Effects of Experimental Ramping Rate on the Invertebrate Community of a Regulated River

By Karen E. Smokorowski[1]

Abstract

In Ontario, Canada, the provincial government regulates water licenses and in recent years has required that all hydroelectric facilities prepare dam operating plans that often include some incorporation of environmental flows. Peaking facilities can be required to implement a minimum flow and (or) have restrictions imposed on ramping rates (rate of change of turbine flow in cubic meters per second per hour) without sound scientific knowledge that these restrictions benefit river health. This paper reports preliminary results from a collaborative, long-term, adaptive management experiment designed to determine if removing all existing operational constraints on ramping rates was detrimental to the downstream riverine ecology, assessed relative to an unregulated river. Invertebrate abundance, diversity, and taxa composition were measured to test the hypothesis that invertebrate communities would be negatively affected by unlimited ramping. During the restricted years, the invertebrate community had greater abundance, diversity, and proportion of sensitive taxa relative to the unregulated river. After unlimited ramping, there was evidence of negative effects on the invertebrate community, implying that the restricted operation was protective of these biota, although results should be viewed with caution because of a confounding climate effect.

Background

Canada has an abundance of freshwater resources, which consequently have been used to a large degree for social and economic benefits, including hydroelectric power generation. In Canada, approximately 60 percent of the total electricity generation is from hydroelectric sources (Canadian Electricity Association, 2006), with many unaltered watersheds holding potential for additional generation. The size of dams can range from a few meters to hundreds of meters, and the operational regime can range from "run-of-the-river" (smaller impoundments, where power generation is largely dictated by inflow volume), which is considered relatively benign, to fully "peaking" where water is released in accordance with electricity demand resulting in large hourly and daily fluctuations (Clarke and others, 2008). Relative to a natural hydrograph, peaking operations greatly alter flow regimes, which have been shown to lead to altered temperature patterns and geomorphology (sediment and physical channel characteristics), reduced habitat diversity, organism physiological stress, and consequently reduced abundance, diversity, and productivity of biota (Cushman, 1985; Richter and others, 1997; Bunn and Arthington, 2002; Sabater, 2008).

Environmental flows (flows prescribed for the benefit of river ecosystem health) traditionally considered only minimum flow levels, but have recently evolved to consider all elements of the flow regime (including magnitude, duration, timing, frequency, and rate of change of flow), largely because of the increasing interest in the importance of natural flows or the natural flow paradigm (NFP; Poff and others, 1997). The NFP theory states that organisms have adapted to the range in variations inherent to natural flows, and that the ecosystem integrity (health) of a river relies on maintaining natural variability (Poff and others, 1997; Richter and others, 2003). Unfortunately, however, it is difficult to run an efficient and profitable hydroelectric dam under the tenets of the NFP, although compromises do potentially exist (Enders and others, 2009).

In Canada, the provincial Ontario Ministry of Natural Resources (OMNR) controls water licensing and now requires that all hydroelectricity producers in the province develop dam operating plans that set operational requirements for management of water flows and levels that are enforceable by law. Often, peaking hydro dams are required to implement a minimum flow regime, but recently some dams have had restrictions imposed on ramping rates (the rate of change of flow passing through the turbines in cubic meters per second per hour, or $m^3 \cdot s^{-1} \cdot h^{-1}$). Ramping rate restrictions mean that peaking dams can, to a degree, still follow the demand in electricity, but at a slower rate, thus reducing magnitude of change, reducing response times, passing excess water, and lowering the facility efficiency (here termed "modified peaking"). However, with the exception of fish stranding

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studies (e.g., Bradford, 1997; Saltveit and others, 2001; Irvine and others, 2009), there is little evidence in the scientific literature that supports the belief that ramping rate restrictions (while systems continue to peak as able, given restrictions) benefit riverine ecology, and direct experimentation is needed.

In order to reduce scientific uncertainties about the effects of ramping rates, Fisheries and Oceans Canada, the OMNR, Brookfield Renewable Power, Inc., and the University of Waterloo are collaborating on a long-term, adaptive management experiment to test whether regulating ramping rates through hydroelectric turbines can provide ecological benefits, while at the same time minimizing production losses. The main purpose of this adaptive management experiment is to determine if removing all operational constraints on ramping rates from a hydroelectric facility that has operated under restricted ramping rates and minimum flows since its initial operation in the early 1990s is detrimental to the downstream riverine ecology.

Benthic Invertebrates as Test Organisms

Macroinvertebrates have long been used as bioindicators for human disturbance because of their widely varying sensitivity to perturbation, short growth rates and generation time (allowing detection of responses to change), and ability to disperse and recolonize disturbed areas (Hodkinson and Jackson, 2005). Invertebrates have been shown to be sensitive to the negative effects of peaking hydroelectric dams and are, therefore, good test subjects for experimental flows. Frequent and rapid fluctuations in flow can contribute to the decrease in macroinvertebrate abundance and diversity in areas close to the dam (Cushman, 1985; Growns and Growns, 2001), with the shifts in species composition observed for kilometers downstream (Céréghino and others, 2002). While periphyton and macroinvertebrates in the varial zone of a peaking river were found to be impaired in terms of density and diversity and were largely represented by tolerant taxa (Fisher and LaVoy, 1972; Blinn and others, 1995; Benenati and others, 1998), invertebrates found in the permanently wetted zone of a "modified peaking" river may experience more favorable environmental conditions because of the lack of rapid change in shear stress (stress of water flow on the river bed that can cause the substrate to move and (or) dislodge material on the river bed) caused by restricted ramping. For example, Parasiewicz and others (1998) introduced a flow constraint that imposed a minimum base flow and reduced peak flows on a regulated river. The result was that invertebrate biomass was found to increase by 60 percent, which the authors attributed to reduced scouring of the substrate during the bed filling (up-ramping) stage (Parasiewicz and others, 1998). This experiment was intended to test the hypothesis that, relative to an unregulated river, invertebrates in the permanently wetted zone would benefit under a restricted ramping rate regime plus the maintenance of a minimum flow (constrained operation), but would respond negatively (via reduced abundance and diversity) to unlimited ramping because of the resulting increased instability (i.e., changing depth and velocity, increased bedload movement) in habitat.

Study Design

We used a before-after-control-impact (BACI) design for this experiment, which in this case involves comparing conditions on a river regulated for peaking hydroelectric power production (impact river) to conditions on an unregulated reference (control) river (i.e., without any hydroelectric dams) before and after implementing a change in ramping rates. This approach should allow detection of a change in invertebrate measures (abundance and diversity) that were caused by the experimental ramping rate changes, since the control river should reflect the influence of temporal changes in regional environmental factors. The experimental site was the Magpie River, Wawa, Ontario, (48°0′N; 84°7′W) on the 40 kilometer (km) stretch between Steephill Falls and the Harris waterpower facilities (WPF) (fig. 1). The reference river was the unregulated Batchawana River (47°0′N; 84°3′W), located approximately 60 km north of Sault Ste. Marie, Ontario. Between 2002 and 2004, data were collected from the regulated Magpie River under the original restricted ramping rate regime: ramping rate could not exceed 1 $m^3 \cdot s^{-1} \cdot h^{-1}$ from October 10 to November 15; 2 $m^3 \cdot s^{-1} \cdot h^{-1}$ from November 16 until spring freshet (early May); from May until early October, the dam was restricted to an increase or decrease of 25 percent of the previous hour's flow. From 2005 to 2007, data were collected with no restrictions on ramping and while the Steephill Falls plant operated in accordance with water availability and market forces (fig. 2). During the entire study period, through all seasons, the Steephill Falls WPF could not release a discharge lower than 7.5 $m^3 \cdot s^{-1}$, which was the regulated minimum flow. All sampling on the Batchawana River was done contemporaneously.

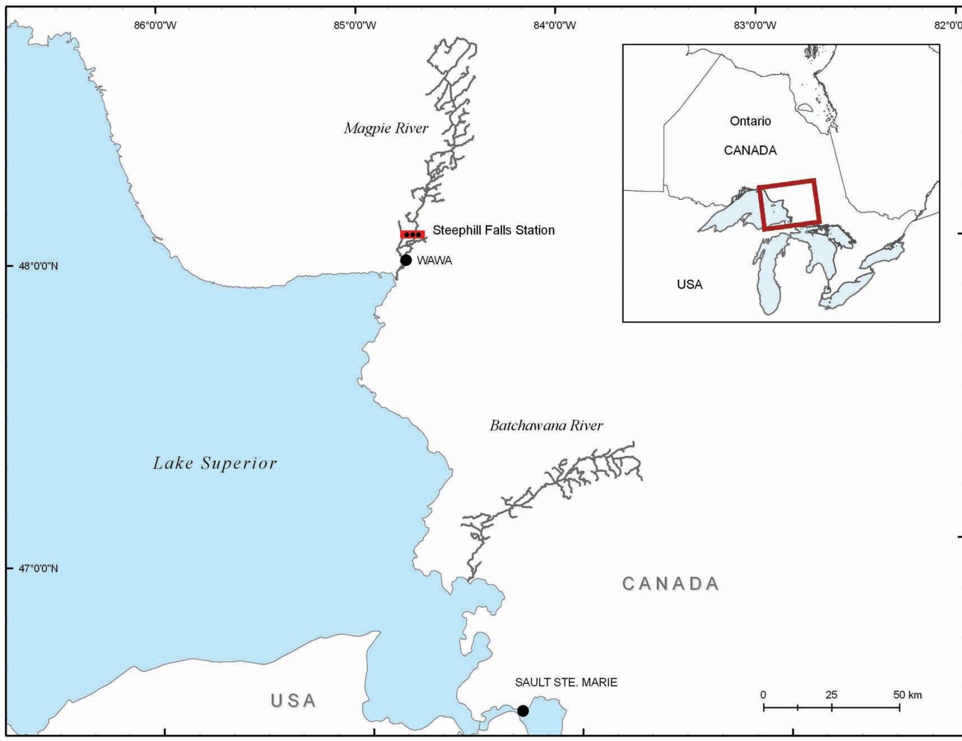

Figure 1. Map showing location of the Magpie and Batchawana Rivers relative to Lake Superior and Sault Ste. Marie, Ontario.

Methods

To assess the benthic invertebrate community, six sites were chosen on the Magpie River, one above the dam outside of the zone of influence and five downstream at distances 2.5, 3, 6, 9.5, and 10.5 km from the dam. The six sites on the Batchawana River were selected to be spatially separated in a similar fashion assuming a hypothetical dam at a point on the river. In each year at each site, five mesh rock bags were randomly placed in a riffle, ensuring a minimum distance of 3 meters (m) apart, and at a depth to maintain a sufficient flow over the bags throughout low-water periods. The rock bags were constructed out of 2-inch net mesh, 48 inches in circumference and 18 inches in length, and were filled with rocks of representative size found along the shoreline at the site of placement until each reached a weight of 7 kilograms (+/– 0.5 kg).The actual number of rocks used, their diameter, and weight of each bag was recorded, as were the depth and velocity (Marsh McBirney Flomate 2000 Portable Flow Meter) in the river at each bag. The bags were left in the river for a period of approximately 60 days (June–August), a sufficient length of time for full colonization to reach fluctuating taxa richness, abundance, and biomass (Mason and others, 1973; Shaw and Minshall, 1980). Once bags were retrieved, the rocks were cleaned and all invertebrates and debris were preserved in 70-percent ethanol. The entire sample was subsampled for identification to taxonomic level of family and enumeration, although in each year a number of samples were identified in their entirety to allow for the calculation of accuracy and precision of subsampling procedure, which were always found to be within acceptable limits (defined as being within 20 percent of true counts, Elliott, 1977).

Invertebrate families were then used to calculate invertebrate diversity (probability of interspecific encounter, PIE; Hurlbert, 1971) and percentage of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (%EPT). PIE is an unbiased diversity measure that calculates the chance that two individuals drawn at random from a population represent different families:

$$PIE = \sum_{i=1}^{s} (n_i / n)\left[(n - n_i)/(n-1)\right] \quad (1)$$

where: n = number of all individuals in the sample, n_i = number of individuals of a family in the sample, and s = number of families (Hurlbert, 1971). PIE was selected over other diversity indices because it provides a statistically and biologically understandable probability (out of 100 percent, the higher the number the more diverse the community), unlike more traditional diversity measures (Gottelli and Graves, 1996). The %EPT calculations were completed by summing the number of individuals within the three families and dividing by the total number of individuals in all invertebrate families found in the samples. These three taxa are known to be sensitive to changes in water quality and flow (Mackie, 2004), and a high percentage of EPT signifies a healthy invertebrate community.

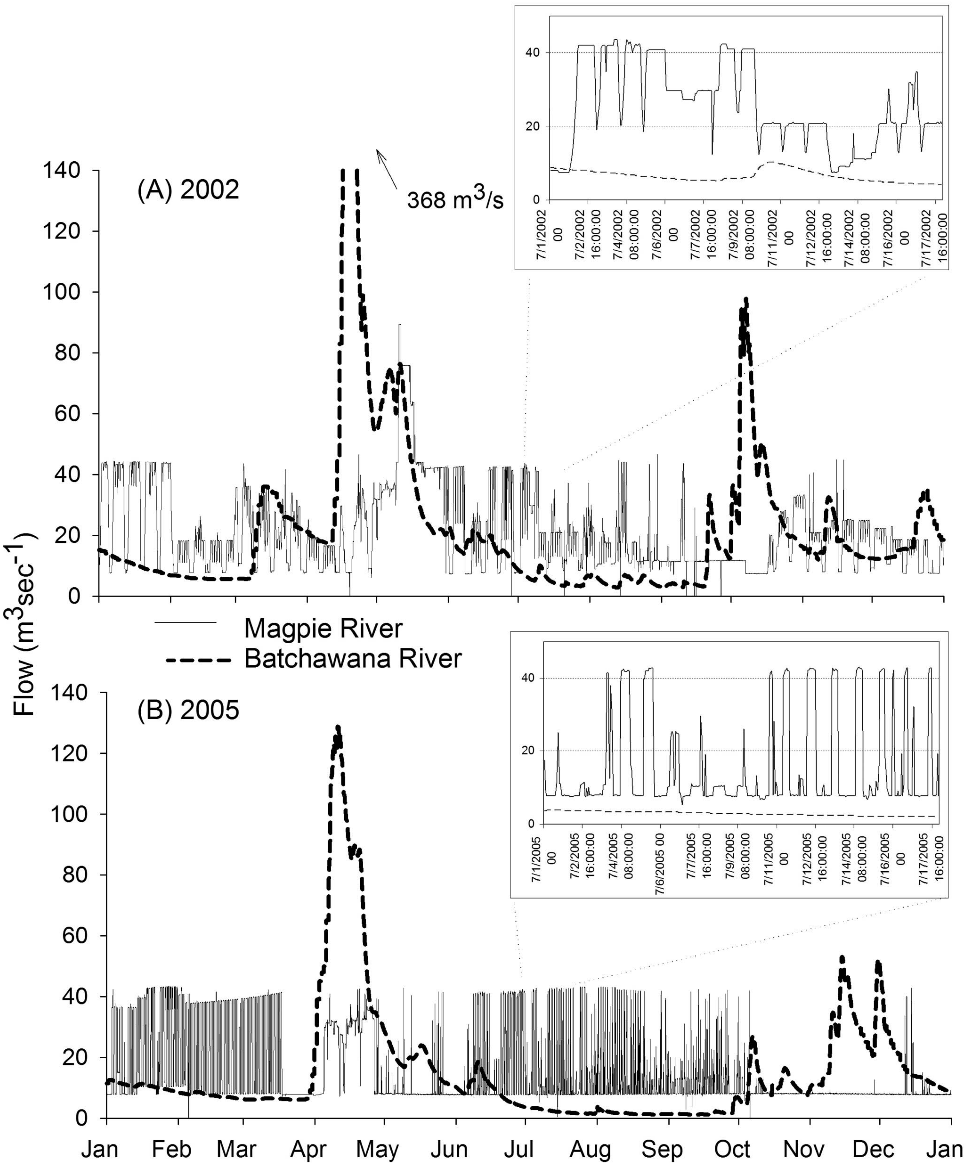

Figure 2. Annual hydrograph of the Magpie (solid lines) and Batchawana (dotted lines) Rivers, (A) in 2002, before ramping change on the Magpie, and (B) in 2005, after unlimited ramping on the Magpie River. Data for the Magpie River from the Steephill Falls waterpower facility (courtesy Brookfield Renewable Power, Inc). (Data for the Batchawana River courtesy of the Water Survey of Canada, Environment Canada.)

Invertebrate abundance, diversity, and %EPT were averaged across all sites and plotted against year for each river. A statistical test (2-way analysis of variance (ANOVA), river by year) was used to determine if there was a significant difference between rivers or years or if the difference between rivers changed through the years (called the interaction term of "river by year"). To simplify the comparison between the years of restricted and unlimited ramping rates, the BACI design was used in a statistical test (2-way ANOVA, treatment by time). In our BACI design, the sites on the Batchawana River plus the one site above the dam outside of the zone of influence of the dam was classified as the "control" treatment, and the sites on the Magpie River downstream from the dam were classified as the "impact" treatment. The years 2002–2004 were classified as the "before" time, and the years 2005–2007 were classified as the "after" time.

For a BACI ANOVA, the statistic of interest is the interaction term (treatment by time), which will be significant if lines defining the differences in before-after samples among rivers cross (or are unparallel to a significant degree). If the lines cross, then the difference between control and impact changes from before to after the treatment, and we can say with some confidence that the change was because of the unlimited ramping. For all statistical tests, p-value of less than 0.05 means that there was a less than 5-percent chance that the difference found was because of chance, and therefore the difference can be considered significant.

Results

It is clear to see in figure 2 that the natural flow of the Batchawana River resulted in much greater peak flows and lower minimum flows relative to the altered Magpie River. In 2002, when ramping rate was restricted, the dam operated on a reduced peaking cycle, "perched" on an elevated minimum during the week (when water supply was high), or did not reach full turbine flow (when water levels were low), and dropped to the minimum flow on weekends (if demand was low). However, in 2005, full ramping from the maximum turbine discharge to minimum regulated flow occurred at a much greater frequency because the speed of change was unrestricted. During the restricted ramping phase between 2002 and 2004, the Magpie River had a significantly greater abundance of invertebrates than the Batchawana River (fig. 3A). After the experimental change to unlimited ramping occurred (2005–2007), however, the Magpie River invertebrate abundance decreased while the Batchawana River invertebrate abundance stayed essentially the same. The change in the difference between the two rivers was enough for the interaction term in the statistical test to be significant, meaning the decrease in the Magpie was much greater than any change on the Batchawana River (fig. 3B).

Similar to the abundance results, our invertebrate diversity PIE and %EPT measurements were both significantly greater on the Magpie River compared to the Batchawana River during the limited ramping period (fig. 4A and C). However, contrary to the abundance results, these measurements increased on the Batchawana River during 2005–2007 while they decreased on the Magpie River, so that they were actually greater on the control river after the change to unlimited ramping (fig. 4B and D).

Discussion

During the period of constrained ramping rate, although the hydrograph of the Magpie River was still considerably altered relative to a natural flow regime, the invertebrate community remained healthy in terms of abundance, diversity, and proportion of sensitive taxa relative to the unregulated river. Yet once the operation of the waterpower facility was unconstrained (unlimited ramping, maintained minimum flow), there was evidence of negative effects on the invertebrate community, implying that the restricted operation was protective of these biota. Without the experimental change in flow regime to unlimited ramping rate, it would have been unclear whether the minimum flow or ramping rate was of greater benefit.

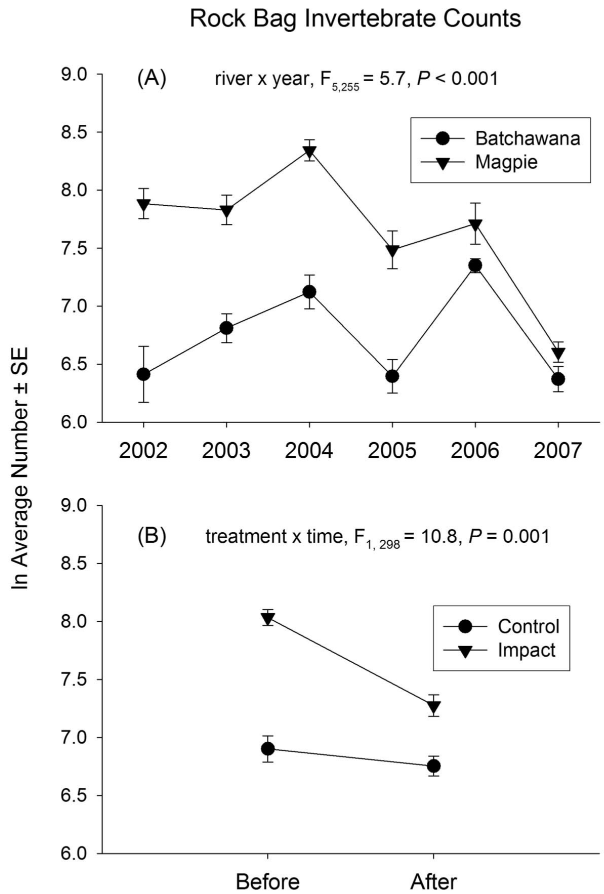

Figure 3. Average abundance (log + 1 transformed) of invertebrates per rock bag ± standard error (SE) plotted as (A) average across sites for each year, and (B) as the before-after-control-impact plot.

The maintenance of a minimum flow has been shown to be important for the protection of river ecosystems, including invertebrates, below hydroelectric facilities. For example, Bednarek and Hart (2005) found a significantly improved invertebrate family richness and proportion of intolerant taxa (%EPT) below dams that implemented a minimum flow regime and increased dissolved oxygen concentrations. The natural flow regime of the Batchawana River allowed minimum summer flows to drop considerably lower than the Magpie River, which could have resulted in elevated peak summer temperatures (Sinokrot and Gulliver, 2000) and cause stress to biota. It is likely that the combination of a minimum flow improving invertebrate habitat conditions mid-summer and restricted ramping alleviating shear stress and bedload movement on the Magpie River allowed the invertebrate community to proliferate relative to the unregulated river during the phase of constrained operations.

The onset of unlimited ramping resulted in decreased invertebrate abundance, diversity, and proportion of sensitive taxa relative to the unaltered Batchawana River. There are a number of potential reasons why unlimited ramping may

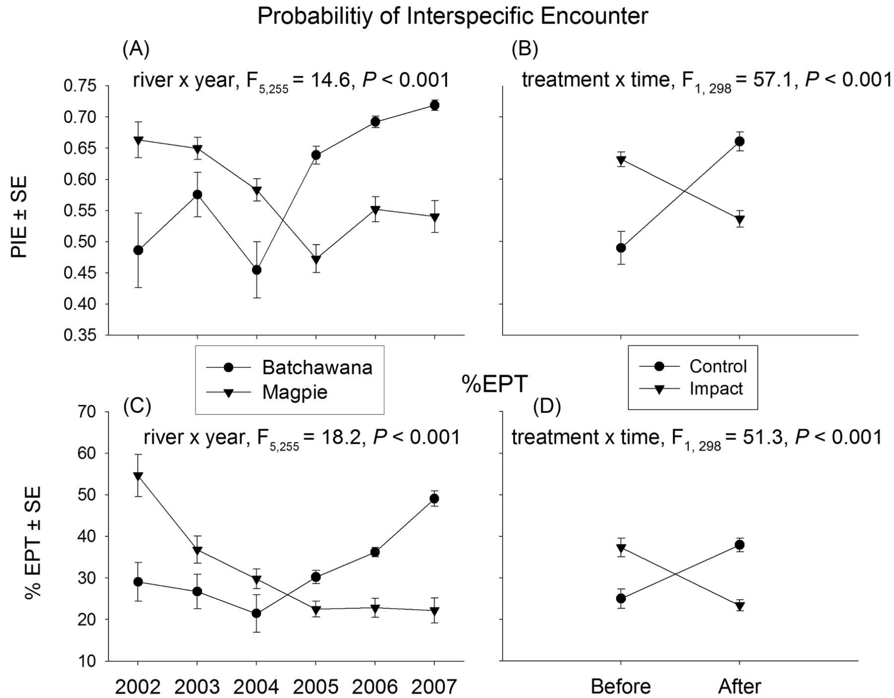

Figure 4. Average diversity (PIE) of invertebrates per rock bag ± standard error (SE) plotted as (A) average across sites for each year, and (B) as the before-after-control-impact plot. Average % EPT invertebrates per rock bag ± standard error (SE) plotted as (C) average across sites for each year, and (D) as the before-after-control-impact plot.

be considered detrimental to aquatic invertebrates, the most probable candidates including stranding, flushing (catastrophic drift), and rapid and extreme temperature fluctuations. Stranding refers to the separation of an organism from the flowing surface water caused by the rapid decrease in flows, resulting in isolation in pools, side channels, or desiccation on formerly wet substrate. During experimental flows, a greater number of insects were found stranded when the rate of decrease in flow was rapid (Perry and Perry, 1986), implicating unlimited down ramping as a potential cause for increased invertebrate mortality. Because invertebrates are continually moving and drifting to different positions in the river, stranding a significant number of invertebrates in the varial zone would reduce the overall abundance in the river including those in the permanently wetted zone. Rapid increases in flow could result in rapid increases in shear stress, potentially causing catastrophic drift, or the large scale displacement of invertebrates from the sediment during increases in river discharge (Gibbins and others, 2007). While these displaced invertebrates may be able to recolonize the riverbed further downstream, they are more vulnerable to predation by fish while drifting. Finally, rapid and frequent changes in flow below a peaking hydroelectric dam are often accompanied by rapid fluctuations in water temperature (Cushman, 1985), which can be highly stressful, if not lethal, to organisms (Stanford and Hauer, 1992). All of these potential negative consequences of unlimited ramping could be more detrimental to sensitive taxa (i.e., EPT) than tolerant taxa, leading to the increased dominance of tolerant species and reduced diversity.

In 2005, when the rate of change of flow occurred as rapidly and frequently as the electricity market and water availability dictated, the Steephill Falls waterpower facility was still required to maintain a minimum flow below the dam. Therefore, any negative effects detected on the invertebrate community between 2005 and 2007 should have been clearly attributable to unlimited ramping. Unfortunately, however, there was a confounding factor affecting our ability to definitively implicate the change in ramping rate as the causative factor. With the change to unlimited ramping in the fall of 2004, the region experienced the onset of a 3-year drought, confounding the clarity of our results (fig. 5). The drought resulted in above-average temperatures and lower-than-normal flows on all rivers, including the reference river, and the ability of the Steephill Falls reservoir on the Magpie River to store the complete spring freshet, which reduced the magnitude and frequency of ramping relative to a normal water-level year. A spring freshet, although reduced, still occurred on the reference river, and the importance of the complete loss of the freshet on the Magpie River is unclear. Therefore, any results need to be viewed with some caution as the study is ongoing to attempt to clarify causation: are observed effects the result of changes in ramping or drying conditions?

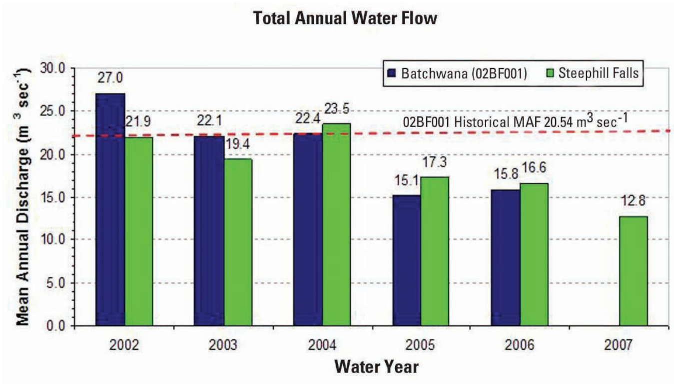

Figure 5. Total annual flow ($m^3 \cdot s^{-1}$) on the Magpie and Batchawana Rivers both before and after unlimited ramping was implemented in 2005. The red dotted line indicates the mean annual flow for the Batchawana River as calculated from historical water survey of Canada data.

Implications for Management

This research project constitutes a significant undertaking, and establishing cooperative partnerships and shared financial support among all partners was essential to success. Many challenges were encountered, including sampling methodology difficulties specific to working on peaking systems. Subsequent field method refinement resulted in an important methodological contribution to future research and monitoring of peaking hydrofacilities in the form of standardized sampling protocols. Other challenges include the modification and fine tuning of data exploration and analyses to best understand stressors and effects and the challenge of unpredictable climate changes.

Results of this and ongoing studies will help inform Canadian provincial and Federal waterpower guidelines and policy, facilitating science-based decisions regarding ramping at hydrofacilities. In addition, methodologies developed will be used to help establish effectiveness monitoring programs for dam operating plans at existing and new hydrofacilities in Ontario. This project generated several successes, including cooperative management, field and data-sharing partnerships, assurance of independent scientific integrity through the design team structure, and development of standardized protocols across a suite of ecosystem measures (including hydrology, geomorphology, invertebrates, fish, and food web) that show a response to subtle flow changes. It is anticipated that these successes will serve as a model for future collaborations to address large-scale, long-term, and complex ecological questions related to resource management.

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