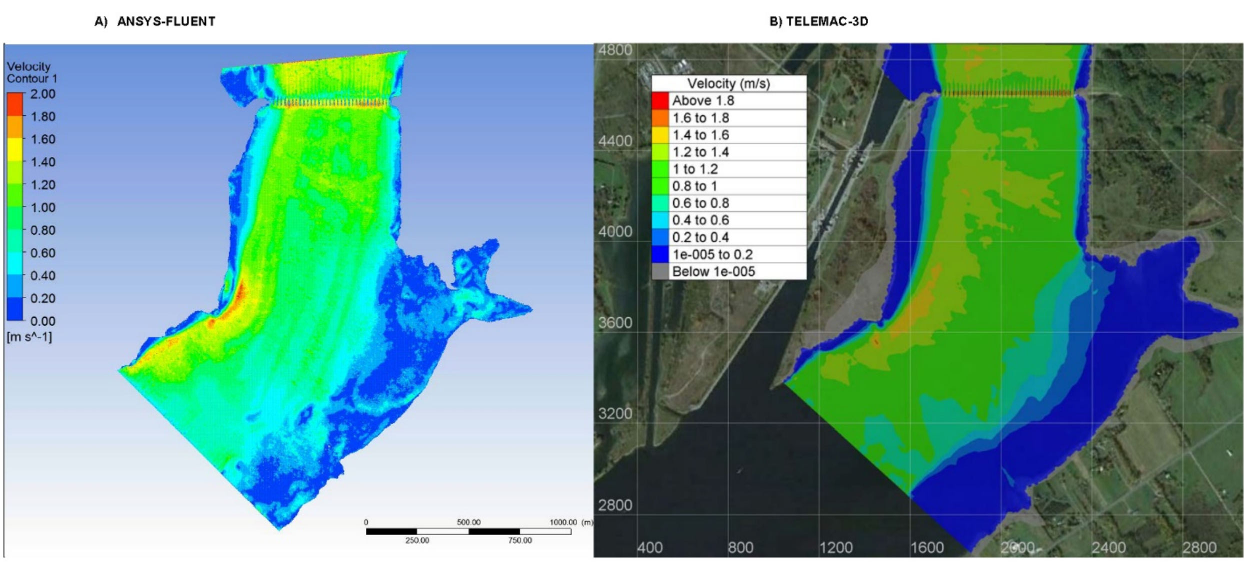

Figure 4-11
Surface velocity profile at 7,992.6 m^3/s (282,250 cfs); (A) ANSYS-FLUENT (left); (B) TELEMAC-3D (right).

Assessment of Three Sonar Technologies to Study Downstream Migrating American Eel Approach and Behavior at Iroquois Dam and Beauharnois Power Canal

To develop and assess the effectiveness of guidance technologies, a suitable technique is needed to effectively monitor eel abundance and movements. This study evaluated the capability of three sonar technologies to estimate eel abundance, determine distribution, and describe approach behavior at IWCD on the St. Lawrence River. A Simrad EK60 split-beam echosounder (120 kHz), Sound Metrics ARIS Explorer multibeam sonar (1100/1800 kHz), and Mesotech M3 multi-mode multibeam sonar (500 kHz) were experimentally tested at the dam (Figure 4-12). Live adult eels, tethered to surface floats, were released upstream of the sonar beams and allowed to swim through at known ranges, depths, and times. Sonars were evaluated for their ability to detect and identify known numbers and sizes of eels while also rejecting other sources of interference such as other fish species, aquatic vegetation, and debris.

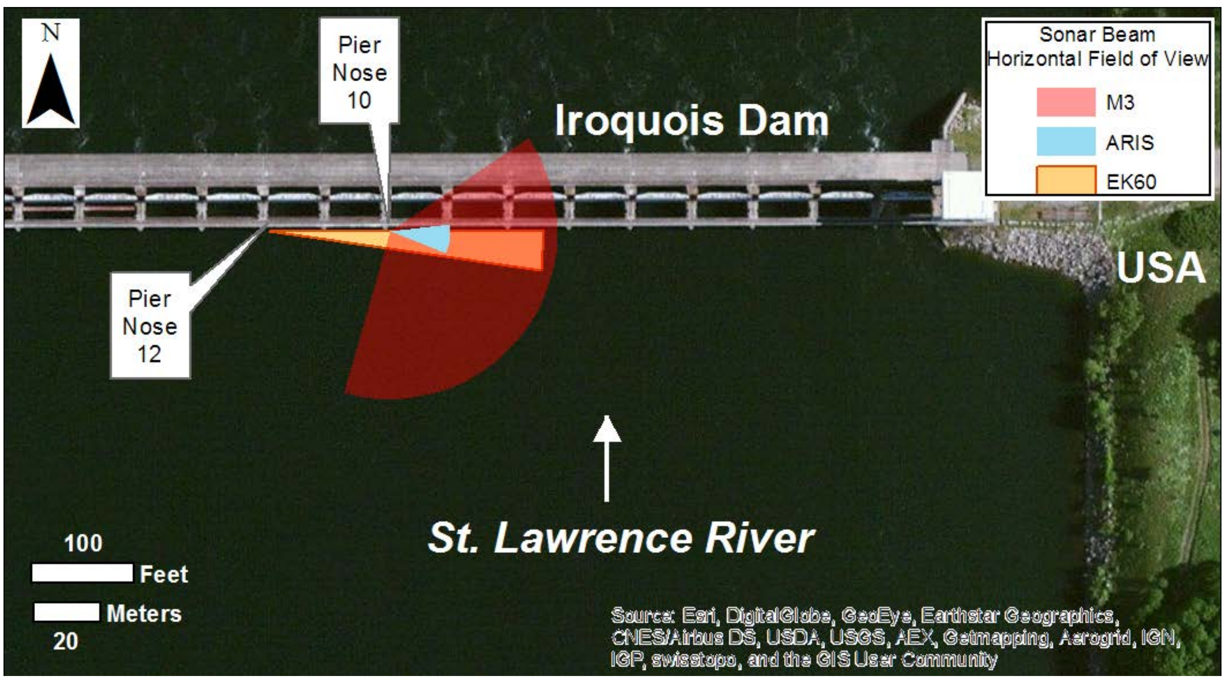

Figure 4-12
Aerial view of the initial location of the Simrad EK60 split-beam transducer (7° circular beam width), ARIS Explorer 1800 imaging sonar (28° horizontal x 28° vertical with spreader lens), and Kongsberg Mesotech M3 multibeam sonar (140° horizontal x 30° vertical in EIQ mode) installed on Iroquois Dam during 27 May-5 June 2015 for subsequent field testing of tethered American Eels and monitoring of out-migrating adult eels until 23 July 2015.

Key Findings

- The ARIS multibeam sonar, operating with 48 beams, holds the most promise for correctly identifying eels out to 16-20 m (52-72 ft.) in range, but the M3 multibeam sonar has value for tracking targets identified by other means (e.g. ARIS) over larger areas.
- The ARIS sonar should operate in the 48-beam mode with a 28° spreader lens and at 1100 kHz for the best identification of swimming eels (Figure 4-13).

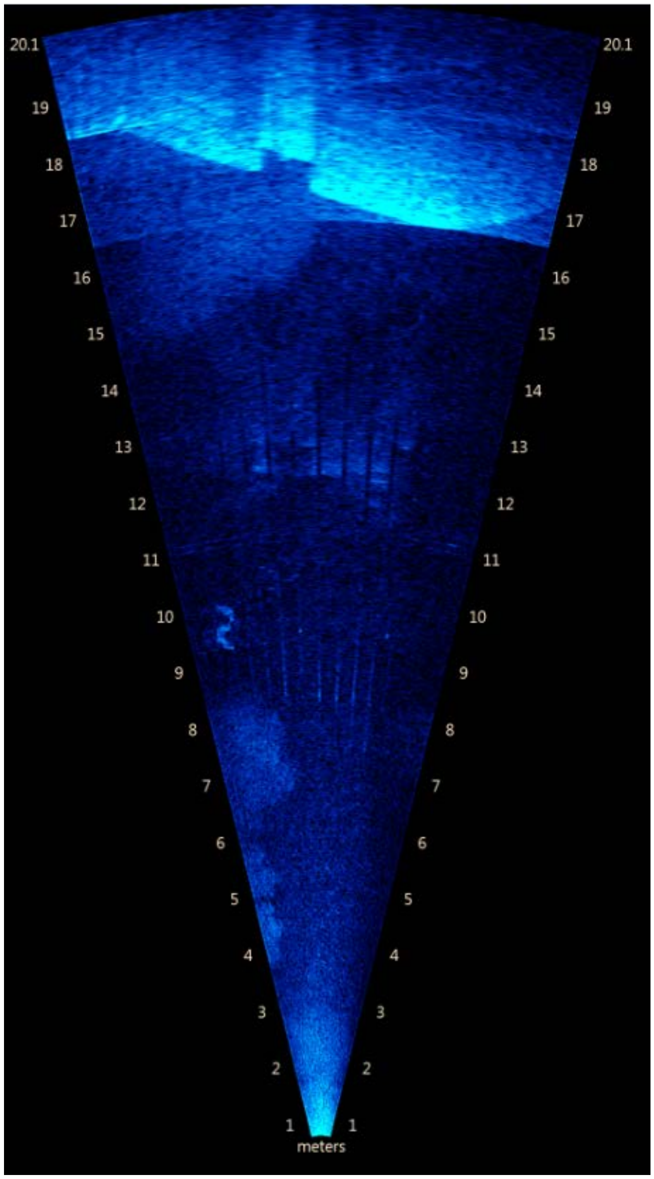

Figure 4-13
Use of the 28° spreader lens with the ARIS. A tethered eel was clearly visible at 10 m range. The opposite pier nose was also visible at the top of the image.

- Motion artifacts in ARIS imagery made it difficult to identify objects, especially when the image distortion of eel-shaped objects (e.g. sticks) mimicked the anguilliform swimming motion of eels. The challenges of eel identification were exacerbated by the combination of high target velocity, long target ranges, and the abundance of other targets.
- The M3 multimode multibeam sonar can detect large moving targets within the effective range of the ARIS sonar and was able to detect the same targets as the ARIS, but its capability to independently identify eels was not demonstrated given its coarser image resolution (Figure 4-14).

- Eels could be seen in EK60 data, especially when their release location was known or their presence was confirmed by ARIS or M3, but identification as a live eel was not possible based only on the EK60 data.
- These results demonstrate it is feasible, with limitations, to monitor American Eel abundance and behavior with the ARIS sonar during the adult outmigration at IWCD (Table 4-2) with the prospect of obtaining supplemental behavioral information of identified targets over a larger, wider field of view with the M3 multimode multibeam sonar.

Table 4-2
Results from the randomized, single-blind classification test of tethered eels and non-eel targets on 17-19 September 2015. Results compare the error rate, by number and percentage, of the true target identity against the identification from ARIS sonar data collected under three settings based on a qualitative classification score system when Q1-Q2 = eel.

			Actual					
			Setting 1 48 beams 2-18 m range -13° Tilt		Setting 2 96 beams 2-12 m range -13° Tilt		Setting 3 48 beams 8-36 m range -32° Tilt	
			True Eel ID	True Non-eel ID	True Eel ID	True Non-eel ID	True Eel ID	True Non-eel ID
Observed	Eel ID	Q1-Q2	4	0	2	0	0	0
			80%	0%	33%	0%	0%	0%
	Non-Eel ID	Q3-Q5	1	8	4	9	5	4
			20%	100%	67%	100%	100%	100%

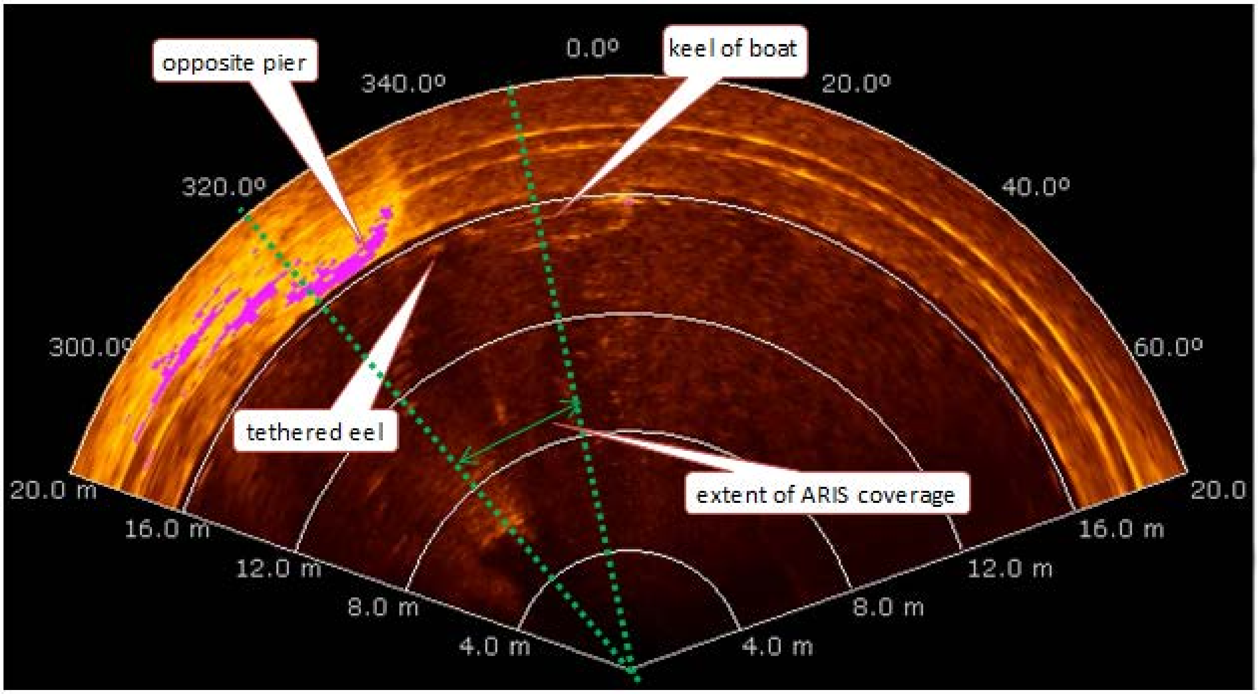

Figure 4-14
Tethered eel release - features that can be seen in an M3 video clip and the approximate extent of coverage shown in the corresponding ARIS file.

White Paper Investigation of the Potential Use of Sound to Guide Outmigrating American Eels Near Iroquois Dam and in the Beauharnois Power Canal on the St. Lawrence River

While there is consensus within the EPRC that light arrays are likely the best means to guide and deter eel movement, the use of sound may hold promise in augmenting the effects of a light array. Following the initial, positive results of the laboratory study, this project produced a white paper updating the findings of the Versar (2009) report on the use of sound to affect the movements of outmigrating silver eels. The project reviewed recent published research on the use of sound for guiding outmigrating eels, material from unpublished reports, and web sites, and acquired additional information through interviews with researchers and other topic experts.

The literature review revealed few new publications on sound detection and behavioral responses to sound in eels since 2008, and none of these provide insight into how sound might be used to affect the behavior of outmigrating silver eels. It is clear, however, that infrasound is not likely to be a viable approach (at least, as it has been used previously) to affect eels. At the same time, new understanding of sound detection by fishes (including eels) demonstrates that since eels are sensitive to particle motion, and particle motion is especially important to all fishes in enabling them to detect and respond in a directional way to a sound source, it is critical that any sounds presented to eels to guide their movements should generate high levels of particle motion. In shallow water, including rivers, this may best be achieved through the generation of sound waves through the substrate and at the substrate-water interface.

The white paper also discusses the types of focused research efforts on sound that would be required prior to developing and implementing an acoustic guidance system on the Upper St.

Lawrence River. Major gaps in current understanding are identified including (but not limited to) those related to the hearing ability of American eels, their behavioral responses to sound in the wild, knowledge of the ambient acoustic environment, and sound propagation in the Upper St. Lawrence River.

The white paper includes a series of research recommendations that focus on obtaining the necessary data to decide whether sound is a suitable tool for affecting eel behavior. Research is proposed to fill the information gaps identified in the white paper.

The authors of the white paper conclude that sound, alone, is unlikely to be a suitable stimulus for affecting the behavior of outmigrating American eels due to the size of the St. Lawrence River and the technological limitations of producing sufficiently high sound levels to be detected by outmigrating eels. The authors suggest, however, that a possible approach would include sound (both sound pressure and particle motion, along with other stimuli (e.g., lights), in a multimodal approach to influence behavior.

Behavioral Responses of American and European Silver Eels (*Anguilla rostrate and A. anguilla*) to Electric Fields Under Both Static and Flowing Water Conditions

Despite the lack of strong or consistent results in the previous electrical guidance study, additional research on this topic was warranted because of the known response of eels and other fish to electrical fields. The inconsistent results from the prior study highlighted the need for baseline information, which this study was designed to address. In addition to the potential for guiding outmigrating eels, narcosis (paralysis) of eels in the fast-flowing water of the St. Lawrence River may facilitate their collection once they have been guided to a collection point.

This laboratory experimental study had two parts:

- Determine the threshold field strengths yielding (1) no response, (2) startle, (3) loss of orientation, and (4) paralysis in silver eels for three different waveform types under static water conditions[9]
- Apply the threshold field strengths for startle and paralysis obtained in the prior set of experiments to test electricity as a deterrent under two flow regimes and two field strengths (mean startle and mean paralysis). This set of experiments recorded the same behaviors as the first set, but also recorded acceleration, switch in orientation, and rejection. Additionally, approach type (passive vs active) and passage type (passive vs active) were recorded.

Behavioral responses under static water conditions appeared at distinct field strengths (Figure 4-15). There was no significant difference in startle or loss of orientation thresholds across waveforms. Waveform, however, did affect the mean field strength threshold for paralysis. Mean threshold field strength producing paralysis was lower for the square wave, 10 Hz, 10% duty cycle waveform than for the square wave and pulsed waveforms at 2 Hs and 20% duty cycle (Figure 4-15). There was no relationship between body length or weight and the threshold field strengths for the three behaviors.

[9] This part of the project was first conducted with American eels at the USGS Conte Anadromous Fish Research Laboratory. The work was subsequently replicated at the University of Southampton. Results presented here are for the Southampton experiments.

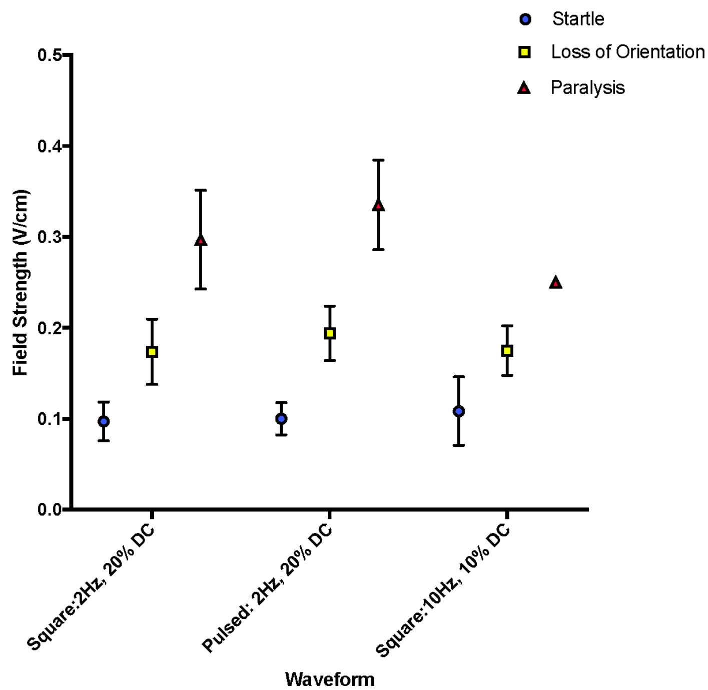

Figure 4-15
Mean threshold field strengths ±S.D. for the three behavioral responses (startle, loss of orientation, and paralysis) under three waveform types. Static water conditions.

Behavioral responses were tested at two field strengths under flowing water conditions: (1) mean startle field strength under static conditions and (2) mean paralysis field strength under static conditions, and under two flow regimes: 0.5 m/s and 1.0 m/s (1.6 ft/s and 3.3 ft./s). There were no differences in behavioral responses between the two field strengths (Figure 4-16), but there was a statistically significant effect of flow velocity on behavioral response. In the low velocity condition, 74% of the eels exhibited a response, whereas in the high velocity condition only 31.2% of the eels responded to the electrical field. Specifically, the incidence of rejection declined significantly from 32.5% under the low velocity condition to 4.0% at the higher velocity (Figure 4-17). Upon first encountering the electrical field under high flow conditions, 87.7% of eels either exhibited no response (67.5%) or acceleration (20.2%). Orientation switching behavior was observed in 8.3% of the eels.

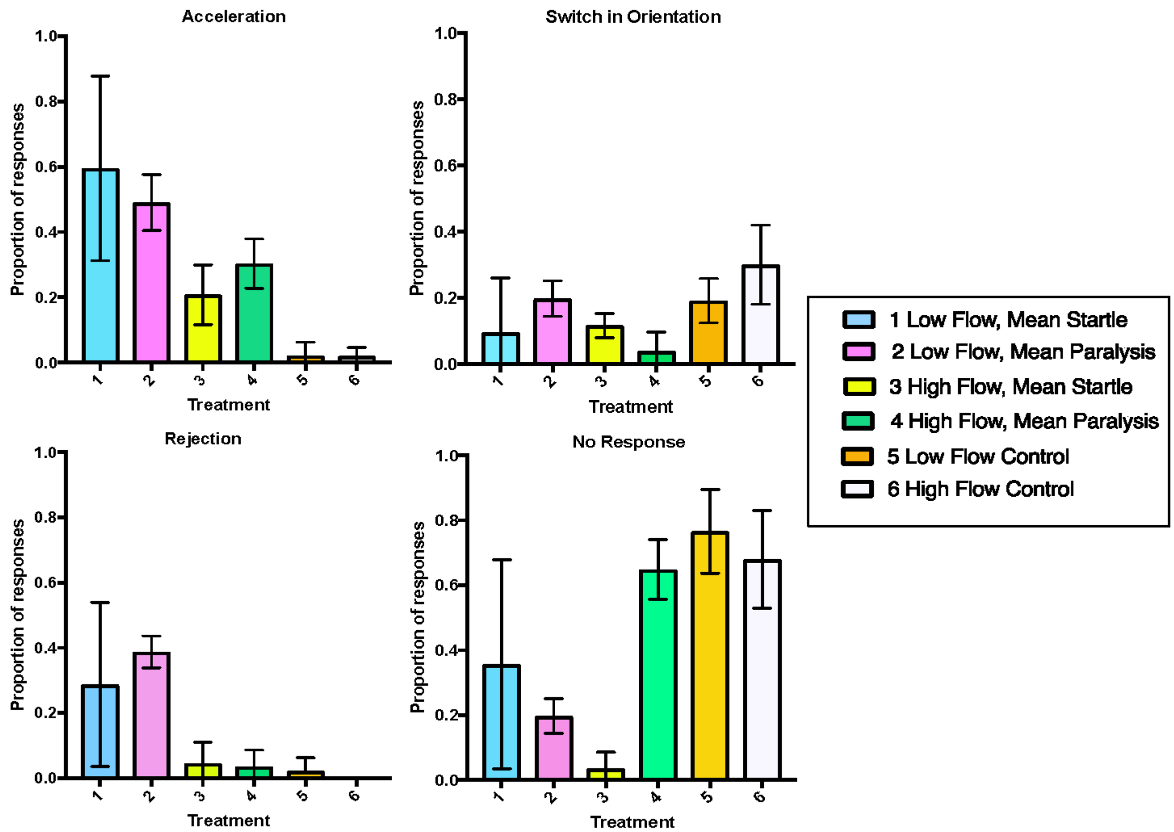

Figure 4-16
The proportion of responses observed for the four behavioral response types across the six treatments including the two control treatments. Error bars are ± 1 S.D.

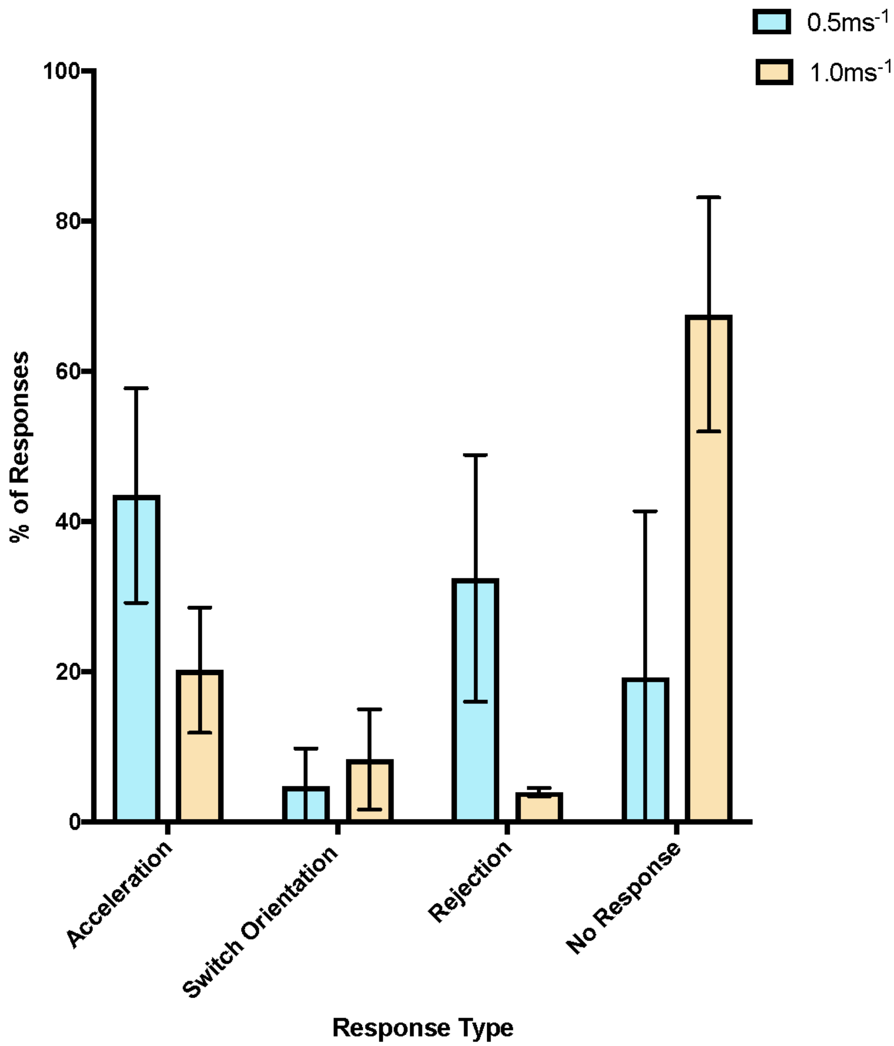

Figure 4-17
The effect of flow velocity, 0.5 m/s and 1.0 m/s on the percentage of four different responses observed. Flow velocity was significant in predicting behavioral response observed (LMM: x2= 10.3, p=0.001). The observed incidence of rejection was also significantly predicted by flow velocity (GZLMM: z=-2.52, p=0.012). Error bars represent ± 1 S.D.

The effects of water conductivity types on eel behavioral response thresholds to pulsed DC waveform were also investigated, using large American eels. Experiments indicated:

- Threshold voltage decreases with increasing conductivity
- Yellow eel thresholds are similar to those for silver eels
- Threshold values (at least for paralysis) are comparable to those of other freshwater fishes

Otolith Aging of Eels Captured in the Kamouraska, Quebec Eel Fishery

In the fall of 2014, 674 silver eels were collected in the St. Lawrence estuary fishery for conducting laboratory behavioral experiments related to downstream migration. Once the study was completed, otoliths were recovered from this large sample of euthanized eels to assess age structure of these seaward migrating individuals. The sample was composed exclusively of large maturing females with body length varying from 607 to 1130 mm (mean= 870.1 mm, SD= 77.2) (24.7 to 44.5 inches (mean 34.3 inches, SD=3.04)). Eels originating from stocking accounted for 1.8% of the sample. Age determination was successfully performed on 626 eels and age ranged from 7 to 36 years. Mean age was estimated at 12.7 y (SD= 3.3) and age structure conformed to a normal distribution slightly skewed towards younger ages. Mean annual growth rate ranged from 22.5 to 133.6 mm/y (0.89 to 5.26 inches/y) for a mean value of 72.2 mm/y (SD= 16.1) (2.84 inches/y; SD=0.634). While size at silvering did not change significantly from previous studies, mean age decreased by more than 7 years and growth rate increased by approximately 50%. This trend was confirmed by additional sampling in 2015 and 2016, although the number of eels sampled on these occasions was lower. Modifications in age structure occurred simultaneously with recruitment decline in formerly used growth habitat. The inverse relationship between growth rate and eel abundance may be an explanation for these shifts in population parameters.

Acoustic Tracking of Eel Near Iroquois Water Control Dam and in Beauharnois Power Canal

Acoustic telemetry tracking studies of American eels in Lake Ontario by the OMNRF stimulated interest in leveraging that effort to investigate eel behavior and migration pathways near IWCD and in Beauharnois Power Canal. Over the last several years deployment of acoustic receiver arrays has been expanded and refined in these reaches, and the number of eels tagged has been augmented to increase the number of migrant eels tracked through the arrays. This project is a collaborative effort comprised of in-kind contributions from several organizations represented on the EPRC Technical Committee. The EPRC has contributed to this collaboration by providing a venue for coordination among project participants and financial support for tag purchases and data analysis by the equipment vendor.

The project adds to the existing information on the diel and seasonal timing of outmigration and it provides unique data on eel migration behavior and corridors in the reaches of interest for deployment of guidance and collection technologies. The resulting information can inform decisions regarding the spatial extent and location of experimental and prototype systems.

The receiver array and individual eel tracks obtained near IWCD in 2017 are depicted in Figure 4-18. Eel tracks appear to be biased toward the U.S. (right) side of the river. Gate-specific passage depicted in the figure is projected from the last location fix for each fish. The distribution of eel passage among the 32 dam gates is significantly skewed toward the U.S. shore, with 66% of the eels (33/50) passing through 44% (14/32) of the gates.

Preliminary results from acoustic tracking in Beauharnois Canal near Saint-Louis-de-Gonzague Bridge indicate approximately 80% of the eels used the center third of the canal (indicated by the green line; Figure 4-19), avoiding the Seaway channel located on the northern shore and the shallower waters of the southern shore. Successive location fixes for individual eels are indicated by like colored dots in Figure 4-19.

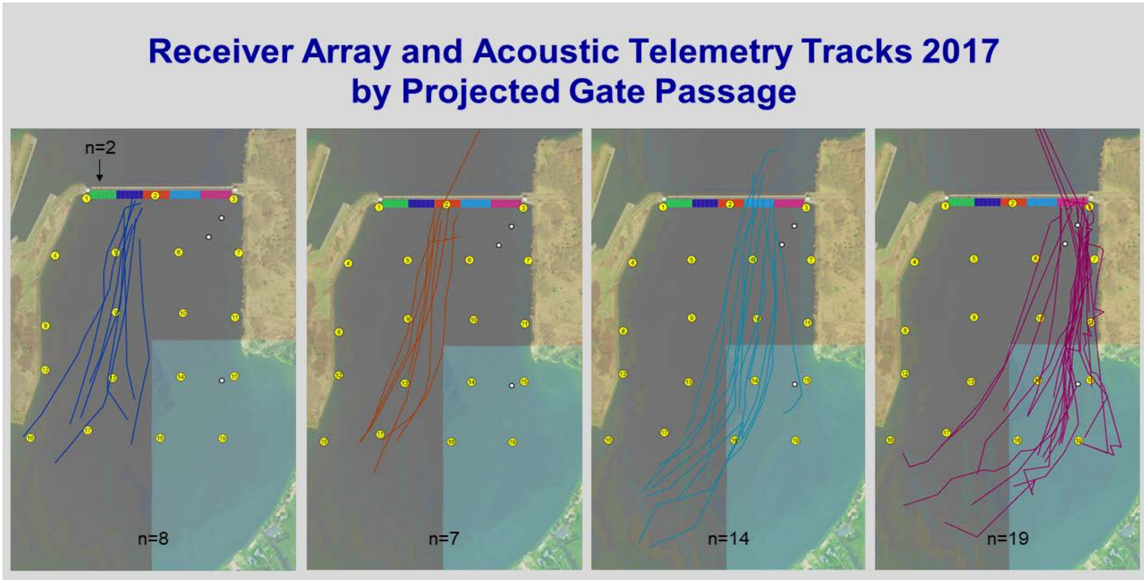

Figure 4-18
Receiver locations (yellow dots) and eel tracks grouped by apparent or projected passage location. N is the number of eels passing the dam via the indicated section of the dam. The two eels projected to pass via one of the six gates closest to the Canadian shore are not shown in this figure.

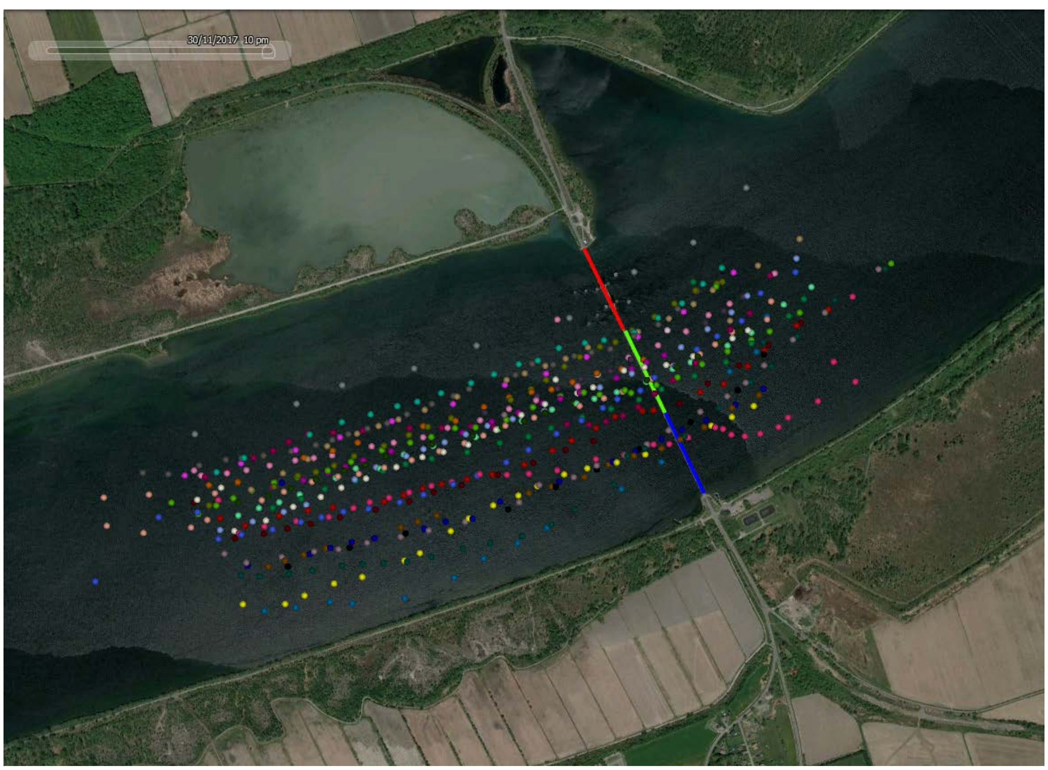

Figure 4-19
Eel tracks obtained by acoustic telemetry near Saint-Louis-de-Gonzague Bridge, QC. Successive location fixes from individual eels are indicated by like-colored dots. The north, central, and south thirds of the bridge are indicated by a red, green, and blue line segment, respectively.

Data collection and analysis related to this project are ongoing.

Summary and Synthesis of EPRC Research

The EPRC provides an institutional framework and the technical foundation for a program of adaptive mitigation to progressively reduce eel turbine mortality. Continuation of the EPRC collaborative R&D model can facilitate increasingly effective mitigation in the face of significant scientific and technological uncertainty. Research conducted by the EPRC reinforces the impression that underwater light should be central to eel guidance systems in the St. Lawrence River. LED technology would reduce both capital and O&M costs and improve reliability and operational flexibility and control compared to other technologies. While the Flow Velocity Enhancement System was not effective in guiding eels when tested in the laboratory flume, other studies with eels (Piper *et al.* 2013, Piper *et al.* 2015, Piper *et al.* 2017) suggest that flow-field manipulation in the near field of a collection device could facilitate entry. Similarly, electricity was not found to be effective for guiding or repelling eels in laboratory flume experiments with water velocities comparable to the St. Lawrence River, but potentially could be effective in reducing or eliminating rejection at the entry to a collection device.

Low frequency sound may prove useful as a secondary guidance or deterrence stimulus, but its use would be highly experimental in the near term. The Alden study (EPRI 2016) provides some insight into acoustic stimuli to test in the field.

Additional laboratory studies are likely to be of limited value for investigating taxis for eel guidance. The behavioral context and spatial scale of laboratory flumes are sufficiently distinct from conditions in a large river such as the St. Lawrence that their utility for future studies may be limited to developing fundamental information on physiological and sensory biology.

Acoustic telemetry results are incrementally providing valuable information on the diel and seasonal timing of eel migration in the St. Lawrence River, and yielding novel information on the pathways migrating eels follow as they traverse reaches where they could be guided to collection points. Much useful information can be gleaned from additional collection and analysis of acoustic telemetry data. Existing acoustic telemetry information suggests that guidance likely will not be needed across the entire river cross-section. Additional data collection and analysis can inform decisions regarding the location and required spatial extent of guidance and collection structures.

Output from the CFD models for Beauharnois Canal and the vicinity of IWCD indicate guidance will be needed in water velocities in the range of approximately 0.6 – 1.5 m/s (2.0 - 4.9 ft/s). The CFD models will prove to be extremely valuable for inferring eel behavioral responses to flow field characteristics from acoustic telemetry data, and for designing and predicting the effects of guidance and collection structures.

5 NEXT STEPS

Concern for the population status of American eel and the other temperate eels (European eel, *Anguilla anguilla* and Japanese eel, *A. japonica*) remains high. Several factors may contribute to the decline in abundance since the 1970s and 1980s. These factors include barriers to migration, habitat loss and alteration, hydro turbine mortality, ocean conditions, overfishing, parasitism, and pollution (Haro et al. 2000, Drouineau et al. 2018). Eel escapement from Lake Ontario can be expected to decline sharply in the next several years due to cumulative escapement of the finite cohorts of stocked eels and the prior decline in the number of wild eels recruiting to Lake Ontario. This compounds the urgency (both conservation and scientific) to develop means to mitigate turbine mortality. A sharp drop off in eel abundance amplifies the biological significance of turbine mortality and it reduces the number of fish available to serve as research subjects for testing and optimizing mitigation technologies. Consequently, it will be important to rapidly transition from adaptive, exploratory R&D to adaptive mitigation and management utilizing early stage guidance, collection, and monitoring technologies to support a trap and transport program. This can be accomplished by rapid, iterative design, deployment, and testing of guidance and collection technologies. This approach would be initiated with design and deployment of a subscale, prototype guidance and collection structure or structures utilizing light and perhaps low frequency sound. This adaptive mitigation approach will enhance mitigation effectiveness over the near term and develop more effective technology over the mid- to long term.

Additional acoustic telemetry will be useful for informing site selection and monitoring technology effectiveness. Near-field monitoring of the collection device (such as stow net or modular inclined screen) can inform decisions regarding need for and means of improving capture efficiency of guided eels. Technologies/stimuli to be considered for application in the near-field of a collection device are electricity and the FVES.

Design and deployment of subscale prototypes will require engagement among river regulatory agencies and facility operators, prior to full scale deployment.

Near-field monitoring of guidance and collection structures will likely benefit from multi-beam imaging sonar (e.g., DIDSON, ARIS, BlueView). EPRI's ongoing, U.S. Department of Energy-funded project to develop machine learning tools for automating eel identification and tracking in imaging sonar data will improve the timeliness and cost-effectiveness of sonar monitoring.

Building upon existing collaborations with University of Southampton, U.S. Army Corps of Engineers – Engineer Research and Development Center, Pacific Northwest National Lab, Carleton University, and other technical resources cultivated during the first term of the EPRC will promote cost-effective and timely execution of the adaptive mitigation program.

Siting and design of a subscale experimental guidance and collection structure can begin in the near-term, utilizing the R&D results produced by the EPRC.

6 CONCLUSION

Research conducted by the EPRC reinforces the impression that underwater light should be central to eel guidance systems in the St. Lawrence River. LED technology would reduce both capital and O&M costs and improve reliability and operational flexibility and control compared to other technologies. While the Flow Velocity Enhancement System was not effective in guiding eels when tested in the laboratory flume, other studies with eels (Piper et al. 2013, Piper et al. 2015, Piper et al. 2017) suggest that flow field manipulation in the near field of a collection device could facilitate entry and capture. Similarly, electricity was not found to be effective for guiding or repelling eels in laboratory flume experiments with water velocities comparable to the St. Lawrence River, but potentially could be effective in reducing or eliminating rejection at the entry to a collection device.

Low frequency sound may prove useful as a secondary guidance or deterrence stimulus, but its use would be highly experimental in the near term. The experiments with sound conducted by the EPRC provide some insight into acoustic stimuli to test in the field.

Much useful information can be gleaned from additional collection and analysis of acoustic telemetry data. Existing acoustic telemetry information suggests that guidance likely will not be needed across the entire river cross-section. Additional data collection and analysis can inform decisions regarding the location and required spatial extent of guidance and collection structures.

An anticipated near-term drop-off in eel escapement from Lake Ontario creates urgency to develop guidance and collection technologies in support of trap and transport to mitigate turbine mortality of outmigrating silver eels. This requires rapid transition from the exploratory, adaptive R&D program of the first EPRC term to a fast-paced adaptive mitigation program built on science and technology R&D. Technical knowledge gained and institutional capacity developed by the EPRC during the first term sets the stage for rapid and technically sound implementation of an adaptive mitigation program to design, deploy, and optimize a sub-scale light-based eel guidance and collection structure than will enhance trap and transport capacity in the Upper St. Lawrence River and reduce turbine mortality without adversely impacting power production.

7
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A

PRELIMINARY ALTERNATIVES IDENTIFIED FOR DECISION ANALYSIS BY THE CANADIAN EEL WORKING GROUP (PARNELL ET AL. 2005B)

Replacement of turbines at the R.H. Saunders and Beauharnois Generating Stations

- Replace all 16 propeller units at Saunders with Alden Research design turbines
- Replace all 10 propeller units and 26 Francis units at Beauharnois with Alden research design turbines

Physical diversion of eels to station by-pass

- Three alternative configurations of 15-, 30-, or 45-degree V-shaped angled bar rack with 3.5 cm spacing diversion structures at the R.H. Saunders hydroelectric dam that would divert eels to ice sluices near the north shore and at the middle of the dam
- Three alternative configurations of linear diversion structures angled across the approach canal at the Beauharnois hydroelectric dam that would divert eels to a spillway near the navigation channel

Operational shutdown of turbine units with spilling of water to pass eels around the station

- At both R.H. Saunders and the Beauharnois hydroelectric dams: shutdown of all units for 8 hours during the night time from June 15 to September 30
- At both the R.H. Saunders and the Beauharnois hydroelectric dams: shutdown of all units for 24 hours per day from June 15 to September 30

Trap eels above Saunders and Beauharnois GS during their downstream migration and relocate them below the Beauharnois hydroelectric dam

- Concentrate eels at the Iroquois Control Structure above R.H. Saunders using a diversion system and capture eels using stow nets or a trap
- Have commercial fishers capture eels in Lake Ontario
- Have commercial fishers capture eels in Lake St. Francis

Increase access to upstream rearing habitat

- Implement improvements at the R.H. Saunders hydroelectric dam near the existing fish ladder to prevent entrainment into the turbines of eels migrating upstream
- Remove one or more smaller dams on tributaries of the St. Lawrence River – a specific alternative was not identified

- Note: a potential alternative of preventing upstream access by eels, discussed previously was dropped from further consideration. This alternative might be considered at a later time if the situation regarding the American eel becomes significantly worse than at present as an option of last resort but with regard to habitat limitation does not make sense at this time.

Implement fishery controls to reduce fishing mortality on eels in the St. Lawrence River

- 50% reduction in fishing mortality rates on each of Lake St. Francis, Lake St. Pierre, and in the St. Lawrence River estuary
- 100% reduction in fishing mortality rates on each of Lake St. Francis, Lake St. Pierre, and in the St. Lawrence River estuary

Stocking eels into available rearing habitat

- Five alternatives (a subset of the stocking alternatives discussed previously) were identified for further consideration:

Stock	From	To
Elvers	Maritimes	Lake Ontario
Yellow eels	Lake St. Pierre	Lake Ontario
Yellow eels	Lake St. Francis	Lake Ontario
Elvers	Maritimes	Ottawa River
Yellow eels	Lake St. Pierre	
Elvers	Maritimes	Below the Beauharnois dam

Further work by a subcommittee is needed to fully define these alternatives.

Habitat enhancement

- Although a conceptually attractive alternative, there is currently insufficient understanding of precisely what is needed for this alternative and it was dropped from further consideration. It might be considered at a later time as research efforts reveal more information.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com