Review of Literature Related to the Downstream Ecological Effects of Hydroelectric Power Generation

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Abstract

There are approximately 804 large and 200 small hydroelectric generating stations in Canada with a total combined capacity of 65.7 Gigawatts (173). As the operating licenses of these facilities come up for renewal, review agencies may recognise an opportunity to enhance ecological conditions in hydro rivers by placing restrictions on the operating regime of hydro facilities. Hydroelectric utilities, while recognising the need to consider ecological concerns in their operation, may be reluctant to implement new controls in light of continuing deregulation in the electrical marketplace.

Instream Flow methodologies (e.g. historic flow, hydraulic, and habitat-based methods) in use in North America, New Zealand and Europe are summarized. Existing literature related to population level effects of hydro generation on aquatic biota (fish and invertebrates), fish microhabitat use, fish migration, and egg/embryo development is reviewed. Finally, a number of mitigative actions currently employed to lessen the effects of hydro generation on aquatic biota and habitat are reviewed and evaluated.

Key Words: aquatic habitat, biota, hydroelectric, instream flow, mitigation, population, microhabitat, egg, embryo, fish, invertebrates

Résumé

On compte actuellement environ 804 grosses et 200 petites stations génératrices d'hydroélectricité au Canada, ce qui représente une capacité totale de 65.7 gigawatts. Lorsque les permis d'exploitation de ces installations viennent à échéance, les organismes examinateurs peuvent en profiter pour améliorer les conditions écologiques des cours d'eau aménagés en imposant des restrictions sur le régime d'exploitation des installations hydroélectriques. Bien qu'ils reconnaissent la nécessité de tenir compte des préoccupations écologiques dans leurs activités, les services d'électricité peuvent être peu disposés à adopter les nouvelles restrictions dans le contexte de la déréglementation continue du marché de l'électricité.

L'article décrit en bref les méthodes de débit minimal (débit historique, méthodes hydrauliques ou fondées sur l'habitat) utilisées en Amérique du Nord, en Nouvelle-Zélande et en Europe. La documentation ayant trait aux effets (au niveau des populations) de la production d'hydroélectricité sur le biote aquatique (poissons et invertébrés), l'utilisation des microhabitats du poisson, la migration des poissons et le développement des œufs/embryons est examinée. Viennent ensuite un examen et une évaluation d'un certain nombre de mesures d'atténuation prises à l'heure actuelle pour amoindrir les répercussions de la production d'hydroélectricité sur le biote et l'habitat aquatiques.

Mots clés : habitat aquatique, biote, hydroélectrique, débit minimal, atténuation, population, microhabitat, œuf, embryon, poisson, invertébrés

Introduction

There are numerous hydroelectric generating stations in operation across Canada. Many have been operating for decades or longer and were licensed when aquatic habitat concerns were not necessarily considered during determination of the bounds in which the plants would be operated. Plants licensed in the last ten to fifteen years tend to have more operating restrictions, which were implemented to achieve some aquatic benefit or protection. In many instances, these restrictions were based on modifications to the downstream flow regime of the plant. However, a report commissioned by the Canadian Electrical Association in 1994, found that many projects had no follow-up monitoring to assess the effectiveness of the water releases in terms of providing benefit to aquatic habitat (98).

As hydroelectric stations come up for re-licensing, licensing agencies are finding an opportunity to negotiate changes to the operation of hydroelectric facilities that they believe will benefit downstream aquatic resources. The agencies typically rely on methods of determining flow releases that do not measure direct response of ecosystem components, but which rely on modelling and or computational methodologies to predict impact. Power companies are reluctant to enter into negotiations because of scepticism with respect to the methodologies proposed, the relevance of the methodology to the watershed in question, and the lack of baseline data against which to compare aquatic conditions following the implementation of any changes.

In Ontario, the Ontario Ministry of Natural Resources (OMNR) is the body responsible for hydroelectric waterpower lease renewals. The Water Policy Branch of OMNR is developing a policy for licence renewal, but that policy is not yet available. Fisheries and Oceans Canada (DFO), is involved because issues related to fish habitat fall under Section 35 of the Fisheries Act.

Recently, DFO's Great Lakes Laboratory for Fisheries and Aquatic Sciences has been awarded an ESSRF research grant to help address this problem. The research is a co-operative effort with involvement from DFO (from across Canada), the hydro industry, OMNR and educational institutions. This literature review was commissioned by DFO to synthesize existing scientific information on the downstream impacts of hydroelectric generation. A parallel review has been undertaken which examines the available models for assessing aquatic habitat impacts in relation to downstream flow (166). The results of these reviews were used as background information for a DFO sponsored workshop which addressed the use of an Adaptive Environmental Management (AEM) approach to evaluate impacts of downstream flow on aquatic biota in Canadian rivers. This workshop developed key hypotheses of effect to be tested during the ESSRF research project on ramping and developed an array of experimental methods to test the effect of hydroelectric ramping rates on the productive capacity of riverine ecosystems.

Basic Concepts of River Science

Ecological Continuums and Disturbance

The River Continuum Concept (RCC) (57) is based on the premise that from headwater to river mouth, the physical variables (i.e. stream width and depth, velocity, substrate composition, and sediment load) present a continuous gradient of physical conditions. Assemblages of aquatic species then respond in terms of occurrence and relative abundance to the physical gradients present. Stanford (22) suggested that alterations of flow regimes and the associated severing of connectivity in riverine ecosystems are the most pervasive influence of humans on river landscapes. Ward (120) termed this severing of connectivity the "serial discontinuity concept". Johnson (1) pointed out that dams cause a discontinuity in the longitudinal distribution of physical properties in a river, which in turn impacts on the biological communities within the longitudinal profile.

Junk (10) analyzed the impacts of alterations in flow regime with respect to the impacts on the connectivity between rivers and their floodplain. Junk introduced the "flood pulse concept", which describes the importance of periodic flooding in terms of nutrient exchange between the main river and hydraulically isolated backwater areas within the floodplain. Junk pointed out that primary production associated with the transition zone between permanently wetted river and floodplain areas was much higher than that of the main river channel and that periodic flooding was critical to cycle this productivity from the floodplain to the main channel. Heiler (34) noted that the opposite was true for the Danube River where low concentrations of inorganic nutrients in the floodplain were periodically supplemented by flooding from the Danube, which was relatively higher in nutrient load. Bayley (37) cited a much higher fish biomass in floodplain lakes periodically connected to the mainstem of large rivers than in those cut off from floods by artificial levees. Ross (8) demonstrated extensive use of floodplain areas during spring high water by a variety of floodplain exploitative fish species.

The flood pulse concept introduced a lateral component to the dynamics of a river system that was not present in the River Continuum Concept of Vanotte (57). Johnson (1) points out that both the RCC and flood pulse concept assume a dynamic equilibrium between biological and physical features of a river. He then cites examples where construction of dams on large rivers has shifted the equilibrium point from what would be found naturally. He also speculates that successive environmental alterations may produce physical and biological changes so great that equilibrium cannot be achieved within the time frames used by humans for managing riverine ecosystems.

Periodic flooding is only one form of disturbance that can occur naturally in a river system. Resh (9) reviews the role of flooding and other forms of disturbance in natural ecosystems. Sedell (80) examines the role of refugia in helping ecosystems to recover from disturbances. Sedell also contemplates the removal and destruction of natural refugia via anthropogenic activities and discusses the importance of re-establishing refugia during river restoration projects.

Importance of Scale

Researchers attempting to determine the impacts of hydroelectric operations on riverine environments must assess the scale at which they are examining the problem. Minns (2) provides a good argument for the necessity of considering scale in the design of studies that attempt to detect responses of aquatic organisms to ecosystem alteration. He argues that "attempts to measure ecosystem response are on a small scale compared with the system being modified". Several other researchers have also provided useful insight into the necessity of considering scale in the design of experiments (22, 156, 158, 159). In recommending a protocol for restoration of regulated rivers, Stanford (22) suggested that the problem be formulated at the catchment scale, which may be difficult in systems (such as hydroelectric rivers) where the river continuum has been disturbed by the placement of dams.

River ecosystem response to disturbance can be measured at spatial levels ranging from river basin, to subwatersheds, to valley segments, to stream reaches and even stream reaches can be divided further into channel units or types (156). Within a given channel unit, one might measure response of fish populations, a single species or, in some cases, individual fish (11, 48, 119).

Maxwell (156) provides a description of the nested hierarchy at which spatial scale operates within aquatic ecosystems.

Poff (20) argues that large-scale hydrological similarities involving precipitation trends, runoff characteristics, and groundwater stability may be influencing stream community structure more than originally thought and that additional research is needed to determine the influence of coarse hydrological descriptors at large geographic scales. To demonstrate this concept, Poff (23) compared fish assemblages against hydrological variability in 34 streams and was able to demonstrate a strong association between the functional and taxonomic composition of fish assemblages and hydrological regimes at a regional scale.

Temporal scale is also a critically important consideration in measuring ecosystem response to perturbations. Riverine systems can react to disturbance at differing temporal scales. The frequency of recurrence of hydrologic events can drive population dynamics. Changes in water flow varying from hourly, to daily, to annually can impact on aquatic systems. For example, Niemi (157) noted that siltation of microhabitats may disturb aquatic biota over the short term, but that the system may recover quickly to pre-disturbance levels.

Existing Instream Flow Determination Methodologies

Since the early 1970s there have been numerous methodologies proposed for determining appropriate instream flows for the protection of aquatic biota.

Historic flow methods such as the Montana Method (12), the Modified Tenant Method (101), the New England Aquatic Baseflow method (13, 14), the Northern Great Plains Method (172), and most recently the U.S. Fish and Wildlife proposed method (69), are based on the historic (pre-development) flow regime of the river in question. These methods assume that, if the flow regime is kept within certain statistical bounds of measured historic variability, aquatic biota will remain unaffected because they have survived these conditions in the past. These methods are attractive as management tools since little to no fieldwork is required for their implementation. However, these methods require that flows represent biological response, thereby eliminating the need for biological assessment.

Hydraulic methods of instream flow determination require the development of a relationship between discharge and some hydraulic attribute of the river which is assumed to be related to ecological function. A comprehensive review of the hydraulic theory used in these types of models is provided by Stalnaker (46). One widely used method is the Wetted Perimeter Method (15, 17, 102). This method assumes that maximum ecological benefit is achieved when the greatest possible area of river channel is wetted. There is generally a rapid increase in wetted perimeter from zero discharge to a point at which additional discharge provides only an incremental increase in wetted perimeter. This point is termed the “inflection” point and minimum flows are often set near this point to achieve wetted perimeter benefit while optimizing baseflow requirements. Gippel (30) and O'Shea (15) have expressed concern about the determination of this point because it is often accomplished by eye from observing a graph of discharge versus wetted perimeter. Gippel's concern was that the relative scaling of the axes of the graph leads to inaccuracies in determination of the "inflection" point. Gippel proposed a mathematical methodology to determine the inflection point.

Habitat based methods of flow determination follow on the hydraulic methods by determining hydraulic response to discharge and then comparing this hydraulic response to the species specific habitat requirements of fish and/or invertebrates. These methods are based on habitat suitability curves developed for a range of life history stages of various aquatic species. Habitat suitability is generally described on a continuum of zero (unsuitable) to one (optimum) and is used to determine weighted useable area of habitat at various discharges. The most widely used habitat based flow determination methodology has been the U.S. Fish and Wildlife Service Physical Habitat Simulation (PHABSIM) Model (103, 104). The PHABSIM approach has formed the basis for the Microhabitat Method which is commonly applied in France (115, 116). In Australia, a similar model known as the River Hydraulic and Habitat Simulation (RHYHABSIM) has been in use since the early 1980s (105). In Norway, physical habitat simulation models known as HABITAT (61) and SSIIM (64, 67) are in use. Scruton (11) has recently reviewed various habitat-hydraulic models in use in North America and Europe. All of these methods rely on the establishment of representative cross sections in the river at which measurements of hydraulic parameters such as depth and velocity can be measured at varying discharges. This field information is then entered into the model which, by comparing hydraulic response (at various discharges) to habitat suitability curves, determines an estimate of Weighted Useable Habitat Area (WUA) in relation to discharge.

Although models such as PHABSIM and RHYHABSIM have been widely applied, they do have limitations. A number of researchers have determined that the correlation between the amount of estimated useable habitat as predicted by PHABSIM and actual species abundance is poor (106, 107, 108, 117). Irvine (79) determined that the relationship between predicted weighted useable area and rainbow trout biomass was poor. The limiting factor for rainbow trout was food availability, which was not accounted for in simply defining weighted useable area. Milhous (66) acknowledges the limitations of PHABSIM by suggesting that " … physical habitat is a necessary but not a sufficient condition for the existence of a species. There are many interactions between species, between life stages, and between many other factors that will influence the state of the ecosystem but are not modelled by PHABSIM". By contrast, other researchers have found positive relationships between weighted useable area and standing stock (53, 109, 110). Gallagher (3) found an extremely strong relationship between PHABSIM predicted weighted useable area (for spawning) and the density of chinook salmon redds in two California rivers.

Heggenes (32) demonstrated that habitat selection by brown trout and Atlantic salmon was partly dependent on temporal factors such as water temperature and light conditions that were not accounted for by traditional physical habitat simulation models. Other researchers have criticized the manner in which PHABSIM results are presented because confidence intervals are not used. Williams (21) demonstrated that a number of factors including choice of transects, and estimation of suitability curves can introduce significant variability into the results generated by PHABSIM. Williams applied the bootstrap method of Efron (114) to develop confidence intervals around estimates of weighted useable area for juvenile chinook salmon. Castleberry (16) and Williams (21) have challenged users of PHABSIM to increase confidence in results by displaying results with calculated confidence intervals.

Sheer (63) used two-dimensional hydraulic modelling to determine pre and post development velocities and water depths downstream of the John Day Dam on the Columbia River. These parameters were then used to calculate the Froude number, a dimensionless function of velocity and depth used to estimate the amount of meso-habitat types (i.e. pool, run, riffle) in rivers (118, 119). The amount of the various habitat types available prior to and following construction of the dam can then be compared.

Lamouroux (60) compared results from a statistical hydraulic model used to predict fish community characteristics with actual long-term observations of fish communities. He found that actual relative abundance of fish was strongly correlated with zoogeographic features that could not be predicted by the model. However, within distinct geographic zones, the model predicted more accurately suggesting that hydraulics in the river played a more important role within a given geographical zone. Poff (23) also argued that geographic regions serve as filters on the relative abundance of fish species.

Hardy (28) provides a synopsis of the potential advancements to habitat modelling that may be on the horizon. Multispectral aerial videography appears promising for mapping mesohabitat features over extended lengths of river as does the use of GPS linked hydroacoustic arrays which can, with the use of global positioning system technology, be linked to GIS mapping systems. Geographical Information Systems (GIS) have been used in an attempt to generate mapping that displays the results of physical habitat modelling or of actual collection of real time data (59, 65).

Recently, Castleberry (16) has argued that no scientifically defensible method of defining instream flow for protection of aquatic ecosystems exists (he includes PHABSIM in this analysis). Van Winkle (58) responds to Castleberry's position by calling for a modelling approach that moves beyond the realm of simply evaluating habitat changes in response to flow changes. Van Winkle calls for habitat based models such as PHABSIM to be used in conjunction with mechanistic models which incorporate factors directly affecting the target aquatic resource (i.e. the individual model fish) (62, 111, 112, 113) rather than just keying on the physical habitat of the organism.

Poff (18) argues strongly for the use of the natural flow regime of a river as the basis for managing altered riverine ecosystems. In doing so, Poff recognized five major components of flow: magnitude, frequency, duration, timing and rate of change as being critical to the overall health of a river ecosystem. He also pointed out that, in the past, flow determination methodologies have examined these components in isolation from each other (for example, methods which determine only minimum flow requirements) and in doing so have failed to recognize the complex interactions between these components. Richter (19) proposes a method known as the Range of Variability (RAV) approach for determining the amount of flow required in a river to ensure ecological sustainability. This approach uses predevelopment hydrologic records and relies very heavily on satisfying the flow subcomponents identified by Poff and, as stated by Richter himself, RAV "… is intended for application on rivers wherein the conservation of native aquatic biodiversity and protection of natural ecosystem functions are primary river management objectives".

The Use of Habitat Guilds

Some researchers have relied on the use of fish habitat guilds to study the impacts of flow alterations downstream of hydroelectric facilities. The concept of guilds was introduced by Root (167) who defined a guild as “a group of species that exploit the class of environmental resources in a similar way”.

Bain (68) provides a synopsis of the arguments for and against the use of habitat guilds in determining fish response to streamflow alterations. Bain argued strongly for the use of habitat guilds because it allows for the simplification of measuring fish response to streamflow when the rivers involved have numerous species of fish present. Bain (24) used statistical analysis of electrofishing results to separate fish into two habitat guilds. His first test guild was made up of species with very specific habitat requirements. These fish were typically small fish that used the shallow and low velocity margin of streams as their predominant habitat type. The second guild was composed of habitat generalists that used deeper and faster water away from the stream margins. Bain was able to demonstrate that, on a highly regulated river with frequent flow alterations, the abundance of the habitat specialists was substantially reduced relative to a control river where no man made flow regulation had occurred. On the regulated river, the habitat generalists dominated the species assemblage. Leonard (55) used snorkelling observations to group a number of warmwater stream fish into four habitat use guilds (riffle, run, pool and margin). Then, using a physical habitat simulation model he was able to demonstrate similar patterns within each guild in terms of the relationship between discharge and weighted useable area. Based on these results, Leonard recommended the use of habitat guilds for physical habitat modelling. He also recommended that the guilds generated should represent the extremes of tolerance to velocity (i.e. swift, riffle and slow pool or margin area species).

Studies of Population Effects

Fish

Several studies have focused on the impact of reduced or fluctuating flows on the population of individual fish species downstream of hydroelectric facilities. Using artificial stream channels, Rutledge (90) tested the impacts of varying frequencies of freshes on the growth of quinnat salmon. The study concluded that the frequency of freshes did not impact on the growth rate of the salmon and that growth rates of salmon exposed to constant low flow and those exposed to fluctuations were the same. Irvine (85) used the same artificial stream channel as Rutledge to estimate the impact of flow fluctuations on the displacement (downstream emigration) of rainbow trout. He found that downstream emigration was not higher in stream channels simulating hydro peaking operations than in stream channels with constant flow. He cautioned, however, that fish size and density dependent factors such as food availability may have influenced the results of his experiment. Other studies (124, 125) using the same experimental channels found that increasing flows in the channels lead to an increased emigration of chinook salmon, quinnat salmon and brown trout.

Aass (76) compared historic predevelopment data collected for brown trout with data collected following the construction of a hydroelectric dam on a Norwegian river. He determined that despite substantially reduced flows downstream of the facility, increased juvenile growth occurred thereby leading to a reduction in the age at smoltification. Brooks (27) found no influence of river regulation on the growth of juvenile Atlantic salmon. Crisp (123) found increased population density and biomass for brown trout in the River Tees following regulation. Anderson (38) determined that in years of average or below average spring discharge, rainbow trout production can be highly successful provided that discharge from the dam does not undergo rapid or extreme fluctuations. Anderson also noted one year where delay in passing the spring freshet, until after the velocity sensitive swim up period for brown trout was over, resulted in an increased survivability of brown trout fry.

Other authors have noted detrimental impacts to fish populations following regulation. Cowx (77) noted a decline in juvenile recruitment (number of age 0+ fish in electroshocking results) of both brown trout and salmon parr following a change in operation of a dam from a continuous discharge to one characterized by large, rapid and frequent changes in flow. Within three years of the change in flow regime, recruitment of juveniles dropped to negligible numbers such that sparse populations dominated by older fish remained.

Auer (95) compared lake sturgeon spawning at a hydroelectric facility between a period when the facility was operated in a peaking mode and subsequent years when the facility changed to a run-of-the-river facility as a result of relicensing conditions. In the years following return of the river to run-of-the-river conditions, Auer noted an increase in the total number of spawning fish, an increase in the number of females, an increase in the number of sexually mature fish, and a reduction in the total length of time in which spawning activity occurred. Auer did not determine whether these changes resulted in positive effects on the overall population of lake sturgeon.

Nelson (47) found that poor year class abundance of age 1+ brown trout was positively correlated with spawning years where flows downstream of a dam were fluctuated up and down within the spawning period.

Invertebrate Studies (Standing Crop)

The effect of flow fluctuations on invertebrates has been the most widely studied topic related to hydroelectric peaking operations. Boon (45) provides an extensive review of invertebrate response to hydroelectric development in Britain.

Gislason (50) measured aquatic insect abundance below a hydroelectric facility with widely fluctuating daily discharges. The following year, he measured abundance again, this time under conditions of stable flow patterns that mimicked the natural hydrograph of a nearby river. He was able to determine that, under stable flow conditions, invertebrate density was concentrated at the river margin and insect numbers decreased as depth and current increased toward midstream. Under conditions of fluctuating flow, overall density was reduced and the majority of the insects were located in the less favourable, mid channel habitat. Garcia de Jalon (35) also noted decreases in invertebrate taxonomic richness, density and biomass in the Rio Tera following the construction of a generating station with daily flow variation from10 to 210 m^3/s.

Munn (78) compared the benthic communities of regulated and unregulated sections of the Clearwater River in northern Idaho. The regulated section underwent large fluctuations in flow on a monthly basis. Munn observed that these fluctuations resulted in an invertebrate community with much higher overall density, but with severely reduced diversity relative to the unregulated system. The regulated community was dominated by orthoclad chironomids, which Munn postulated were taking advantage (from a feeding perspective) of dense aquatic moss growth over the riffle areas of the regulated stream.

Troelstrup (82) used artificial substrates to compare the response of invertebrate communities to diel flow fluctuations below a hydro peaking operation to a period where flows were held stable. In the absence of peaking, he detected a four-fold increase in taxa richness and an eight-fold increase in overall density relative to the peaking situation.

Cereghino (29) observed a statistically significant reduction in the density of stoneflies (Plecoptera) downstream of a hydroelectric dam with fluctuating discharge when compared to an upstream reference site. However, he did note a recovery in densities of some stonefly species as the downstream distance from the discharge increased.

One difficulty faced by researchers is the lack of predevelopment data against which to compare effects of a hydro facility that has altered the flow regime of the river. Englund (168) collected invertebrate samples from both regulated and unregulated streams in northern Sweden. Data from the unregulated streams were then used to predictively model the invertebrate community prior to development on the regulated streams. The difference between the observed and predicted invertebrate community was then used to measure the impacts of regulation. His results, from several rivers, indicated that reduced flows downstream of hydro facilities had resulted in a mean loss of six invertebrate species (maximum 30) and a mean reduction in total abundance of 12% (maximum 54%).

Boon (36) observed a marked decline in the density of filter feeding hydropshychid caddisflies immediately downstream of a highly variable discharge in northern England. A continued decline was also observed for as much as five kilometres. The filter feeding hydrophyschids were replaced by a predatory caddisfly species. At sampling stations 10 and 28 km downstream of the discharge, he was able to demonstrate recovery of the filter feeding caddisfly populations. Boon speculated that the change in species complex was related to catchnet retreat damage as a result of fluctuating flows in the river.

Some researchers have determined that overall density of macroinvertebrates remains the same below hydro peaking facilities, but that the species complex shifts to favour taxa that are better adapted to fluctuating flows (136, 137). This shift is sometimes observed as a displacement in functional feeding groups (33, 35, 81). For example, Camargo (81) found that, following construction of a dam with fluctuating discharge, predator diversity increased substantially compared to the diversity of shredders and scrapers, whose feeding requirements tend to be more specialized.

Fjellheim (138) noted a shift in the basic faunal composition of a Norwegian river from a lotic community to lentic following diversion of flows from the river. However, when the same area was tested following a severe flood, the fauna had shifted to rheophilic species, more tolerant of flowing water, and the abundance of lentic caddisfly had decreased considerably (44).

The majority of the studies focusing on the effects of flow fluctuations on invertebrates have examined population-based response to modification in flow without examining the specific interactions of invertebrates with hydraulic features which vary in relation to changes in flow. Recently, Biggs reviewed specific interactions between velocity fluctuations and invertebrates at the microscale of the individual organism (139). He concluded that microscale velocity responses of individual benthic organisms play an important role in how benthos responds to velocity change and that considering only velocity change at larger spatial scales may overlook these critical microhabitat responses.

Invertebrate Studies (Drift)

The above-noted studies focused on the impact of flow fluctuations on invertebrate abundance and diversity by measuring standing crop. Other research efforts investigated the impact of flow fluctuations on invertebrate drift patterns downstream of hydroelectric stations.

Invertebrate drift may be stimulated when river flows are reduced by regulation (96, 144, 145, 146). Hunter (73) postulated that this increase in drift could be a response to avoid stranding in nearshore areas or it might be a response to overcrowding in intergravel habitat.

Several studies have documented an increased invertebrate drift following rapid increases in flow (40, 140, 146, 143). Matter (141) observed that these increases drift accounted for a 14% loss of the benthic standing crop. Irvine (88) found that drift densities increased with sudden flow increases and were correlated with increases in periphyton drift. Irvine (89) also discovered that invertebrate drift densities increased following an initial increase in flow if previous flows had been stable. However, in situations where frequent and successive flow increases occurred, no further increase in drift was experienced after the initial flush of invertebrates.

Borchardt (83) used artificial laboratory flumes to simulate a lowland stream environment. He determined that two species of invertebrates began to drift at different critical velocities and that the presence of woody debris (as refugia) substantially reduced the incidence of drift. He determined that certain species of invertebrates make good use of refugia during high flow conditions while others are not adapted to use the refuge and therefore enter the drift at a greater rate. There is also significant evidence within the scientific literature that demonstrates that invertebrates will change position when faced with unfavourable velocity conditions. Edington (147) demonstrated that the caddisfly *Hydrophysche instabilis* (which favours high velocities) moved to an area of higher velocity when water velocities were reduced, and returned when velocities subsequently increased. Scullion (143) found an increase in invertebrate drift rate following an increase in stream flow. However, the increase in drift was short-lived rapidly returned to levels experienced prior to the velocity increase, suggesting that during peak discharge, many invertebrates sought some form of shelter. There is also evidence that some invertebrate species may move downward into the river substrate in response to flow increases (74, 148). Scott (149) demonstrated that larvae of the caddisfly *Glossoma* sp., inhabiting exposed stretches of a river, moved to sheltered microhabitats as velocities increased.

Lauters (31) examined invertebrate drift rates downstream of a hydro-peaking operation and compared them to natural drift rates (measured at an upstream site) in the same river. He found that, at the upstream site, drift was concentrated during the nighttime hours (a natural phenomenon). Nighttime drift occurred at a higher density at the downstream site compared to the upstream site. As well, uncharacteristically high drift densities were observed during the daytime. Lauters also noted a marked decline in drift following the end of a daytime peaking cycle and concluded that increased daytime drift was a result of the increased velocities experienced in the river during peaking flows.

Fish Microhabitat Studies

One of the predominant criticisms of instream flow methodologies is that rather than measuring actual biological response, modelled flow changes are assumed to be representative of this response (99). Early attempts to determine how fish reacted to changes in flow (51, 121,) relied on the physical trapping or capture of fish in artificial stream channels. More recently, advances in radiotelemetry have allowed response to flow change to be studied at the individual fish level. Perry (71) radiotagged individual fish in an attempt to determine how brook trout and Atlantic salmon responded to changes in flow. Results showed that fish habitat preferences were not consistent over the range of flows tested and that fish responded to increases and decreases in flow by adjusting position. Bunt (48) used radiotelemetry on individual brown trout to observe movement and habitat use in response to pulsed discharge from a hydroelectric generating station. He found that brown trout did not move great distances in response to flow changes, but did make small movements into different habitat types in response to flow. For example, during periods of high discharge the trout tended to move closer to shore into slower velocity areas provided by cover such as root complexes. These findings are similar to those of Pert (72), who use snorkelling observations to determine the response of individual fish to changes in flow. Holm (70) obtained similar results when he tested the response of juvenile Atlantic salmon to varying flows in a laboratory flume. These findings fundamentally challenge the assumption of many physical habitat simulation models, which assume that habitat preferences are consistent over a range of discharge. However, as pointed out by Heggenes (32), "…despite these limitations, habitat-hydraulic modelling can remain a useful tool in a "no net loss of habitat" management strategy regardless of these shortcomings."

Pert (75) used snorkelling to locate the preferred position of individual age 0 rainbow trout. The hydraulic gradient surrounding the focal point of individual trout was then determined. The distribution of focal point depths and velocities for the entire population of fish sampled were statistically similar to the distributions of depths and velocities surrounding the fish. However, at the individual fish level, focal point velocities and depth varied considerably from the hydraulic gradient surrounding the fish. It appears that the juvenile trout locate themselves in cells that are deeper and slower than their higher velocity surroundings. This finding has implications from a habitat modelling perspective since traditional habitat suitability criteria, which are based on focal point observations, may be less than adequate for describing trout habitat.

Fish Migration and Movement

The discharge regime of a hydroelectric facility can impact on migration and movement of fish downstream of the facility. For example, some hydro facilities generate downstream flow during peak hours (daytime) and eliminate flow below the power plant at night when turbines are not operating. McMaster (43) conducted experiments to determine if the complete elimination of flow at night would impact on upstream salmon migration and passage. McMaster determined that, regardless of whether there was nighttime flow or no nighttime flow from the facilities, there was no statistical difference in the number of fish moving through fish passages at the dams. McMaster also determined that elimination of nighttime flow had no statistical impact on the rate at which adult salmon and steelhead migrated (km/day) upstream.

Trepanier (5) found that the number of landlocked Atlantic salmon moving upstream through a fish ladder was higher in periods of decreasing flow than when flows were increasing. He cited other examples (131, 132) where movement of migrating fish corresponded to declines in the spring freshet and suggested that, although fish may begin to move into a river at the onset of the freshet, migration over the most difficult (i.e. steep) sections of stream likely occurs on the downside of the hydrograph.

Barnes (4) used a HEC 2 backwater hydraulic model to determine the range of velocities that would be encountered in the West Salmon River, downstream of a newly constructed hydroelectric facility. Barnes was able to demonstrate that the range of velocities experienced by migrating salmon would be within the velocities deemed acceptable by the licensing agencies. At the time, Barnes noted that very little information existed on the critical swimming speeds of the fish in question (landlocked Atlantic salmon and brook trout). Scruton (127) has recently undertaken the development of swimming speed criteria for these species in order to assist in the design of biological criteria for mitigation of velocity barrier problems associated with hydro facilities. This work has resulted in considerable additional information being made available on the swimming speeds of these species as well as brown trout, lake sturgeon and walleye. The swimming speed of numerous other species has been studied (6, 128, 129, 130)

Egg Incubation and Embryo Development

Fluctuating flows below hydroelectric stations can impact on the success of spawning, egg incubation and subsequent larval life stage of fish.

Reiser (41) examined the influence of streamflow reductions on chinook salmon and steelhead trout egg incubation, embryo development and fry quality. Reiser found that reduction in streamflow resulted in reduced embryo survival when the fines (fine substrates) in the redd were kept between 3 and 13%. At levels higher than 13%, embryo survival was more dependent on the concentration of fines than on the availability of surface flow. Reiser recommended that, in determining acceptable flow reductions, the amount of fines present in the sediment should be assessed first.

Both Reiser (41) and Shumway (155) emphasized the importance of intragravel velocities for oxygen supply and waste product removal during egg incubation. Reiser observed that intragravel velocities could be computed using the relationship developed by Bovee (150) between these velocities and mean surface velocities. Testing this method of computation, he found good correlation between computed and observed intragravel velocities. He recommended the computed method be used because extragravel hydraulic parameters are much easier to measure in the field than intragravel velocities.

Several studies have shown that salmonid eggs can tolerate periods of dewatering. Reiser’s studies on chinook salmon and steelhead (97) showed essentially no effect on hatching success when eggs were dewatered for 4 weeks (steelhead) and 1 to 5 weeks (chinook). Dewatering also had no effect on the development and growth rate of alevins and juveniles provided that sediment moisture was maintained at a minimum of 4 %.

Hawke (151) observed viable quinatt salmon eggs in redds which had been dewatered for three weeks in the Mathias River, New Zealand. In a laboratory test of the impacts of redd dewatering, Becker (53) determined that the pre-hatch phases of chinook salmon development were tolerant to dewatering, but that post-hatch (alevin) phases were highly susceptible. Eggs subjected to daily dewatering for periods of up to 22 hours over 20 consecutive days demonstrated no mortality. By contrast, nearly all pre-emergent alevins died when exposed to one hour daily dewatering. Stober (152) determined that, if sufficient intragravel space is present, some alevins could survive dewatering by descending through these spaces.

Reiser (97) cited the proximity of the redd to local groundwater elevations as one factor which might influence egg survival during dewatering. Reiser (97) and Becker (53) also cited the presence of fines as an influencing factor since fines can help keep eggs moist during dewatering by capillary action of subsurface water.

Chapman (52) found that flow fluctuations on the Columbia River at Vernita bar did not prevent female chinook salmon from building redds and laying eggs above the minimum flow elevation. Furthermore, he found that 84–87% of redds constructed above the minimum flow elevation and subjected to regular dewatering (eight hours per day) contained live embryos. He did not, however, quantify the number of live embryos present but rather used the presence/absence of any live embryo as an indication of spawning success. Although Chapman did not describe the nature of the substrate in which the redds were built, there was likely a reasonable representation of fines in the substrate which would have aided in moisture retention as per the discussions of Becker (53) and Reiser (41). Presumably, even if the eggs did survive to hatching, dewatering would result in the stranding death of newly hatched alevins.

Some researchers have noted behavioural response of spawning fish in relation to flow fluctuations. Bauersfield (153) found that successive dewatering of chinook salmon spawning grounds resulted in individual fish abandoning attempts to spawn and moving to sub-optimal spawning habitats. Hamilton (154) observed behavioural change in spawning salmon subjected to fluctuating flows. Female chinook salmon were observed to abandon a redd site when flows changed and then reinitiate redd activities when flow fluctuations ceased. Neither of these studies related behavioural responses of fish to impacts on the fish population.

Studies Dealing With Flow Mitigation

<u>Minimum Flows</u>

The establishment of a minimum flow downstream of a hydroelectric generating station is often considered when attempting to enhance the aquatic ecosystem. Although this method has been employed at a number of hydroelectric facilities across Canada, only a low percentage of facilities have actually monitored its effectiveness (98).

Weisberg (25) measured a marked increase in the total density of benthic organisms below the Conowingo Hydroelectric Dam when minimum summer flows were implemented. This increase was observed predominantly as increases in chironomid and hydrophyschid caddisfly densities. When the summer minimum flow was discontinued after September 15, the density of these animals declined two to three orders of magnitude. Although decreases in standing stock of these species of up to one order of magnitude can be expected due to natural fall mortality and subsequent drift, the observed declines were much larger. The greatest impacts of flow regulation on these invertebrate populations were noted in the shallow shoal habitats where the effects of desiccation are greater than in the main channel.

Weisberg (49) also found that both fish condition (weight at length) and growth rate (length at age) for white perch increased following institution of a minimum flow regime of 142 m^3/s in a river with a 3 m^3/s baseflow. Stomach content analysis of white perch, yellow perch and channel catfish revealed a decrease in the number of empty stomachs and an increase in the amount of food consumed following the start of minimum flow. Increases in benthic invertebrate abundance were cited as the main reason for the increase in consumption. Weisberg noted that these improvements were observed despite the fact that the frequency of flow peaking above 142 m^3/s remained unchanged following the institution of the minimum flow.

Wolff (100) measured a four- to six-fold increase in the standing stock of brown trout when minimum flow from a water storage dam was increased to 5.5 ft^3/s after 23 years at a minimum flow of 1 ft^3/s. Using the PHABSIM model, Wolff estimated that the increase in standing stock was associated with a doubling of wetted perimeter and an almost five time weighted useable area increase.

Weisberg (25) demonstrated that the increase in minimum flow from a hydroelectric generating station from 3 to 142 m^3/s increased the abundance of the filter feeding caddisfly *Cheumatophysche* sp. in the downstream benthic community by almost two orders of magnitude despite continued peaking of up to 1000 m^3/s.

Pope (7) determined that holding a constant flow during spawning period might force brook trout to spawn at certain elevations (equated to particular discharges). Then, by instituting a minimum flow during egg incubation, the redds would be protected from dewatering. Determining the minimum flow needed to achieve this protection required extremely detailed field observations of the elevation of brook trout redds in relation to various flows from the upstream hydro facility.

Flushing Flows

In general, regulation of a river for hydroelectric purposes tends to reduce the magnitude and frequency of peak flows relative to the natural hydrograph. In some river systems, the result can be that sediment downstream of the facility can accumulate, sometimes changing the physical characteristics of aquatic habitats, in particular spawning areas for fish. The response of river managers has been the desire to establish flushing flows that are released periodically from the dam to scour or clean the river downstream.

Reiser (91) was concerned with the removal of fines in the spawning gravels of the Feather River in California. Reiser recognized that the flushing flow required would need to remove the fines while leaving the gravel sizes critical for spawning. Reiser also noted that removal of fines laying on top of the gravels would require far less velocity than removal of the fines located in the armoured, interstitial areas of the gravel. This is consistent with the observations of Milhous (133). Reiser (91) measured hydraulic parameters over spawning bed areas at three different flows and then used extrapolation (Manning's equation) to develop depth-discharge and velocity-discharge curves at a variety of different flows. Using a standard shear stress index, he was able to predict the point at which bed material on the spawning beds would begin to move. He then recommended a flushing flow that would provide surficial flushing of both gravel and cobble but would maintain the majority of the critically limited spawning gravels in place. Nelson (54) provides a case study of the development of flushing flows in the Trinity River, California which used a similar methodology to Reiser (91) to determine flushing flows for various channel maintenance requirements. By calculating the predicted minimum velocities that would result in incipient motion capable of moving various bed materials, Nelson was able to recommend a flushing flow that would remove sand from spawning gravels but leave the gravels largely intact.

Cobb (94) noted that benthic insect densities declined in response to increasing discharge intensity and the associated movement of bed material. The disturbance of invertebrates must also be a consideration in the determination of flushing flows.

Wesche (134) recommended flushing flow requirements for a river proposed for development of water diversion facilities in Colorado. During construction of the facility, extreme rainfalls caused excess sedimentation of the river. Wesche then monitored actual movement of bed material in response to natural increases in river runoff (86). He was able to demonstrate that three peak discharges, which exceeded his flushing recommendation, were successful in reducing the quantity of material deposited by the spill.

Burt (84) provides a case study review of the use of flushing flows on the Big Qualicum River where flushing was used to improve the quality of spawning gravels.

Stalnaker (46) distinguished between flushing flows and channel maintenance flows. Flushing flows are those required to periodically clean the stream bed of accumulated fines while channel maintenance flows are those required to maintain channel form through processes such as the scouring of pools, and prevention of vegetation encroachment at the stream margin.

The methods used to determine flushing flows are varied and Reiser (42, 87) provided a comprehensive review of available methods at the time. Reiser concluded that remarkably few formal methods had been established for prescribing flushing flows in streams and few of the available methods had considered all necessary aspects of a flushing flow (magnitude, timing, duration and effectiveness). Milhous (135, 170) has expanded on the variables to be considered when calculating flushing flows.

More recently, Milhous (169) proposed a new method of instream flow modelling which was applied to the Gunnison River in Colorado to determine the flushing flows required to remove fines from spawning beds, remove coarse sediment from pools and to create side channels and backwater areas used as nursery habitat. The modelling approach incorporates the definitions of habitat requirements as well as a hydraulic component that determines the flows required to attain the biological goals identified. The model also includes a selection component that identifies the required magnitude, frequency and duration of flows required.

Natural Attenuation

The hydraulic response of a river in relation to changes in discharge from a hydroelectric facility varies both as a function of channel morphometry and distance downstream from the discharge. In a study of flow regulation on the Nipigon River (7), the change in river stage following a large drop in plant discharge was significantly muted downstream of a large lake. The buffering effect of the lake was dependent on the initial elevation of the lake following the decrease in discharge. A hydraulic response study on the Magpie River (126) found that rapid changes in plant discharge were attenuated at brook trout spawning areas downstream of the plant. In this instance, the dampening of hydraulic effects was due to a series of natural pool areas located on the river. Hunter (73) cites examples of attenuation increasing as the distance downstream of the discharge point increases. He cautions, however, that depending on specific river morphology, maximum decrease in river stage may not necessarily occur at sites immediately downstream of the discharge, but rather, at some distance away.

Downramping Control to Minimize Stranding

A potential impact of flow regulation is fish stranding downstream of a hydroelectric generating station. Stranding occurs when a fish is isolated from the flowing surface of a river as a result of rapid flow decreases.

Stranding research has focused mainly on salmonids and has been associated with flow regimes downstream of hydroelectric operations (24, 26, 39, 122, 153 160).

When water temperatures drop below 4-8 degrees Celsius, salmonids tend to associate closely with cover and may conceal themselves in the interstitial area of rock and cobble substrates (164, 165). Moreover, Woodin (122) found that the incidence of juvenile salmonid stranding is higher when downramping occurs during the day as opposed to during hours of darkness. This is consistent with the findings of Saltveit (163). Bradford (92) speculated that this may be because salmonids tend to conceal themselves in interstitial gravel during the day but move freely throughout the water column at night (161,162). To test this theory, Bradford (92) simulated rapid flow decreases at low temperature (3.5-4 degrees C) in artificial stream channels designed to mimic gravel bar conditions and measured the response of coho salmon and rainbow trout juveniles. He found that stranding rates for both species were much higher during the daytime than at night. He also observed that during the day both the cohos and rainbow trout sought cover by burrowing into the gravel substrate. At night, most fish swam freely in the water column and did not seek cover. Bradford (93) found that the incidence of chinook salmon fry stranding on artificial gravel bars increased by up to six times when temperature was reduced from 12 to 6 degrees Celsius. Saltveit (163) also found higher incidences of stranding when water temperatures were less than 4.5 degrees C.

Bradford (93) also simulated the effects of ramping on fish occupying side channels or pools. He noted that during dewatering, 5-25% of the chinook salmon fry in side channels were trapped at a drawdown rate of 6 cm/hr. When the drawdown rate was increased to 30 cm/hr, the percentage of fish trapped was 30-40%. River morphology determines whether side channels and potholes exist which will be isolated from the main flow during flow reductions.

Higgins (56) noted that catastrophic stranding of juvenile coho and chinook salmon and rainbow trout in side channels of Bridge River, British Columbia occurred when flows receded rapidly following a snowmelt-induced flood.

Some authors, on the basis of experience gained from stranding experiments, have recommended rates of water level decline to minimize stranding of juvenile salmonids (73, 92). Recommendations range between 2.5 to 6 cm/hour.

Conclusion

One of the main purposes of carrying out this literature review was to determine results of research that has been carried out to date with respect to fluctuating flow regimes downstream of power plants. From this determination, we hope to focus the scoping efforts of the ESSRF team to identify knowledge gaps and to develop experiments that will provide a basis for recommending instream flow regimes below hydroelectric facilities. Several key points, emerging from the review, warrant consideration by the ESSRF team:

- The study team will have to consider at what scales (temporal and spatial) the experiments will be carried out. The recognition of the scale at which ecological response is measured is critical to the success of the experiment. Separating the influence of large-scale (i.e. regional hydrology, basin morphometry) impacts from flow related impacts would be the challenge.
- Existing research has focused predominantly on salmonids, in particular chinook salmon, Atlantic salmon, rainbow trout and brook trout. Since understanding is limited to these species, the applicability of using this knowledge in designing experiments for systems containing diverse communities remains a concern.
- The use of fish growth as a parameter for measuring response to flow manipulation appears problematic since many factors affect fish growth.
- The use of guilds may simplify examination of multispecies systems. Guilds can be used in physical habitat simulation modelling and have also been used in measuring specific response of fish populations to flow manipulation.
- Criticism of hydraulic habitat simulation models is considerable. One of the main concerns is the inability of these models to relate habitat area to actual fish abundance or biomass. In addition, ineffective transferability of species specific HSI curves from one physiographic region to another creates the

need for costly and time-consuming development of site specific HSI relationships.

- Hydraulic habitat simulation models assume that fish habitat preferences are constant over a range of discharges. Studies on the response of individual fish to flow manipulations indicate that fish adjust their position as hydraulic conditions in the channel change. Therefore, the absence of ideal habitat (as per HSI curves) may not be as critical as these models indicate. The bioenergetic costs associated with constantly adjusting position in response to flow have yet to be studied.
- In terms of fish stranding, the rate and time of day at which flows decline are critical factors. To date, only laboratory data (i.e. artificial shoals and side channel) have been used to recommend drawdown rates. Field observations of stranding in relation to flow are needed. The literature cautions, however, that stranding in the field can be grossly underestimated because fish stranded in the interstitial spaces of the substrate may not be counted. Stranding of fish is not influenced solely by rate of drawdown. Water temperature and light (night vs. day) also influence degree of stranding and must be considered in any experimental designs.
- Invertebrates have been, by far, the most popular test group for determining aquatic ecosystem response to flow. Separating the invertebrates into functional feeding groups (as per Merritt and Cummins (171)) appears to be quite popular and also reduces the degree of taxonomic analysis as well as data analysis. The disadvantage seems to be that a high number of samples

are required to achieve statistical validity, mainly because of inherent natural variability in invertebrate distribution.

- Invertebrates provide the opportunity to examine both standing crop and drift. With stomach content analysis of fish, invertebrate drift can be correlated with fish feeding thus linking two aspects of the aquatic environment. However, any experiment must distinguish between drift induced by flow changes and natural drift (i.e. nocturnal drift).
- Invertebrates seem to be more responsive to the temporal aspects of flow fluctuations (frequency, duration, and seasonality) than are fish.
- There is a significant body of evidence to suggest that fish eggs (at least salmonids) may tolerate certain degrees of dewatering. Aspects that control the degree of tolerance include proximity to groundwater and degree of fines present in the redd.
- River morphology plays an important role in terms of attenuating the impacts of flow fluctuations. The ESSRF study should consider stratifying the test rivers according to channel form to determine the impacts of river morphology on reducing effects of fluctuating flows.
- The occurrence of high water events (overbank discharges) downstream of the hydro facilities appears to be important from a floodplain-river nutrient and productivity exchange perspective. The reduction in frequency of these events, through regulation (i.e. dampening of peak flow), is one possible aspect of flow regulation that might be studied.

- Impacts of flow regulation on fish and invertebrates have been studied mainly in the shallow margins of rivers. It appears that little consideration has been given to impacts within the main channel, which does not necessarily dewater but may undergo significant changes in hydraulics as a result of flow change.

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