NSERC'S HYDRONET: CONSOLIDATING FIVE YEARS OF RESEARCH DESIGNED TO DEVELOP KNOWLEDGE AND TOOLS ABOUT THE EFFECTS OF HYDROELECTRIC FACILITIES ON AQUATIC ECOSYSTEMS

Figure 1. HydroNet Logo

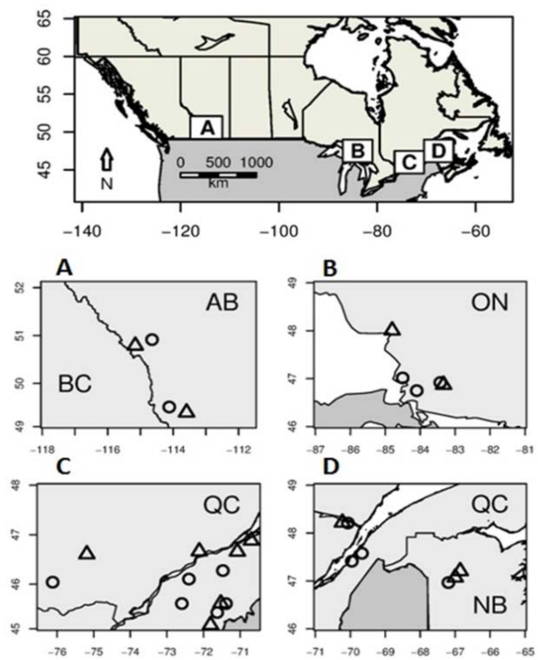

Figure 2. Map of the HydroNet river study areas showing the 15 unregulated rivers (circles) and 13 regulated rivers (triangles) distributed across Canada (from Boisclair et al. 2016a).

Context:

NSERC HydroNet (HydroNet) was a national research network whose overall mission was to provide government and industry with the knowledge and tools that will contribute to the sustainable development of hydropower in Canada (please see hydronet website for additional information). HydroNet recently completed its final year of a 5-year mandate (2010-2014). The research activities of HydroNet were developed based on consultations with numerous hydropower companies and government agencies to identify what research activities would provide the most value to these organisations. At the time of HydroNet's development, it became clear that the implementation of the principle of "no net loss of the productive capacity of fish habitats", which was central to the previous Habitat Management Policy of DFO, was hampered by the difficulty of estimating and predicting the productive capacity of fish habitats (PCFH). As such, the development of new knowledge and tools to support the implementation of the principle of "no net loss" formed the central axis of the research mission, and the production of metrics of PCFH was highlighted as the main focus. With the amendments to the Fisheries Act (FA) being *introduced in June 2012, the focus of the regulatory process moved from PCFH to fisheries productivity, but the principle of 'balancing losses and gains' has been maintained. The metrics of PCFH being developed within HydroNet were always biologically focussed and therefore remain highly applicable to implementing the Fisheries Protection Provisions (FPP) of the new FA.*

HydroNet undertook and completed 21 projects under a Strategic Network Grant focussing on PCFH of riverine environments below hydropower dams (supported by Fisheries and Oceans Canada), and two projects under complementary Collaborative Research and Development Grants that included 1) Mesoscale Modeling of the Productive Capacity of Fish Habitats in Reservoirs with Manitoba Hydro, and 2) Predicting the Entrainment Risk of Fish in Hydropower Reservoirs with BC Hydro.

With the substantial financial, intellectual and managerial contributions by DFO and industry towards achieving the objectives of NSERC's HydroNet, it is important that the new knowledge and tools gained about the effects of hydroelectric facilities on aquatic ecosystem be disseminated in a concise and transparent manner. The Canadian Science Advisory Secretariat process provides an ideal environment to consolidate and peer review the knowledge gained from HydroNet's substantial research efforts. The intention is to use this science advice to help achieve HydroNet's general objective: to develop science-based practical solutions that will provide government and industry resource managers with new tools to assess, mitigate, and offset potential impacts of hydropower generation on aquatic ecosystems.

This Science Advisory Report is from the national peer review meeting of September 15-17, 2015 on the NSERC's HydroNet: consolidating five years of research designed to develop knowledge and tools about the effects of hydroelectric facilities on aquatic ecosystems. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- This Science Advisory Report (SAR) provides advice to policy and management arising from five years of research exploring how to best estimate and predict various metrics of fisheries productivity on aquatic systems impacted by hydropower production, to aid in implementing the Fisheries Protection Provisions (FPP) of the *Fisheries Act (2012)*. Research documents reviewed at the meeting consolidated research under four themes, and the scientific advice provided is organized accordingly:
    1. Key physical and chemical drivers of fisheries productivity in various Canadian regions (Lapointe et al. 2015). This theme included presentation of a useful remote sensing tool for quantifying fish habitat that will be available in the proceedings of the workshop, with more detail available in Hugue et al, 2015.
    2. Modelling the effects of chemical and physical drivers on fisheries productivity metrics across rivers of varying hydrological regimes (Boisclair et al. 2016a);
    3. Mesoscale modeling of fisheries productivity metrics in reservoirs (Boisclair et al. 2016b); and
    4. Upstream passage and entrainment of fish at hydropower dams (Gutowsky et al. 2015).
- HydroNet developed a series of empirical models linking fish productivity metrics to environmental conditions. As with any empirical model, these models are most applicable to systems with similar environmental and/or biological conditions as found in the HydroNet systems, however, the general relationships observed may be applicable on a broader basis.

Physical and Chemical Drivers

- The alteration of flow regimes was assessed with a useful office-based approach that uses readily available hydrometric data sets. It can serve as a complementary analysis to indicators of hydrological alteration (or as a substitute where insufficient historical data are

available). The flow regime of regulated rivers can be placed in a regional context by quantifying the degree of anomaly of various aspects of their flow regime relative to regimes of unregulated systems (meaning systems unregulated by a dam, see Glossary in the Appendix) and other regulated systems of broadly similar watershed characteristics located in the same region.

- The degree of flow anomaly in relation to unregulated systems and other regulated systems could help guide the degree of study required, or help prioritize systems for study that are to be regulated.
- An analysis of thermal data from paired regulated vs. unregulated rivers demonstrated important differences in the thermal regimes of storage and peaking systems (systems with reservoirs) vs. unregulated systems.
- Various statistical tools to describe the thermal regime of rivers were developed and compared, and advice is provided regarding the selection of thermal models and their use in management decisions. Given that collecting temperature data is relatively inexpensive and straightforward, and given the biological importance of temperature, the collection of temperature data should be considered for incorporation into monitoring programs.
- An analysis of the literature (mostly North American systems) revealed strong relationships between total phosphorus and fish biomass that were regionally dependent. However, if species richness is factored in, regional differences no longer existed. Including mean depth improved models further, and there was no difference between lakes and reservoirs.
- The literature-derived nutrient-fish biomass model for rivers and streams had a different slope than for lacustrine systems, but there was no difference between regulated and unregulated rivers. However, a paired regulated-unregulated analysis was not conducted and this question should be explored further.
- A method that couples current sub-meter resolution satellite imagery with *in situ* depth transects to create low cost maps of water depth (and velocity if discharge is known) for very long river segments (many tens of km long) was developed. Application and cautions for this remote sensing method are briefly described below in the Analysis section.

Biological Drivers

- Fisheries productivity metrics (density, biomass, species richness) in rivers located downstream of run-of-the-river facilities tend to be similar to unregulated rivers. Rivers located downstream of storage dams had 33% higher biomass but 1.7% lower species richness than predicted for an unregulated river. Rivers located downstream of peaking facilities have 39%, 48%, and 13% lower fish densities, biomass, and species richness, respectively, than that predicted for unregulated rivers.
- A number of metrics of flow regimes at the analysed peaking facilities were highly anomalous relative to the suite of unregulated rivers studied in HydroNet. Thus a peaking facility that is less strongly anomalous relative to unregulated rivers may not have the same negative effect on fisheries productivity metrics. An among-river comparison of a multidimensional index of flow anomaly (derived from 105 flow metrics) hinted that there may be a threshold beyond which a significant negative effect on biota occurs. Further research should be conducted to confirm whether such a threshold exists.
- Results from projects aimed at developing fish-environment relationships for a variety of fisheries productivity metrics, at a range of organismal scales (total fish community, guild of species, species, combinations of species and size classes), spatial scales (site, habitat type, river segment), and using multiple modelling techniques (multiple regression, artificial neural networks, phylogenetic habitat modelling) were presented.

- The models developed identified key environmental drivers in rivers. Under the correct circumstances, these models could be used to predict the future state of fisheries productivity metrics (different organismal scales) in rivers (different spatial scales). These tools may be used to predict the effects, to identify mitigation measures, and to assess residual effects of hydropower on fisheries productivity metrics in rivers.

Mesoscale Modelling in Reservoirs

- The reservoir work was largely a methodological study with the objective of testing a variety of methods to determine the most appropriate for sampling reservoirs in monitoring programs.
- Hydroacoustic methods were evaluated as a viable sampling method for the pelagic zone (> 3m depth) in reservoirs. The results on fish size classes fit theoretical expectations and were found to be consistent and repeatable.
- Several different methods (boat electrofishing, seining, and gill netting) were explored as viable sampling methods for the littoral zone (< 3m depth). Each of these methods has benefits and limitations and the research document contains many recommendations on what, when, and how sampling should be conducted in the littoral zone in a reservoir.
- Fish-environment relationships were derived when possible, however, there were large differences in relationships between years suggesting that modelling and validating such relationships requires multiple years of sampling.
- A combination of local (e.g., macrophyte coverage) and contextual (e.g., distance to large tributaries) habitat variables appeared useful in explaining variation in fisheries productivity metrics in the littoral zone of reservoirs.

Fish Passage

- Any new fishways should be evaluated for fish attraction and passage efficiency (see Glossary for definitions). From an ecological perspective, providing fish passage minimizes impacts where the dam is altering fish passage. However, the need for fish passage should be evaluated on a case-by-case basis using a community-based approach including considerations of the habitat availability after project development.
- Fishway evaluation should include biological (e.g. attraction, full passage, etc.) and hydraulic (e.g., velocity, turbulence) data collection and associated modeling using a multidisciplinary team.
- The evaluation of fish passage success through a fishway should be based on site-specific, *a-priori*, biologically based targets linked to fisheries management or conservation objectives. Simply monitoring a complete passage of fish through the fishway (i.e., capture in a trap at the top) is not sufficient to evaluate passage success, since there is a need to know the number of fish seeking and attempting passage to establish a success rate. Ideally such information is then considered in the context of the population biology of target species/populations.
- Entrainment risk assessments using desktop methods represent a first step in evaluating the need for, and prioritization of, more detailed studies.
- Modelling the physical environment of the forebay (including flow field dynamics and water temperature) is critical to understand factors leading to entrainment. Thus, entrainment is best evaluated by a multidisciplinary team including engineers and biologists.
- Entrainment must be considered on a species-specific and life-stage basis, covering all relevant spatial (fine and coarse) and temporal (e.g., diel, seasonal) scales.

INTRODUCTION

The Natural Sciences and Engineering Research Council of Canada (NSERC) HydroNet was a national research network whose overall mission was to provide government and industry with the knowledge and tools that will contribute to the sustainable development of hydropower in Canada (please see the NSERC HydroNet Network's web site for additional information). HydroNet recently completed its final year of a 5-year mandate (2010-2014). The research activities of HydroNet were developed based on consultations with numerous hydropower companies and government agencies to identify what research activities would provide the most value to these organizations. The research platform of HydroNet consisted of a series of projects that focused on two themes:

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

The theme “modeling of fisheries productivity in rivers” included projects on productivity of fisheries and its chemical, physical, and biological drivers. The theme “modeling of fish-habitat interactions in reservoirs” comprised projects on the mesoscale modeling of fisheries productivity metrics and on the prediction of fishway passage and fish entrainment risk.

At its inception the research conducted within NSERC HydroNet was directly coupled to the regulatory framework. At the time of HydroNet’s development, it became clear that the implementation of the principle of “no net loss of the productive capacity of fish habitats”, which was central to the previous *Habitat Management Policy* of Fisheries and Oceans Canada (DFO 1986), was hampered by the difficulty of estimating and predicting the productive capacity of fish habitats (PCFH). As such, the development of new knowledge and tools to support the implementation of the principle of “no net loss” formed the central axis of the research mission, and the production of metrics of PCFH was highlighted as the main focus. With the amendments to the *Fisheries Act* (FA) being introduced in June 2012, the focus of the regulatory process moved from PCFH to fisheries productivity, but the principle of ‘balancing losses and gains’ has been maintained. The metrics of PCFH being developed within HydroNet were always biologically focused and therefore remain highly applicable to implementing the Fisheries Protection Provisions (FPP).

With the substantial financial, intellectual, and managerial contributions by DFO and industry towards achieving the objectives of NSERC’s HydroNet, it is important that the new knowledge and tools gained about the effects of hydroelectric facilities on aquatic ecosystem be disseminated in a concise and transparent manner. The following Science Advisory Report presents a summary of the findings and discusses research gaps.

To consolidate and integrate knowledge and tools gained from five years of HydroNet Research activities were described under five themes:

a. Physical and chemical drivers (flow, nutrients, and temperature) of fisheries productivity across rivers of varying hydrological regimes: lessons learned from NSERC’s HydroNet 2010-2015 (Lapointe et al. 2015)
b. Biological drivers of fisheries productivity across rivers of varying hydrological regimes: lessons learned from NSERC’s HydroNet 2010-2015 (Boisclair et al. 2016a).
c. Mesoscale modeling of fisheries productivity in a reservoir: lessons learned from NSERC’s HydroNet 2010-2015 (Boisclair et al. 2016b).
d. Downstream entrainment risk and upstream fish passage at dams: lessons learned from NSERC’s HydroNet 2010-15 (Gutowsky et al. 2015).

e. Remote sensing of riverine geomorphology as a tool for the assessment of riverine physical habitat.

The 5th theme was covered via a presentation at the meeting only and is not summarized in a research document. Meeting participants agreed on key points arising from the remote sensing presentation to be included in the SAR and they can be found under the ‘Physical and Chemical Drivers’ section (for more detail on the approach, see Hugue et al 2015).

ANALYSIS

This SAR describes the development of a wide range of statistical models, i.e., fitting relationships between the response and the explanatory variables. Any model developed by HydroNet using data collected by empirical sampling applies only to water bodies with characteristics encompassed by the suite of systems used in their development. For the 28 rivers studied as part of HydroNet, the relatively narrow ranges of environmental conditions are shown in Table 1. Similarly, the reservoir projects involved single systems with unique characteristics. Extrapolation of these results to systems with characteristics outside of this range of environmental conditions is not recommended in the absence of further research. Despite this limitation, some of the conceptual contributions of this study may be applicable on a broader basis (e.g., the existence of general relationships between fisheries productivity metrics and environmental conditions; the possibility of identifying a few key flow and thermal indices out of hundreds of potential indices). Literature-derived models presented may also have broader applicability as their development was based on hundreds of systems across a broad geographic area.

However, any model has to be calibrated, tested, and validated before it can be used effectively. Some of this was achieved via cross-validation, or the process of removing observations from the dataset, calibrating models with the remaining observations, and predicting the removed observations from models that are naive about the removed observations. By comparing the observed values with predicted ones, R^2_{CV}, a metric of the model's predictive power, can be calculated. Before applying models to a broad range of new rivers, it would be prudent to first validate them in at least one river, and ideally in many rivers. In this sense, validation results from collecting data from new rivers, totally independent of the present study, in order to assess how the models can accurately predict new systems. New data should then be incorporated into models to improve their capacity to explain and predict an even wider range of rivers as part of an adaptive modelling approach. Given the fact that a number of existing and proposed hydroelectric facilities in Canada exist on large rivers, it is important to upscale to larger systems to broaden the applicability of the results.

Table 1. Range of characteristics at time of fish sampling encompassed by the 28 rivers (regulated and unregulated) studied as part of Themes 1-2 of HydroNet. Additional detail on the characteristics of each river can be found in Boisclair et al. 2016a, Table 1.

	Minimum	**Maximum**	**Overall Mean**
Mean wetted width at low sampling flows (m)	14	116	47
Mean depth at low sampling flows (cm)	28	58	40
Mean flow rate during sampling ($m^3 \cdot s^{-1}$)	2.5	66.5	18.5
Mean flow velocity ($m \cdot s^{-1}$)	0.07	0.6	0.3
D50 (cm)	0.05	15.5	5.2
Species richness	6	25	15.7

	Minimum	Maximum	Overall Mean
Macrophyte cover (%)	0	21	2.2
Water transparency (m)	0.6	12	3.4
Total phosphorus ($\mu g \cdot L^{-1}$)	0.5	14.7	7.1

Both flow and thermal data should be monitored on a regular basis (including both unregulated rivers that serve as reference as well as sites in regulated reaches). Despite the potential to create 100s of flow and thermal indices from such data, redundancy among indices reduces the required number considerably. For example, a relatively small number of flow indices (11) was found to explain a significant portion of the information comprised among 105 flow indices (~61% to 91%), and only three thermal indices appear particularly important in explaining variations in fish guild density and biomass (defined in Boisclair et al. 2016a, Table 2). In an analysis relating them to alteration of biotic metrics, the 11 flow indices that contributed the most to the inter-river variability were: MA3 and nML6 (magnitude), FH1 (frequency), DL12 and DH6 (duration), TA2 and TH2 (timing), RA7 and nRA1 (rate of change), and RL2 and MA60 (hourly flows) (Table 2). While flow data are (and should be) regularly collected as part of hydro monitoring programs, thermal indices were significant in most fish-environment relationships, and it is recommended that thermal data should also be collected in all monitoring programs due to its significance.

Table 2. Definition of the 11 flow indices that contributed the most to the inter-river variability for each of the measured flow components. Details of how each index is calculated can be found in Boisclair et al. 2016a, Table 2.

Code	Flow component	Description
MA3	Magnitude	Variability in daily flow
nML6	Magnitude	Mean minimum monthly flows (Jun)
FH1	Frequency	Flood frequency 1 (High flood pulse count–75th percentile)
DL12	Duration	Normalized 7-day annual minimum flow
DH6	Duration	Variability of annual maximum daily average flow
TA2	Timing	Predictability of flow
TH2	Timing	Variability in Julian date of annual maximum
RA7	Rate of Change	Change of flow (falling)
nRA1	Rate of Change	Rise rate
RL2	Hourly	Hourly Flash Index 2 (low flow)
MA60	Hourly	Coefficient of diel variation

Physical and Chemical Drivers

Flow Regime

The evaluation of any new or existing hydropower project in support of a regulatory decision necessarily involves the examination of the degree of flow regime modification, since flow is the primary variable altered by dams. Here, we use the terms flow *alteration* and flow *anomaly* (see Glossary in the Appendix) to clearly distinguish these two useful but complementary approaches to quantify the extent to which a system's flow regime is modified by hydro-power operations. The complementary information given by these two approaches, which are based on different data and answer different questions, are discussed in Lapointe et al. (2015).

When adequate historical (pre-regulation) flow data are available (minimum 20 years), indicators of hydrological alteration (e.g. IHA software) are useful to quantify precise flow regime *alteration* metrics by comparing simulated future hydrographs to pre-dam conditions. As a complementary analysis to indicators of hydrological alteration (or a substitute where insufficient historical data are available) another useful approach was described by Lapointe et al. (2015). The flow regime of regulated rivers can be placed in a regional context by quantifying the degree of *anomaly* of various aspects of their flow regime relative to regimes of unregulated systems and other regulated systems of broadly similar watershed characteristics located in the same region.

To characterize unregulated regimes, daily flow data from geographically proximate unregulated systems with a comparable drainage area (i.e., generally within 50-200% of the regulated watershed area) are required (Water Survey of Canada or other gauge data, with all flows normalized by each system's mean annual flow to account for differences in watershed size). Time series of at least 20 years are ideal. A robust mean and standard deviation for a large set of metrics of flow magnitude, duration, frequency, timing etc. from the set of reference systems is required, thus 10-15 systems should be included in the reference dataset when possible.

The degree of anomaly in relation to proximate unregulated systems and other regulated systems (for example quantified as a Z-score, or standard score that indicates, for each metric studied, how many standard deviations a measure is from the mean of the references, see Glossary) could help guide the degree of study required for the system that is to be regulated. In the absence of a large set of proximate suitable unregulated systems, fewer systems could be used to generate the reference flow metrics, but this should increase the degree of study required commensurate with the increase in the degree of uncertainty associated with the reference flow metrics.

The geographical distance from a particular regulated system that is acceptable to seek reference systems will necessarily increase with the size of the watershed under study (i.e., the larger the system, the greater distance you must go to find appropriate reference systems of the right size). Thus quantification of regime anomalies in this way becomes impractical for sites located along very large rivers, as similarly large watersheds may be separated by thousands of km and thus often have significantly different hydroclimates (precipitation, temperature and thus unregulated runoff regimes).

Temperature

Water temperature is considered one of the primary drivers shaping aquatic communities, and along with flow, is often altered to a large degree by the installation of a dam. Thus, collecting temperature data is highly relevant and useful for monitoring programs. Since collecting temperature data is also relatively inexpensive and straightforward, it should be collected as standard in monitoring programs.

An analysis of paired regulated (peaking, storage, run-of-river) vs. unregulated rivers in Eastern Canada was completed. It was found that run-of-river systems did not differ significantly in their thermal regimes from unregulated rivers, but peaking and storage systems were different in the following ways:

- The peak temperature was often shifted later in the year.
- The magnitude of daily fluctuations was often dampened.

- The number of reversals in temperature over a diel cycle was increased.
- Ice cover was prevented downstream of some dams due to the release of relatively warmer wintertime water temperatures.

The summer mean daily range and the mean number of reversals per day represented the greatest difference between regulated (storage and peaking) and unregulated rivers, highlighting the importance of considering sub-daily scales in thermal assessments.

Various statistical tools to describe the thermal regime of rivers were developed and compared. While deterministic models (see Glossary for definition) can allow for the simulation of temperatures along the river reach, their use is often impeded by large data requirements. Statistical models (see Glossary for definition) often performed better than the deterministic models, but most are only able to simulate water temperatures at one point on the river, with one noted exception. Statistical models do not necessarily replace deterministic modeling approaches and may not be able to provide the same predictive capability, but they are simpler to develop and calibrate, as they use less environmental data. The selection of models should be based on the following criteria:

a. data availability,
b. model capacity to account for flow variability,
c. the requirement to simulate water temperature at different locations, and
d. the relative ease of calibration and validation.

Nutrients

Nutrients are well known drivers of primary productivity in both rivers and lakes. Energy flow pathways through secondary productivity to fish make it reasonable to expect a predictive relationship between fisheries productivity (estimated via fish biomass) and the nutrient regime (TP - Total Phosphorus, and TN - Total Nitrogen) exists. A wide range of published and unpublished sources representing different system types (flowing and standing water), ranging widely in depth, and including a mix of regulated and unregulated systems, were mined for both nutrient and fish biomass data to compare fish biomass, nutrient richness, and species richness among regions and ecosystem types.

An analysis of the literature (including mostly North American systems) found significant and important differences among regions and ecosystem types, with fish biomass estimates and nutrient levels in rivers and streams being higher than in lacustrine systems. Conducting log-log regressions revealed strong relationships between total phosphorus and fish biomass (range of R^2 = 0.44 – 0.69, see Lapointe et al. 2015, Table 3) that were regionally dependent (to a maximum of 150 $mg \cdot m^{-3}$ total phosphorus, beyond which point the relationship no longer exists) but did not differ between rivers and lakes, indicating that the main driver of higher fish biomass in rivers was their overall greater nutrient richness. However, if species richness is factored in, regional differences no longer existed. Including mean depth improved models further (range of R^2 = 0.74 – 0.82, see Lapointe et al. 2015, Table 4), and there was no difference in the model between lakes and reservoirs. The model for rivers had a different slope than for lacustrine systems, but there was no difference between regulated and unregulated rivers. However, a paired regulated-unregulated analysis was not conducted and this question should be explored further.

It was recognized that total fish biomass is applicable to whole communities and not to fisheries. Thus, a method was presented whereby the nutrient models could be used as a starting point for a fishery analysis. Precision of predictions from the models has at best a standard error of 2-fold – so the models can provide an approximate value, that maybe considered a potential production for the system, but will not provide specific targets. The actual production of the system may differ from this potential due to ecosystem conditions that have nothing to do with nutrient levels. For example recruitment limitation can be a factor for some systems if the species present do not have the habitat necessary to complete their life history (e.g., fluvial dependent spawners who may not have adequate spawning habitat in a reservoir after flooding) or some niches can be empty after impoundment (e.g. pelagic predators may not be present). These situations will tend to reduce the overall production of the system from its estimated potential.

Remote Sensing

A method that couples current sub-meter resolution satellite imagery with *in situ* depth transects was used to create low cost maps of water depth for very long river segments (many tens of km long) (Hugue et al, 2015). The method does not apply to very small or very deep and turbid rivers (where canopy or water transparency prevents light from reaching bottom). Assuming discharge is known from a nearby gauge for the time of satellite image capture, the method can also estimate velocity patterns by apportioning the discharge into the mapped river using empirical 2D flow rules (so called "pseudo-2D" hydraulics).

This remote sensing method allows for low cost coverage of meter resolution hydraulic habitat patterns over long river segments and for the selection of representative areas (e.g., areas of high habitat heterogeneity) that may be studied further for physical and/or biological attributes. Over long time spans, this remote sensing method could document large-scale shifts in the river's depth and velocity habitat.

Biological Drivers

Rivers

The implementation of the Fisheries Protection Provisions of the *Fisheries Act* includes the estimation of the pre-development state of an aquatic ecosystem and the prediction of the effect of a project on fisheries productivity metrics. Explanatory or predictive relationships between fisheries productivity metrics and environmental conditions have long been known to exist in lakes, but very few have been developed for rivers. The biological drivers component of HydroNet aimed to develop explanatory, and eventually predictive, fish-environment relationships that will facilitate the assessment of the effects of hydropower development and/or operations on fisheries productivity metrics.

A river selection process designed to maximize the range of variables studied while minimizing the effect of confounding variables resulted in the inclusion of 15 unregulated and 13 regulated rivers (including run-of-the-river, peaking, and storage systems, described in Boisclair et al. 2016a, Table 1) distributed from Alberta to New Brunswick (Figure 2). A number of variables were collected at these sites including:

a. fisheries productivity metrics (density and biomass by species and size-class, species richness) estimated using a combination of electrofishing and snorkelling,
b. site scale variables (e.g., depth, velocity, substrate, macrophytes),
c. reach scale variables (e.g., flow, nutrients, habitat heterogeneity, thermal indices), and
d. landscape scale variables (e.g., watershed area, landuse).

An assessment of the among-river variations in density, biomass, and species richness (Models 1-3 in Boisclair et al. 2015 a, Table 6) demonstrated that fisheries productivity metrics (density, biomass, species richness) in rivers located downstream of run-of-the-river facilities tend to be similar to unregulated rivers. Rivers located downstream of storage dams had 33% higher biomass but 1.7% lower species richness than predicted for an unregulated river. Rivers located downstream of peaking facilities have 39%, 48%, and 13% lower fish densities, biomass, and species richness, respectively, than that predicted for unregulated rivers.These peaking facilities had large flow amplitudes and low minimum flows and peaking facilities that had less extreme flow fluctuations might not have the same negative effect on fisheries productivity metrics.

Multidimensional flow anomaly indices derived from 105 flow metrics have the potential to explain a large fraction of variation in multidimensional biotic anomaly indices derived from 25 biotic metrics (Model 4, Boisclair et al. 2016a Table 6). For unregulated systems, the range of variation was greater for biotic metrics than for flow metrics, but this may be due to other factors (e.g., temperature, nutrients, biotic interactions) affecting biotic variables, or could be the challenge of sampling biotic vs. physical variables. The degree of multidimensional flow anomaly may have a threshold that has a significant effect on biotic variables. Further research, particularly including rivers that would fall in the moderate to high range of flow anomaly, should be conducted to confirm if such a threshold exists. Predicted post-development flow regimes can be transformed into a degree of flow anomaly and can help guide assessment and monitoring requirements based on the degree of anomaly.

A guild approach (i.e., behaviour, habitat, reproductive, trophic and morphological guilds plus taxonomic grouping) appeared to be useful in situations with a large number of fish species (Models 5-10 in Boisclair et al. 2016a, Table 6). Flow and thermal indices explained a relatively large fraction of among-river variation in fish guild density and biomass (range: reproductive guild (32%) – habitat guild (44%)), outperforming the model developed using taxonomic grouping (26%). The magnitude of summer water temperatures was the primary explanatory variable in all guild-biomass models, followed by intra-annual flow variability (5 guilds) or long-term flow variability (morphological, trophic, behaviour, taxonomic guilds). Removing thermal indices reduced the explanatory power of the models more than removing flow indices from the analyses, again emphasizing the importance of including thermal indices in monitoring programs. A small number of thermal indices:

1. degree days,
2. average July water temperature, and
3. summer average water temperature, appeared particularly important in explaining variations in fish guild, density, and biomass.

A cross-validated model (Model 11 in Boisclair et al. 2016a, Table 6) was created to explain variation in total fish community biomass with a change in environmental variables (e.g., post-development). Using an artificial neural network model (ANN), total phosphorus, degree-days, and one flow index (nRA1 – a dimensionless rise rate index normalized to median daily flow) explained 83% of among-river variations in total fish biomass. Degree-days (positive effect, relative contribution 53%) had a greater relative importance in the model than total phosphorus (positive effect, relative contribution 28%) or the flow index (negative effect, relative contribution 19%).

A model (Model 12 in Boisclair et al. 2016a, Table 6) was created to explain variation in species richness in rivers and could be used to predict change in species richness with a change in environmental variables (e.g., post-development). Degree-days (a measure of energy availability) and habitat heterogeneity (HMID: a hydro-morphological index of habitat diversity based on spatial variation in water depth and velocity) explained 69% of among-river variations in species richness. Species richness increased exponentially with degree days (R^2=60%) and reached a maximum value at intermediate levels of habitat heterogeneity (HMID: R^2 = 48%). Degree-days had a more direct effect on species richness than habitat heterogeneity.

Fish distribution within rivers can be predicted relatively well for rivers with high total fish biomass. A river with a total fish biomass of <2 g·m^{-2} may have too few fish to develop a within-river fish distribution model. When fish biomass is higher than 2 g·m^{-2}, water velocity, depth, and substrate size should be prioritized over other environmental features (width, macrophyte, periphyton, woody debris, temperature, conductivity, transparency) to predict within river fish distribution. Linear mixed models that nested sites within rivers and within regions were developed to predict density (R^2_{cv} = 66%), biomass (R^2_{cv} = 43%), and species richness (R^2_{cv} = 51%), at the local scale in response to flow regime at the river scale, and habitat at the local scale (Models 13-15 in Boisclair et al. 2016a, Table 6). These models could be improved by the addition of non-flow variables (e.g., total phosphorus, temperature, habitat heterogeneity) which is the subject of ongoing research.

One of HydroNet's objectives was to identify novel ways to describe fish-environment relationships and some of this work is still the subject of ongoing research. Matrix modelling (phylogenetically explicit habitat models, Model 16 in Boisclair et al. 2016a, Table 6) is being explored to predict species presence given a set of environmental conditions. Similarly, physiological indicators (e.g., blood glucose, lactate, cortisol) are being explored as a means to link variations in environmental conditions (e.g., flow, temperature) to fish fitness and productivity through growth (Models 17-19 in Boisclair et al. 2016a, Table 6).

For use in practical applications, the development of a simple computer interface would facilitate the use of the various models developed as part of HydroNet (particularly for Artificial Neural Networks or other more complicated modelling exercises) and would ensure that the output was consistent.

Reservoirs

The reservoir work was largely a methodological study with the objective of testing a variety of methods to determine the best suite for sampling reservoirs in monitoring programs. The overall objective was to contribute to the development of knowledge and tools that improve our capacity to estimate and predict metrics of fisheries productivity in reservoirs (Boisclair et al. 2016b). Only one reservoir (Lac du Bonnet, MB) was studied and thus results may not be transferrable to other systems. The system was divided into two zones: pelagic (> 3m depth) and littoral (< 3m depth) and different methods were explored in each.

Pelagic zone recommendations:

Hydroacoustic methods were explored as a viable, cost-effective sampling method in reservoirs and the results on fish size classes fit theoretical expectations of aquatic ecosystem size structure, and were found to be consistent and repeatable. If hydroacoustic methods are to be used, it is important to control for boat avoidance and some form of ground-truthing (e.g., sampling fish to confirm species relative to acoustic signal) is required. Boat avoidance should be assessed by repeated transects with and without a motor, and resulting densities from motor transects should be corrected if necessary. Inter-annual and intra-annual dynamics of size structure could be captured by repeated acoustic surveys (changes observable in terms of intercept and slopes), and were indicative of variable recruitment and mortality over the size spectrum. Longer time series (multi-year) of size spectra would enable the description and prediction of ecosystem state based on changes in size spectra height (intercept) and slope. Among-ecosystem comparative analysis (lakes vs. reservoirs) may inform about human effects (e.g., reservoir operations, land-use changes, etc.) on resident fishes.

Littoral zone recommendations:

The research document contains many recommendations on what, when, and how to sample the littoral zone in a reservoir and analyze data. Specifically, the reservoir littoral zone research was designed to determine:

a. the effect of sample size and of within-year or between-year replication on the potential to develop relationships between metrics of fisheries productivity and environmental conditions,
b. identify the sampling method/combinations of sampling methods (using gill netting, seining, electrofishing) that may be best to estimate/predict metrics of fisheries productivity,
c. assess the relative roles of local (i.e., within site), lateral (i.e., nearby features), and contextual (i.e., position of a site relative to landscape attributes) environmental conditions in models, and
d. to evaluate the difference between daytime and night-time estimates/models of metrics of fisheries productivity.

For a given amount of sampling effort, sampling more sites within a year (i.e., to increase spatial coverage) may be preferable to develop fish-environment relationships in reservoirs than repeatedly sampling fewer sites within a year (i.e., to increase temporal/seasonal coverage). The mean and often maximum predictive power of fish environment relationships in Lac du Bonnet was frequently low, suggesting that fish may not have very strict habitat requirements in this reservoir. There were large differences in developed relationships between years suggesting that modelling and validating such relationships requires multiple years of sampling. The timing of sampling should consider the date of ice melt to ensure habitat associations are not affected by winter or spawning distributions. Sampling fish 10-12 weeks after ice melt may improve fish-environment relationships.

Seining appeared to be superior for estimating species richness and fish biomass, whereas boat electrofishing was the best gear to develop fish-environment relationships**.** Given that it took 2 days to complete the sampling of 43 sites with the electrofishing boat, and that it took 25 days with the seine, it is obviously more efficient to develop fish-environment relationships using electrofishing. This gain in efficiency can be used to increase the number of sites sampled thus increasing spatial coverage (see above). There was some indication that the explanatory capacity of relationships between total fish abundance and environmental conditions was higher at night (73%) than day (60%) but this should be interpreted cautiously given the sampling occurred in different years. Although electrofishing was better than seining for developing fish-environment relationships, if using a seine, night sampling was better for developing relationships than day seining. Gill netting was not useful for developing fish-environment relationships. A combination of local (e.g., slope, macrophyte coverage, substrate) and contextual (e.g., distance to tributaries or marshes, fetch) habitat variables should be used to explain variation in fisheries productivity metrics in the littoral zone of reservoirs. In Lac du Bonnet, significant variables with respect to fisheries productivity metrics were macrophyte coverage and distance to large tributaries.

Fish Passage/Entrainment

Fishways

From an ecological perspective, providing fish passage minimizes impacts where the dam is altering fish passage ability. However, the need for fish passage should be evaluated on a case-by-case basis using a community based assessment and the habitat availability after impoundment. Passage is more likely to be required if the fish species in the affected community require access to upstream habitats to complete life cycle functions and if the predicted habitat characteristics above the passage facility are likely to provide suitable habitat for those functions. Passage is less likely to be needed if species do not require access upstream or if there is an ecological trap/no suitable habitat available upstream after impoundment. In some cases (e.g., invasive species control), passage may in fact be deleterious to upstream fisheries productivity. Considering target fish species and life stages is also important.

Attraction and passage efficiency has been evaluated for very few fishways in Canada (8% of 211 fishways, excluding culverts) and only one study was found where passage efficiency was compared to a control system, i.e., in the absence of a barrier. Where possible, effort should be made to include appropriate controls when assessing fish passage through fishways. The majority of fishway design evaluation has been done on vertical slot fishways and other fishway designs, including nature-like and pool and weir fishways, particularly need additional evaluation. Any new fishways should be evaluated for attraction and passage efficiency.

The research document contains a summary of technical considerations and tools to improve both fishway design and evaluation of effectiveness. Technical changes in fishway design should be considered to facilitate faster fish passage, reduce the energetic cost, which should reduce post-passage mortality. Improvement in fishway design criteria should consider hydrodynamic variables for a range of fish sizes and the fish community, both within and downstream of the passage facility. Turning basins are a common design feature of fishways that need to pass fish over a relatively tall structure. They redirect the flow of water, minimize flow energy to provide a resting space for fish, and allow for a more compact design thus facilitating a more optimum location for the fishway entrance (i.e., closer to the hydraulic barrier). However, turning basins can represent a particular challenge for ascending fish, and options to modify or remove them if possible should be explored. Given the high energetic expenditure and physiological (i.e., stress) consequences, species-specific physiological tolerance to the hydraulic conditions presented by existing and future fishway designs should be considered and ideally referenced to upstream migration over a natural barrier.

Fishway evaluation should include collection of biological (e.g., attraction, full passage) and hydraulic (e.g., velocity, turbulence) data and associated modeling using a multidisciplinary team. Evaluations should incorporate physiological parameters and knowledge to determine whether the impediments to passage success are behavioral or related to physiological capacity. The evaluation of fish passage success through a fishway should be based on site-specific, *a-priori*, biologically based targets linked to fisheries management or conservation objectives. Simply monitoring a complete passage of fish through the fishway (i.e., capture in a trap at the top) is not sufficient to evaluate passage success, since there is a need to know the number of fish seeking and attempting passage to establish a success rate. Ideally such information is then considered in the context of the population biology of target species/populations. Any reported efficiencies should be critically evaluated prior to use in decision making.

Downstream entrainment

Fish entrainment, when a fish travels downstream into the tailrace through turbine or spillway intakes, can be a concern due to the potential impact on fisheries productivity. Most research on entrainment has focused on the early life stages of migratory fishes (e.g., salmon smolts), and thus little is known about the risk of entrainment to adult resident fishes in reservoirs. The objective of this component of HydroNet was to use a multi-disciplinary team of engineers and biologists to generate an informed understanding of entrainment of adult resident fish and to help guide future entrainment research based on lessons learned.

A working conceptual model on the potential risk of entrainment for adult resident fish species is included in the research document. Entrainment risk assessments using desktop methods represent a first step in evaluating the need for, and prioritization of, further more detailed studies.

The risk of entrainment is site specific. Knowledge gained from HydroNet focused on adult Burbot (*Lota lota*) and Bull Trout (*Salvelinus confluentus*) in Kinbasket Reservoir, B.C. and other life stages should be considered if possible. Results demonstrated that the incidence of entrainment for both species occurred when reservoir conditions were isothermal (i.e., temperature was relatively constant through depth). Adult Burbot rarely spent time in the forebay and likely had little overall risk of entrainment. In contrast, 52% (n=97) of tagged adult Bull Trout were detected in the forebay, with eight of those individuals being detected in the tailrace over the two year study period. The movement patterns of the entrained Bull Trout indicated they were likely engaged in exploratory behavior that brought them near (< 15 m) or inside the turbine intakes, since fluid dynamic models predicted velocities that these strong-swimming adults would overcome to avoid non-volitional entrainment.

Modelling the physical environment of the forebay (including flow field dynamics and water temperature) is critical to understand factors leading to entrainment. Thus, entrainment is best evaluated by a multidisciplinary team including engineers and biologists. Entrainment must be considered on a species-specific and life-stage basis due to substantially different movement, behavior and forebay use leading to different vulnerability estimates. All relevant spatial (fine and coarse) and temporal (e.g., diel, seasonal) scales should be covered. A standardized set of data collection and analytical tools is recommended, including telemetry, which allows for detailed evaluations of species-specific and individual-level spatial ecology. Telemetry remains one of the most effective tools available to evaluate entrainment vulnerability in the face of uncertainty that may result from desktop risk assessments.

Overall population-level consequences of adult fish entrainment remain largely unknown; assessing these consequences would require population estimates and evaluations of recruitment and early life history, and entrainment of all life stages. Future research should evaluate population level consequences for target species if possible.

Sources of Uncertainty

The lack of available expertise may limit the widespread applicability of some of the results from this HydroNet research, particularly for the use of some of the more complex modelling exercises and for the use of hydroacoustics as a sampling method.

The analysis of flow regime anomalies presented in Lapointe et al. (2015) did not include hydro systems with diversions of water. Here, the term diversion refers to surface water abstracted from a river that does not return to the same river downstream (e.g., the water is routed to other watersheds for power generation or it is used for irrigation) or to a short diversion within the same river directing water through a pipe or tunnel to a downstream powerhouse, leaving a dewatered reach the length of the pipe or tunnel. While diversions could be studied in an anomaly framework, they would make the principal components analysis different by introducing a new axis of variation. In theory, a river with a significant diversion abstracting flows will show up as a system where one particular flow metric (specific runoff = mean annual flow divided by drainage area) will be lower than in the local reference group. Specific runoff should be more or less the same for all regulated and unregulated systems with no diversion in the same region, and this was the case in the HydroNet dataset. If a diversion system (or reach) is included in the comparison, specific runoff would show a glaring anomaly, while its other metrics(related to flow timing, frequency of fluctuations, etc.) may or may not display anomalies (depending on the schedule of diversions, which can vary).

To generate reference unregulated regimes for the flow anomaly approach, availability of flow time series for a *common period of at least* 20 years at all sites is recommended. This is the minimal series length required to average out possible multi-year runoff cycles and arrive at minimally stable averages for many key metrics of ecological and ecosystem interest, such as the mean high and low flows with various durations and recurrences. Due to climate change, there may be changes in background levels in water availability. Thus, the data for proximate reference systems used to compare a regulated river may have to be iteratively renewed depending on the potential effects of climate change on what constitutes a natural flow regime in an unregulated river system.

Unfortunately, there are no internationally agreed quantitative criteria for the degree of flow alteration defining the three types of river regulation terms used in HydroNet (peaking, storage, run-of-the-river). These types are really 'end members' on a continuum of degree and type of hydrograph change (i.e., "idealised types" of hydrograph alteration, where most actual projects actually lie somewhere along a spectrum of combinations of these types, with various intensity for each). For example, for peaking, there appears to be no commonly agreed standard on the amplitude of downstream discharge change ratio (Qhigh/Qlow), or the frequency of peaking releases, per week or per month, that are necessary to officially label a project as peaking. In the absence of precise definitions, projects that have limited storage (and thus minimize impacts to downstream discharge patterns) or with moderated peaking ratios (ratio of daily high to low flows) are close to being considered run-of-the-river and are less likely to cause environmental impacts, but are not true 'run-of-the-river' systems (as defined in the Glossary) and should not necessarily be reviewed as such. This lack of clarity in usage is a major reason why environmental managers need quantitative tools (such as indicators of flow alteration and flow anomaly, see Glossary) to assess the exact type and degrees of regime change involved in any project. In HydroNet, knowledge of mode of operation and relative size of storage volume were used to classify study systems as run-of-the-river, or as large storage, with or without regular peaking, and these criteria can be found in the Glossary section of this report.

Changes in temperature downstream of large reservoirs that thermally stratify depend on depth of intake and other physical factors and thus may not be easily modeled. Reservoirs used in the thermal work were generally shallow and may not be typical of all hydro reservoirs.

Under saturation of a system due to recruitment limitation (e.g., a lacustrine system with a lack of fluvial spawning habitat availability and no true lacustrine specialists) may have implications for use of the nutrient-fish biomass model since severely recruitment limited systems do not produce potential biomass for a given nutrient level and were excluded from the model development. Under saturation of the available trophic web (e.g., the food chain in a reservoir without a pelagic planktivore makes less efficient use of plankton productivity than one with a pelagic planktivore) has implications for use of the nutrient-fish biomass model, but incorporating the species richness term in the model should correct for this effect. If a new hydro development impounds a river, thus creating a reservoir, it does little to the nutrient regime and thus to the predicted fish biomass, so long as all available trophic niches are utilized by fish species present in the reservoir, and the habitat is not recruitment limiting. However, it should be noted that the nutrient models were derived from mining data from previous studies and not from before and after data from a newly impounded system.

The ability of hydroacoustics to quantify the fish community during day vs. night may be confounded by vertically migrating plankton, thus, when sampling is conducted, plankton should be sampled.

The littoral zone sampling in the reservoir focused on fish > 3 cm (total-length) due to limitations of the utilized gear in efficiently capturing fish smaller than 3 cm. Smaller size classes (young-of-the-year) were not used in the analyses and may have different distribution patterns.

The level of transferability of results on fish passage is uncertain, but methods used should be transferrable and applicable to new facilities or when an opportunity arises to evaluate the need for, and evaluation of, fish passage at existing facilities undergoing a retrofit or rebuild. The use of fishways for downstream fish passage was not evaluated as part of HydroNet, but should be considered in fishway evaluations and as a subject of future research.

Large water level fluctuations and environmental noise from dam operations present challenges for acoustic telemetry in reservoirs. The use of multiple transmitter frequencies can improve detection efficiency. Detection efficiency should be calculated (using beacon tags) and forebay use by fish corrected when using acoustic telemetry systems in reservoirs. Safety concerns near hydro-dams (i.e., the inability to acquire field based measurement of flow and temperature directly above or adjacent to intakes) make verification of lab-based computational fluid dynamic (CFD) calculations difficult, but data should be obtained as close to the dam as possible using secure mooring to calibrate and validate models and then results can be extrapolated to the intakes.

CONCLUSIONS AND ADVICE

NSERC's HydroNet successfully operated as a national research network that achieved many of its objectives. The main conclusions arising from five years of HydroNet research are all included in the Summary section. The advice is contained in all sections of this SAR, organized by theme.

OTHER CONSIDERATIONS

While future research suggestions are not normally included in a Science Advisory Report, the nature of this report being a consolidation of five years of research into tools and advice for management lends itself to including priority research items that naturally followed from the extensive research efforts of HydroNet. The following is a brief description of some of the future work that was discussed but does not identify priority of these research needs:

- It may be possible to develop a simple scaling model using the volume of water flowing through the intakes relative to the cross sectional area of the intakes to provide a rough estimate of the velocity environment encountered by fishes in the areas close to intakes. This could be conducted for the sites where the detailed CFD modelling has been done to compare results and gauge the utility of the simple model.
- Hydropeaking dams are not all operated in a similar way and an analysis of the range of hydropeaking operations (e.g. ratio of daily high flows to low flows or the range of daily fluctuation in tailrace water level) should be explored and potentially classified.
- Many of the models that were presented would benefit from validation or further validation to expand their range of applicability.
- The tool for high resolution multi-spectral satellite coverage could be tested for larger rivers using existing data.

- Nutrient modeling was conducted on the basis of species richness, but the approach may work as well, or better, using a guild approach, which should be explored.
- Size spectra analysis (hydroacoustics in the pelagic zone) has the potential for pairwise comparisons of reservoirs and natural lake systems and should be explored further.
- Hydroacoustics has the potential to provide quantitative seasonal cohort analysis in lacustrine systems (for estimates of mortality, growth, etc.) and could be explored further.
- Results from day vs. night boat electrofishing suggested that night sampling was better for models to predict fish abundance. However, it was not conclusive as they were conducted in different years. Future work could investigate this further by electrofishing day/night in the same year.
- Investigate the mechanisms that draw fish to turbine intakes and subsequent entrainment including potential attraction to noise, vibration or prey.
- Identify how turbine configuration influences behavior and the likelihood of entrainment of target species.

SOURCES OF INFORMATION

This Science Advisory Report is from the national peer review meeting of September 15-17, 2015 on the NSERC's HydroNet: consolidating five years of research designed to develop knowledge and tools about the effects of hydroelectric facilities on aquatic ecosystems. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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DFO. 2016. Proceedings of the national peer review of NSERC's HydroNet: consolidating five years of research designed to develop knowledge and tools about the effects of hydroelectric facilities on aquatic ecosystems; September 15-17, 2015. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2016/042.

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Hugue, F., Lapointe, M., Eaton, B., Lepoutre, A. 2015. Satellite based remote sensing of running water habitats at large riverscape scales: Tools to analyze habitat heterogeneity for river ecosystem management, Geomorphology. doi: 10.1016/j.geomorph.2015.10.025

Lapointe, M., Rasmussen, J.B., Maheu, A., Kwak, J.A., Beaupré, L., St-Hilaire, A. 2016. Key physical and chemical drivers of fisheries productivity (flow, nutrient and thermal regimes) across rivers in various Canadian regions: lessons learned from NSERC's HydroNet 2010-2015. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/047. vi + 55 p.

APPENDIX: GLOSSARY

Fish Entrainment occurs when a fish is drawn into a water intake and cannot escape

Fish Impingement occurs when an entrapped fish is held in contact with a structure like a trashrack or an intake screen and is unable to free itself.

Fishway Attraction Efficiency: the proportion of fish tagged and released during a given study that are subsequently located within less than approximately 3 m from a fishway entrance

Fishway Passage Efficiency: calculated by dividing the number of fish of a particular species that exits a fishway by the number that is detected at the fishway entrance.

Flow alteration: the alteration of any flow metric is calculated from a direct comparison of pre-regulation versus post regulation hydrographs (each at least two decades long) on the one river studied. Assuming negligible inter-decadal land use and climate change effects, this comparison is a good quantifier of the effect of regulation on the system's flow regime. However, sufficiently long pre-regulation records may in many cases not be available.

Flow anomaly: addressed the question to what extent is the regulated regime anomalous in comparison to the natural range of unregulated flow regimes in the same broad region assessed using many reference rivers of comparable sizes and watersheds to the regulated one. This analysis (explained in Lapointe et al. 2015) neither depends on the availability of pre-regulation flow records nor on steady climatic and land cover conditions.

Flow regulation terms (as used in the context of HydroNet): In HydroNet, local knowledge of mode of operation and relative size of storage volume (with respect to mean annual flow) were used to classify study systems as run-of-the-river or as large storage, with or without regular peaking. More specifically, criteria were as follows:

Unregulated: sites with a flow regime that is unaffected by upstream dams and only affected by the variability in hydrological inputs and outputs (precipitation, evaporation) and natural water storage (such as natural lakes and groundwater). At these sites the response in terms of amplitude, timing, duration and frequency of flow events may be affected by land uses but are unaltered by artificial reservoir.

Run-of-the-River: sites with very small storage (relative to the mean annual flow of the river) and no trace of peaking on the hydrograph.

Storage: sites with very large storage (relative to the mean flow of the river), significant seasonal reservoir level fluctuations clearly dampening high flows downstream; but never or almost never had any peaking.

Peaking: sites with storage that had regular, significant almost daily peaking, where peaking is defined as the operation of a hydropower plant to meet peak electrical demands, resulting in large hourly or daily fluctuations in flow.

Water temperature models - deterministic*:* Mathematical tools (usually differential equations) developed to estimate the evolution of water temperature, based on the physics of the processes of heat exchanges. Typically, deterministic models for water temperature calculate a heat budget at each time step and at one or many points along the river and in the latter case, will account for upstream-downstream heat advection.

Advantages: They are based on the physics of the phenomenon, so presumably are better extrapolators (temporal or spatial) than statistical models (see next).

Disadvantage: Typically they require much more input data than statistical models (and data of types not often monitored; e.g., data on weather variables such as local wind and humidity, cloud cover, solar radiation at ground, and data on diverse watershed characteristics such as aquifer locations and flow rates).

Water temperature models - statistical*:* Mathematical tools developed to estimate water temperature (in this case) based on purely empirical relationships (identified and quantified by correlation, for instance) with appropriate predictor variables (e.g., air temperature, river discharge).

Advantage: Usually require fewer inputs than their deterministic counterparts and usually easier to calibrate for a particular system and set of conditions.

Disadvantage: Typically require relatively long time series (e.g., of water and air temperature) for calibration. Difficult to export to other systems.

z-score: z-score (or a standard score) indicates how many standard deviations an element is from the mean. A z-score can be calculated from the following formula. $z = (X - \mu) / \sigma$ where z is the z-score, X is the value of the observation, μ is the population mean, and σ is the standard deviation.

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