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The Environmental Impacts of Run-of-River Hydroelectric Projects in British Columbia

FRST 497 Grad Essay

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Abstract

Run-of-river hydroelectric schemes have grown rapidly in British Columbia since BC's 2002 Energy Plan was released. These projects are often claimed to be one of the most environmentally friendly methods of electricity generation, in particular as a tool to combat climate change. However, the body of literature on the subject highlights that these facilities have the potential to have wide-ranging impacts on the environment. Changes to abiotic factors in the aquatic system brought about by these projects include increased temperatures, reductions of in-stream flows, increased fine sediment concentrations and rapid changes to discharge. These abiotic alterations lead to biotic impacts: namely, reducing the quantity and quality of available fish habitat (in particular to Salmonids) as well as reducing the amount of aquatic invertebrates, a primary food source for fish. Moreover, to have these projects operational, they require dozens of kilometers of linear infrastructure, most notably rehabilitated resource roads and newly constructed transmission line networks to connect to BC Hydro's grid. The upshot of my research indicates that run-of-river projects are not as environmentally benign as some would have the public believe, and it is uncertain whether their climate change mitigations trump their immediate aquatic and terrestrial impacts.

Introduction

Defining Run-of-River

Run-of-river is a particular method of generating electricity from the flowing water in streams. While there are many forms of hydroelectric generation that harness the gravitational potential energy of water, what distinguishes run-of-river from the rest is the absence of a dam and reservoir (Cleantech Investor 2008). Run-of-river projects also operate on a much smaller scale, in terms of electricity production: the capacity of a project usually ranges between 1 – 50 megawatts[1] (MW). Relative to other hydroelectric projects in BC such as the W.A.C. Bennett Dam, with a capacity of 2,876 MW, or the recently approved 1,100 MW Site C Dam, run-of-river projects are comparatively small. In place of a dam and reservoir, these projects store very little water (or none at all) behind a small weir[2]. The weir produces a small headpond, or a pool of low velocity water, behind it. The purpose of the headpond is to promote quiescent, efficient flow into the intake of the water pipeline, called a penstock, and to ensure that water depths are sufficient to keep the penstock intake constantly submerged. Keeping the penstock constantly submerged is critical to avoid cavitation[3]. In order to be called a run-of-river project, the headpond cannot contain more than 48 hours of water supply to the system (Cleantech Investor 2008). A portion of the water volume in the headpond is diverted down this penstock to a powerhouse at a lower elevation. The rest of the water in the stream that was not diverted flows freely over the crest of the weir and resumes its downhill flow in its natural channel. This segment of the original channel, between the point of diversion and the point at which water is returned, is known as the diversion reach. The powerhouse contains turbines and generators and it is here that the electricity is ultimately harnessed. All of the diverted water is then fed back into the original channel, downstream, by way of a tailrace. Proponents of these projects claim they are one of the most environmentally friendly forms of energy production, seeing as, among other things, they do not inundate a large area, that the facilities are located in reaches of streams that are above natural fish barriers so as to avoid adverse effects on anadromous fish populations, and that once a run-of-river hydroelectric project is constructed, it emits no greenhouse gasses over its life cycle.

[1] A megawatt (MW) is a unit of power equal to 1,000,000 Watts.

[2] A weir raises the level of water upstream of it and allows water to flow over the top of it during high water levels. A dam impounds water and routes it to an intake or spillway.

[3] Cavitation is the formation of air bubbles that become entrained in the water entering the penstock. This may cause implosion and damage to the interior wall of the penstock and to hydromechanical equipment.

Run-of-River's Growing Popularity

Independent Power Producers (IPPs) are private sector firms that produce energy through a variety of methods, such as solar, wind, hydro and biomass. Most run-of-river projects in British Columbia are operated by IPPs. These IPPs subsequently sell the electricity they have produced to BC's public utilities Crown corporation, BC Hydro, under the terms of what is known as an Electricity Purchase Agreement (EPA). The companies that own and operate the run-of-river IPPs in BC are a mix of publically traded corporations, such as Innergex Renewable Energy Inc. and Alterra Power Corp., as well as private companies that are not listed on any stock exchange, such as Narrows Inlet Hydro Holding Corp. and Enmax Corporation. Although the Independent Power Producers Association of BC (IPPBC) was created in 1992, it was in 2002 when IPPs in BC began to grow in earnest. There were some run-of-river projects in operation prior to this date (e.g. Lower Mamquam), but it was in November 2002 that the BC Liberal's announced their new Energy Plan. Among other things, this piece of legislation mandated that all future electricity generation in the province would come from the private sector, with BC Hydro's role reduced to improvements at existing plants (Province of BC 2002). Furthermore, what with BC's goals, as stated in the province's 2007 Energy Plan, of becoming "energy self-sufficient" by 2016 and for all new electricity generating facilities in the province to emit zero net greenhouse gasses (GHGs), "green" IPP's were one tool in which to achieve these goals. Run-of-river was particularly attractive to developers due to the aforementioned enabling and supportive legislation, but also due to run-of-river's GHG-free and renewable nature, as well as BC's suitability for this form of energy production (tremendous precipitation, snowpack and topographical relief). Furthermore, the reliable and known revenue stream that would be paid to IPP's from BC Hydro under the terms of the EPA's they signed (which were up to 40 years in length) provided an attractive, and certain, investment climate for private sector developers who were able to accurately predict profitability for their owners and shareholders decades into the future.

When BC Hydro commissioned the consulting firm Kerr Wood Leidal Associates Ltd. (KWL) in 2007 to conduct an inventory of BC's run-of-river potential using geographical information systems (GIS), they found that there were 8,242 potential sites around the province, capable of producing 12,384 MW (BC Hydro 2007). Granted, many of these sites were economically unfeasible in the current electricity market; indeed, of the 8,242 potential sites identified, just 121 (or 1.4% of the sites), comprising 1,388 MW, would cost below $100/MW, a rough metric for project profitability that the report used. This can at least partially be attributed to the remote nature of much of the province, in particular the mainland coast of BC. For instance, between Pemberton, BC and Bella Coola, BC, there is a remarkable 350 km stretch of the province where there are no paved roads or any settlements. Aside from a few isolated logging camps at the heads of the fjords that penetrate the Coast Mountains, it is mainly devoid of human habitation and as a result the majority of the region is not connected to the BC Hydro grid. This terrain would provide excellent hydroelectric generation due to remarkable hydraulic head[4] and countless high volume streams draining massive snowpacks and icefields. However, the remote nature and great distance from the BC Hydro transmission network means that access and powerline costs make most of these projects prohibitively expensive. Many developers have realized, as the report indicates, that "clustered developments…could greatly improve cost effectiveness of many projects" (BC Hydro 2007, p. 60). A cluster project is a series of run-of-river diversion projects in the different tributaries of a single watershed. It is cost effective as the per-unit-power cost is less because roads and transmission lines can be shared for the component projects. The hydro project in the Toba River valley and the proposed projects in Bute and Knight Inlets are examples of cluster projects.

The point in mentioning the KWL report is that the sheer number of potential developments in the province is concerning, regardless of how seemingly benign these small projects purportedly are, or even how small a fraction of them that will actually be constructed. It is especially concerning, too, in light of the fact that there is little in the way of land use planning for the sector. Furthermore, since they produce much less electricity than large hydro projects, it is uncertain whether the environmental impact per MW of energy produced is any less than a few select mega projects. As it stands, many of these potential sites have been developed by numerous companies since the 2002 Energy Plan (although several were constructed prior to 2002): as of October 1, 2014, there were 51 "non-storage hydro" IPPs, a term synonymous with run-of-river (i.e. less than 48 hours of water storage), supplying 1,016 MW of electricity to the BC Hydro grid (BC Hydro 2014). Also, BC Hydro has signed 21 more EPA's with run-of-river IPPs that are currently in development and construction stages, that will supply a further 994 MW of non-storage hydro capacity when they eventually come online in the next few years (BC Hydro 2014).

[4] In the hydrology vernacular, hydraulic (or elevation) head refers to the vertical distance between the intake of a penstock and the turbine. The higher the head, the greater the water pressure exerted onto the turbine and the greater the power that may be generated

Essay Objective

The growth of the sector has been impressive across the province. The sector has, however, also been a very contentious issue with regards to the environmental impacts of these projects. Csiki and Rhoads noted that, "compared to the impact of large impoundment dams, the effect of run-of-river dams on the geomorphology of rivers has received scant attention" (2010, p. 774). It is not just the geomorphological effects that have been ignored, either, according to certain groups. Environmental organizations (such as the Vancouver-based Wilderness Committee) have argued that the environmental impacts, such as fish mortality and the land clearing required for the construction of transmission lines, roads and penstocks, have largely been ignored under the guise of "green energy" in favour of economic development. Therefore, it would be appear there is a discrepancy between what the government and industry are saying and what some environmental groups are saying on what impacts, precisely, these projects can have on the environment. In that vein, this essay's primary objective is to fill that knowledge gap with unbiased and science-based information. It will comprehensively highlight and identify the range of impacts run-of-river has on BC's environment, both aquatically and terrestrially. To achieve this objective, the literature pertinent to the topic will be searched and summarized. Furthermore, I will draw from local hydro projects in south west BC to better illustrate and quantify their effects.

Run-of-River's Environmental Impacts

The effects that run-of-river has on its surrounding environment can be subdivided in a number of ways. This essay proposes to break the impacts into two relatively discrete areas. First will be the aquatic impacts. This will include abiotic impacts (i.e. the impacts regarding non-living entities such as water and sediment), as well as the biotic impacts, demonstrating just how living organisms are influenced by these projects. Obviously, there is a causal link between many of the abiotic impacts and the biotic impacts. The second and last impact class that this essay will bring to light is the terrestrial environmental impacts of all the associated linear infrastructure needed to have a run-of-river operation working. This includes resource roads to access the facility, the penstocks to transport the water downslope to the powerhouse, as well as the transmission lines that are necessary to ultimately bring the electricity to market. Each will be discussed in turn, drawing from the relevant literature and from local examples.

Aquatic Impacts

Reduced in-stream flows

One of the most immediate and obvious impacts of these projects is the reduction of stream width, depth and velocity in the diversion reach, the segment of stream between the point of diversion and where the tailrace discharges all the water back into the stream. The greater the volume of water that is diverted from a stream, the more power that the project can produce and subsequently sell to BC Hydro. Therefore, there is a financial incentive for IPPs to divert as much of the stream's volume as possible. The provincial government, under the Ministry of Sustainable Resource Management and the Ministry of Water, Land and Air Protection, have developed a procedure for how a water licence applicant can determine the instream flow requirements for streams, depending on if those streams are fish-bearing or non-fish-bearing (Hatfield *et al.* 2003). The instream flow thresholds serve as a "coarse filter" during the review of proposed projects, to allow the proponents to assess whether adverse effects to fish are likely to occur. It should be noted that these flow thresholds set by government are not legally binding decision rules and do not define whether any given project should be approved. If the applicant has good quality physical and biological data, "it may indicate that it is safe to undertake water diversions in excess of the thresholds" (Hatfield *et al.* 2003 p. vi). If the run-of-river developer does not, however, have more in-depth data, then they assume much more risk and uncertainty by exceeding the government-set thresholds without conducting any further assessments, as they will be deemed to not have exercised due diligence and therefore be liable if their actions negatively affect the environment. As mentioned, the recommended flow threshold for a given stream depends on whether it is fishless or fish-bearing. For fishless streams, the instream flow requirement (for the entire year) is equivalent to the median monthly flow during the low flow month for that given stream. For streams that are fish-bearing, the instream flow requirements are seasonally-adjusted; they vary throughout the year, allowing less water to be available for diversion during low flow months and allowing more water to be available for diversion during high flow months. They are calculated as percentiles of natural average daily flows for each month. To ensure higher protection during low flow months, the percentiles vary throughout the year.

According to Hatfield *et al.* (2003), the authors of the Government's instream flow requirements, the fishless stream diversion thresholds allow "on average almost 50% of flows to be diverted" (p. 59), based on a set of BC test streams, both interior and coastal, the authors modelled. For fish-bearing streams, the diversion rules allowed, on average, approximately 22% of flows to be diverted on the same test streams. According to a report by the Watershed Watch Salmon Society, however, the percentage of water diverted appears to be considerably higher on some projects. For instance, based on the project's submissions to the BC Environmental Assessment Office, the run-of-river facility on Dalgleish Creek, part of the Upper Toba project north of Powell River, has an allowed diversion flow of 5.7 m^3/s and a minimum instream flow requirement of only 0.18 m^3/s (Gower *et al.* 2012). In other words, in the case when the volume in the diversion reach is equal to the minimum instream flow requirement, just 3% (0.18 m^3/s of a total flow of 5.7 m^3/s) of the stream's volume will be flowing in the diversion reach; 97% of the stream's total volume will be diverted down through the penstock. Other projects, too, appear to have similarly high maximum diversion rates, such as Ashlu Creek (92%), Tyson Creek (95%) and Kwoiek Creek (96%), to name a select few (Gower *et al.* 2012).

A plausible answer to this discrepancy may lie in the fact that run-of-river applicants are able to reduce their instream flow requirements, rather than rigidly following the guidelines created by Hatfield *et al.* (2003). For instance, in the Environmental Assessment for the East Toba River Montrose Creek Hydroelectric Project, it states that "the Ministry of Environment is concerned that the Proponent is proposing in-stream flow releases that are substantially lower than the minimum flows recommended in the BC In-stream Flow Guidelines" (BC Environmental Assessment Office 2007 p. 53). The proponents requested, successfully, to reduce the in-stream flow requirements by around 50% for the two project streams (East Toba River and Montrose Creek), from 1.56 m^3/s and 0.99 m^3/s, respectively, to 0.70 m^3/s and 0.52 m^3/s, respectively. The proponents' rationale was that the Ministry guideline represents an average of all streams across the province and thus does not correctly apply to the cold, turbid, oligotrophic streams draining the Coast Mountains, where Toba Inlet lies. They also were quite frank in admitting that the Ministry requirements have "a direct bearing on project finances" and thus "compromise Project feasibility" (p. 54).

Biotic effects of reduced flow

In any event, when at least 50% of the volume of a stream is reduced, there will certainly be ramifications for the biota that depend on that stream. Reducing the volume, the width and the depth of a stream decreases fish habitat, defined in the fisheries Act as "spawning grounds and nursery, rearing, food supply and migration areas on which fish depend directly or indirectly in order to carry out their life processes" (Government of Canada 1985, Section 34(1)). The amount of fish habitat is generally thought to have a positive correlation with fish production and, indeed, this forms the basis of much of the existing legislation and policy. Bradford et al., for instance, posit that "the production of [coho] smolts from freshwater habitats appears strongly limited by the availability of suitable physical habitat" (p. 678). Despite the fact that these projects are typically above migration barriers to anadromous fish, such as a waterfall, there are still resident salmonids in the majority of those streams: the Pacific Salmon Foundation found that salmonids were present upstream, in the diversion reach, or downstream at 43 of the 44 operational run-of-river facilities that were studied (Connors *et al.* 2014). Most of these were resident salmonids; however, 19%, 7% and 2% of the facilities studied had anadromous salmonids in the downstream reach, in the diversion reach and in the upstream reach, respectively. This study also concluded that, based on the limited data available, most run-of-river projects are not likely causing a decrease to salmonid abundance. In the 44 sample sites, it was "likely" in just 1 project that salmonid abundance had changed in the upstream reach and in the diversion reach as a result of the run-of-river project, but "possible" in 30 and 36 facilities, respectively (Table 1). Also, it was "likely" in 0 of the projects that downstream reach abundance was negatively impacted. The authors' rationale for a conclusion of "possible", as opposed to "unlikely" or "not possible", was because of no data, inadequate monitoring and/or ongoing monitoring.

Table 1 - Summary of conclusion reached by stream section when considering the hypothesis that salmonid abundance / species composition has changed as a result of the operation of a run-of-river hydroelectric facility. Formatted from Connors *et al.* 2014.

	Not Possible	Unlikely	Possible	Likely	Rationale for "Possible" conclusions[a]		
					% no data	% inadequate monitoring	% ongoing monitoring
Upstream reach	12	1	30	1	80%	17%	3%
Diversion reach	7	0	36	1	58%	17%	25%
Downstream reach	5	0	39	0	87%	5%	8%

[a] Rounded to nearest percent

The reduction in water volume not only decreases the available physical habitat for salmonids, but also for benthic invertebrates (aquatic insects). The production of benthic invertebrates in the diversion reach will also likely be reduced as a result of the reduction in available habitat (Gower *et al.* 2012) and will thus have a reduction in the drift of insects that otherwise would have travelled downstream to subsidize downstream fish populations. Wipfli *et al.* (2007) noted that invertebrates (both terrestrial and aquatic) are transported from headwater streams to aquatic habitats lower in the drainage and that this material transport can, in some instances, support "up to 2,000 juvenile fish per kilometer of stream length in downstream habitats" (p. 78). Moreover, not only is the quantity of habitat being reduced for salmonids (i.e. through a reduction in water volume in the diversion reach), but also the quality is being negatively impacted by the reduction in the supply of large wood to lower reaches of the watershed, because the reduced volume has less carrying capacity to transport large wood. The point in mentioning this is that although some of the headwater streams may not directly hold fish – whether that be the salmonids that our society has placed a high importance on for economic and cultural reasons, or other more obscure species – these headwater streams are critical to the vitality of entire river networks, including the fish-bearing reaches further downstream.

Changes to sediment levels

These findings highlight that run-of-river hydroelectric projects do indeed have a significant reduction in the volume of water in the diversion reach. This flow depletion leads to other abiotic changes, such as alteration to the capacity of fine-sediment transport. A study of 13 mountainous streams with flow diversion dams in Colorado and Wyoming States found that the stream reaches downstream of diversions contained significantly more fine sediment and low velocity habitat, relative to control reaches above the diversion. The theory is that fine sediment is deposited in the diversion reach and accumulates there, as the reduced volume and velocity there similarly reduces the capacity of that segment of stream to keep the sediment suspended. The researchers did, however, find this to be more evident on stream channels with a slope less than 3%. Channels with a greater slope than this threshold of 3% did not display any significant difference in the amount of fine sediment. Most run-of-river projects in BC are in much higher gradient streams due to topographical and economic reasons, as a high hydraulic head (elevation difference) allows more potential energy to be converted into electricity. For instance, the three component streams of the Upper Toba Hydro Project (Dalgleish Creek, the Upper Toba River and Jimmie Creek) have average stream slopes of 21.8%, 8.4% and 9.7%, respectively (BC Environmental Assessment Office 2009). There is scant information on whether these findings on Colorado and Wyoming rivers can be applied to streams in British Columbia.

Run-of-river projects can also cause more discrete, and more dramatic, sediment release events. A great example of this occurred in 2009 at the Tyson Creek IPP, which incidentally has the highest head of any hydro project in North America, at 865 m. It is located near the head of Narrows Inlet and the mouth of the Tzoonie River, approximately 50 km north of Sechelt, BC. This IPP was unique in that it used a high elevation (1400 m) alpine lake as its headpond and the penstock actually taps into the lake from its bottom. When the IPP was up and running, it began to draw down the level of the lake, as was planned. The bottom of the lake was composed of fine glacial flour, no doubt deposited by the recent glacial history of the region. However, the drawing down of the lake caused an underwater slide of glacial flour which subsequently entered the penstock. The company's President and Senior Engineer, Peter Schober, described the aftermath: "a milky trail of turbid water stretched from our tailrace down into Tyson Creek, along the Tzoonie River, and out into Narrows Inlet" (Schober 2010, p. 54). These types of events are relatively rare but still demonstrate how these projects can quickly have dramatic adverse effects on the local environment.

Biotic effects of increased fine sediment accumulation

A sudden accumulation of fine sediments in reaches of streams not historically exposed to it poses threats to the biota that inhabit those streams. For instance, Suttle *et al.* (2004) warned that if "land uses that increase loading or decrease transport of fine sediments continue unabated…areas of formerly suitable juvenile rearing habitat may be lost from the riverbed long enough to cause irreversible population declines in resident salmonids" (p. 973). Their research demonstrates that any deposition of fine sediment, even at low concentrations, can decrease growth and reduce the survival of juvenile salmonids. An unregulated stream tends to have series of pools and riffles that provide variations in water velocity and depth (Wu 2000). When sediment is deposited in these stretches, the pool-riffle sequences tend to become less defined and more homogenous, resulting in a net loss of quality habitat. Moreover, the intrusion of fine sediment into spawning gravels can limit the supply of oxygenated water to developing salmonid embryos and similarly decrease the removal of their metabolic wastes (Wu 2000). Wu notes that this reduction in the dissolved oxygen content (DOC) is concerning, because DOC is positively correlated with juvenile salmonid survival. Yet another threat of fine sediment accumulation is the fact that this deposition of fine material can effectively smother the incubating eggs and entomb alevins. Increased fine sediments can also irritate a fish's gills and sometimes induce mortality (Robson *et al.* 2011). These above examples have shown the effects of increased fine sediment directly on the fish or the fish habitat, but benthic macroinvertebrate communities are likewise negatively impacted. Kaller and Hartman (2004) found a consistent negative relationship with abundance of fine particles less than 0.25 mm and taxa richness of insects in the Ephemeroptera, Plecoptera and Trichoptera families in their studied Appalachian streams. This relationship did, however, only exist beyond a certain threshold of fine sediment accumulation, and it is uncertain how well it may apply to British Columbian streams. Regardless, even a potential reduction of insect biomass – a primary food source of many salmonids – is a concerning side effect of run-of-river facilities in BC.

Ramping Rates

Flow ramping can be defined as "a progressive change of discharge in a stream channel" (Department of Fisheries and Oceans 2005, p. 2). A ramping rate, by extension, is the rate of change of discharge, measured as flow per unit time, usually in units of $m^3/s/s$. Ramping usually occurs as a result of starting up or shutting down the turbine(s) which necessitates increasing or decreasing the flow diverted from a stream, respectively. Obviously, a glance at any river's hydrograph will show that ramping is a natural hydrologic process that occurs naturally in response to seasonal changes, precipitation events, etc. Run-of-river operations, due to minimal water storage, generally cause much more rapid changes to flow, on a time scale ranging from seconds to hours (DFO 2005). These flow changes exceed in rapidity of onset, magnitude, frequency and duration of those recorded under natural conditions and warrant closer examination of their effects.

"Up-Ramping", or a positive change in discharge (i.e. discharge in the diversion reach is increasing, perhaps because the turbines are shutting down for planned maintenance) has effects that may vary from site to site. In general, this type of ramping typically has the effect of altering the channel morphology by scouring the river bed. This material might then subsequently be deposited at gravel and sand bars, where eggs and alevins may be present, smothering them. Even the Department of Fisheries and Oceans concede that the "effects on aquatic habitat due to rapid increases in flow have not been well documented to date" (Department of Fisheries and Oceans, p. 12).

"Down-Ramping", or a negative change in discharge (i.e. discharge in the diversion reach is decreasing), has greater potential to directly result in fish mortality. The stranding of fish as a result of rapid reductions in stream depth is a serious ecological problem associated with hydro projects that abnormally alter the flow regime of streams (Irvine *et al.* 2009*).* Stranding may occur by entrapping fish in a side pool that becomes isolated from the main channel, by beaching the fish on land if they are caught above the water line as it decreases, or by the subsurface dewatering of the interstitial spaces (voids) of the coarse substrates used by fish. Ramping has other effects, too: it can lead to dewatered substrate gravels which in turn may lead to egg desiccation and death if stream levels are too low for a prolonged period of time. However, studies have shown that the eggs of salmonids are able to survive for weeks in dewatered gravel, so long as they are kept moist (Casa-Mulet *et al.* 2015). Ramping also may inhibit growth of and deplete the food source of aquatic invertebrates (e.g. by reduced transport of large wood, used by detritivores as food). Similar to instream flow requirements, run-of-river operations also have to comply to ramping rate regulations. The DFO allows a maximum rate of ramping of 2.5

cm/hr when fry are present and 5.0 cm/hr at all other times (Lewis *et al.* 2013) However, when the Wilderness Committee was granted access to an internal report compiled by the Ministry of Forests, Lands and Natural Resource Operations through a Freedom of Information request, they learned that there were over 300 instances of ramping non-compliance on just the 16 facilities on the South Coast in the year 2010 alone (Menezes 2012). Granted, the majority of these ramping non-compliances occurred at just four facilities (Upper and Lower Clowhom, Montrose and Lower Mamquam) and just three projects were known to have stranded and killed a total of 94 fish in that year. This is perhaps not a considerably large amount of fish mortality, but it certainly highlights that these projects can and do kill fish. Moreover, the amount of non-compliance to the regulations that are intended to preserve the aquatic habitat is worrisome.

Changes in temperature

Water temperature has been called "the abiotic master factor for fishes" (Brett 1971, p. 99). The growth of fish is affected by temperature, either directly or indirectly, and is manifested through changes in spawning, migration and feeding behaviour, timing of development and the production of food organisms such as insects. Run-of-river schemes reduce water volume in the diversion reach, as we have learned. Robson *et al.* (2011) noted that in depleted stretches of streams caused by reductions in stream flow, stream temperatures can increase as a result of both the shallower water and reduction in wetted area. This increase in temperature may not actually be a bad thing as it may allow fish to grow faster and larger, increase the probability of survival and shorten time to maturity (Gower *et al.* 2012). This is because fish such as salmon, for instance, respond to thermal cues. However, it may lead to a mismatch between the particular life cycle stage an individual fish is in and the environmental conditions. For instance, the much studied Carnation Creek Valley on Vancouver Island experienced increased stream temperatures in all months of the year due to large scale clear-cut logging of the watershed (Holtby 1988). This increase in stream temperature was associated with earlier emergence of Coho salmon fry and larger and more abundant yearling smolts. However, the increased temperatures also resulted in earlier seaward migration of smolts which the author stated likely resulted in decreased survival rates of smolts becoming adults in the marine environment. In this case, the abnormally warmer water temperatures resulted in salmon migrating to sea earlier than usual, which in turn resulted in less marine survival. Another way water temperature may harm fish is directly: if water temperatures exceed the species' upper lethal temperature thresholds it will stress and may kill fish.

Gower *et al.* (2012) also raised the point that in winter it is possible that a reduction in stream flow might also increase the possibility of harmful ice formation. This ice may either take the form of anchor ice (which forms on the bottom of the stream) or as frazil ice (which is a collection of loose, randomly oriented needle-shaped ice crystals in water). Frazil ice is particularly harmful to fish as it can scrape and irritate a fish's gills and may lead to suffocation. However, the authors did concede that not enough is known about ice formation in rivers affected by flow diversion, or its effects on fish and other aquatic life.

Terrestrial Impacts

The effects of a run-of-river hydroelectric facility on its environment do not only occur in the stream channel it is situated in. In order to have these facilities in operation and in order to bring the electricity to market, these projects also require linear infrastructure such as penstocks, resource roads and transmission lines. The physical effects of roads, in particular on the hydrologic and geomorphic watershed processes, have been well studied and documented (Gucinski *et al.* 2001) and the biological impacts have likewise been well understood. In the interests of brevity, this essay will be unable to parse apart the entire gamut of physical and biological effects of resource roads in great detail. It will, however, describe the high-level range of impacts. To begin with, the geomorphic effects of resource roads are an increase in sediment erosion and transport (Rood, 1984). This can range from long-term chronic contributions of fine sediments into streams to more catastrophic and discrete mass movement events. The contribution of fine sediment to streams occurs due to surface erosion from road surfaces, cut banks and ditches and this usually represent one of the most significant sources of road-related sediment yield to streams. This sediment production from road surfaces changes through time: it tends to be highest in the years immediately following road construction and diminish rapidly over time (Fredriksen 1970). The road-related sediment yield caused by landsliding and other mass wasting events, however, sometimes may surpass the chronic sediment yield from road surfaces, but this typically occurs only in the aftermath of extreme storm events (Wemple *et al.* 2001).

In terms of hydrology, Gucinski *et al*. noted that roads have three primary effects on water: "they intercept rainfall directly on the road surface and road cutbanks and intercept subsurface water moving down the hillslope; they concentrate flow, either on the surface or in an adjacent ditch or channel; and they divert or reroute water form flow paths that it would take were the road not present" (p. 16). The results of these processes include increasing the density of streams in the landscape (by intercepting subsurface and surface flows and concentrating it in ditches, channels etc.) and altering the timing of peak flows. Many road problems occur as a result of inadequate road layout and engineering, in particular at stream crossings. When culverts, for instance, that were designed and sized to only accommodate water, become obstructed by wood and sediment, the water may spill onto the road surface and increase the likelihood of initiation of landslides and debris flows.

There are other effects of roads, too, that may also be caused by transmission lines and any other linear infrastructure. The loss of site productivity, although more prevalent for roads, is a serious concern as it has long lasting impacts on the landscape and permanently reduces habitat for wildlife. Roads and transmission lines also result in habitat fragmentation, which causes the reduction of habitat quality. Wildlife, in particular large mammals, will alter their behaviour to avoid roads (Lyon 1983) as it will increase the amount of edge habitat and reduce the amount of core habitat. This is a concern for species such as grizzly bears that require large, undisturbed home ranges.

It would be informative to know what proportion of access roads for run-of-river facilities are newly constructed versus those that are just rehabilitated logging roads from previous decades. For indeed, one of the main arguments espoused by run-of-river proponents is that the majority of these projects are located in watersheds which have a long history of timber extraction and therefore have the attendant access infrastructure such as roads, bridges and culverts already in place, which the IPPs just "piggy back" on. Therefore, if most of the "damage" has already been done, so to speak, then perhaps it would be unfair to attribute these environmental impacts to IPPs. To look into this, I examined the largest run-of-river project in BC – the 196 MW East Toba-Montrose cluster hydroelectric project – to quantify how many new roads were built. The Watershed Watch Salmon Society (2009) created a Google Earth file with the major projects in southwestern BC, with new roads, old roads and transmission lines superimposed on the satellite imagery. By analyzing this file, the total length of road used in this project was 47.5 km. Of that amount, 46 km (or 97%) were rehabilitated roads that were constructed in the 1980's by logging companies. Around 1.5 km (3% of total roads) were newly constructed. Most projects in coastal BC would appear to have a similar ratio of new to old roads due to the widespread extent of forestry in the region. Projects located in the Ashlu, Clowhom, Furry, Rutherford, Soo, Lillooet, Kwoiek, Tyson and Mamquam watersheds, to name a few, all have a long history of forestry and are scattered with logging roads. This is not to minimize the impacts these projects can have, but to suggest that perhaps the claims that these projects require dozens of kilometers of new roads is a bit disingenuous. However, there is certainly no getting around the transmission line right-of-way that these projects need. The East Toba-Montrose project, for instance, required a 148 km transmission corridor from the project site to near Powell River (BC Environmental Assessment Office 2007). Like roads, these reduce the quantity and quality of habitat for a variety of species. They also pose a direct mortality threat to bats and birds such as the threatened marbled murrelet. These species tend to fly during times of poor lighting conditions of night or early morning. They therefore have a higher chance to crash into powerlines and die by electrocution. Research indicates anywhere from hundreds of thousands to 175 million birds are killed annually through collisions with transmission lines in the United States (Manville II 2005), which is another environmental impact of building hundreds of kilometers of transmission lines associated with run-of-river schemes.

Conclusion

Global climate change has provided a strong impetus for society to harness less energy from fossil fuels and more from GHG-free and renewable energy sources, including hydroelectric power. In British Columbia, the government has encouraged the private sector to invest in microhydro run-of-river projects to ensure B.C. becomes energy self-sufficient, to produce marketable clean energy and to grow the economy. Run-of-river has been touted as the least environmentally disruptive method to produce hydroelectricity in BC, mainly because it does not require inundating a large productive valley bottom and claims to not harm anadromous fish and other biota. However, the environmental effects of these hydro schemes are numerous and far-ranging. Aquatically, they alter biotic and abiotic factors upstream, within and downstream of the diversion reach. Terrestrially, these projects necessitate the rehabilitation or construction of resource roads and new transmission lines, along with their attendant impacts on the environment such as increased sediment yield, habitat fragmentation and habitat loss. Certainly, all energy development comes at a cost environmentally. However, especially with these projects situated on Crown land, the public has the right to be aware of the entire range of their impacts. Currently, the standard rhetoric espoused by IPP proponents is that that since run-of-river schemes emit no greenhouse gasses, flood no valley bottoms and are small, they must therefore be environmentally friendly. As the wide body of literature suggests, this is not the case. Run-of-river should have a place in B.C.'s energy portfolio, but I would argue that it likely should play a more limited role due to the scarceness of suitable sites that would have acceptably low environmental impacts. The criteria defining which project sites, precisely, could be said to have "acceptably low" environmental impacts is subjective and up for debate. In general, however, projects that would be situated in watersheds already developed for other resources (e.g. timber extraction) and close to existing transmission lines would be preferable as they would minimize the need for new construction of infrastructure. Placing projects above natural barriers to fish migration is also ideal, as are areas with no species at risk in the vicinity. Obviously, these are quite restrictive criteria and would decrease the potential run-of-river projects available. It is likely that other forms of energy production will have to provide for the majority of BC's new electricity production. Attempts to decrease energy demand in households and businesses are not expected to entirely compensate for greater population growth in the province, so new sources of energy will have to come online, in one form or another. Run-of-river projects, if selected carefully on a case by case basis and if environmental mitigation measures are in place, have the ability to partially meet that demand in an economically, socially and environmentally responsible way. Society, moving forward, will have to make difficult decisions between choosing the optimal balance between the immediate negative terrestrial and environmental impacts of energy production and the more long term benefits of harnessing carbon-free energy sources.

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