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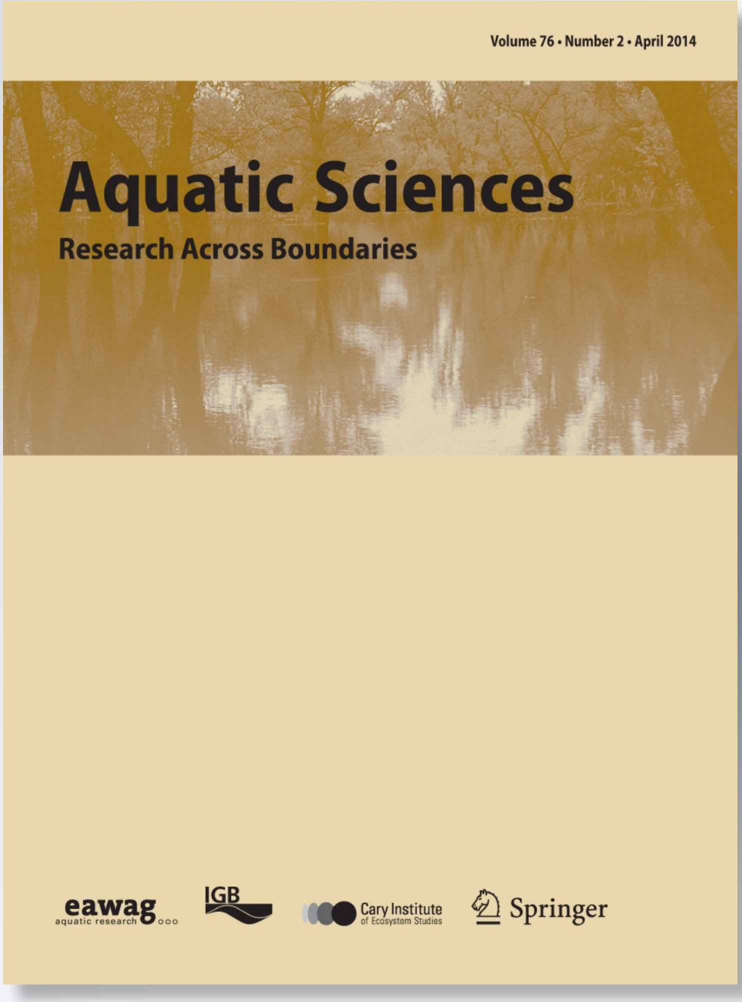

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Aquatic Sciences

RESEARCH ARTICLE

Effectiveness of pulse flows in a regulated river for inducing upstream movement of an imperiled stock of Chinook salmon

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Abstract We assessed the effectiveness of pulse flows in facilitating the upstream migration of an imperiled summer-run Chinook salmon (*Oncorhynchus tshawytscha*) stock in the Puntledge River, BC, Canada. During July and August, over 3 years, we tracked radio-tagged fish ($n = 100$) in a reach of the Puntledge River where water is diverted for power generation, resulting in stable low flows that are believed to impede migration. Over the course of 13 pulse flows, we measured migration rate, passage rate at natural barriers that are difficult to pass during low flows, movement away from the turbine outlet pool that creates distracting flows, and locomotor activity. Mean river flow during the peak of the pulses varied from 12.1 to 42.5 $m^3 s^{-1}$ and was at least 6.1 $m^3 s^{-1}$ above residual base flows. Typically, the pulse flows lasted 48 h. Migration rate was higher during some pulse flows, but results varied among pulses. Passage at natural barriers was only higher during an abnormal pulse where flows reached twice that of the prescribed flow (i.e., 24+ $m^3 s^{-1}$). Some fish moved away from the turbine outlet pool during pulse flows. Pulse flows did not affect fish activity levels, as measured by electromyogram telemetry. Although the effect of pulsed flows on the migration of the Puntledge River summer-run Chinook salmon was unclear, no negative impacts, such as hyperactivity or downstream displacement were observed. The use of pulse flows as a management tool still requires further research.

Keywords Artificial freshets · *Oncorhynchus* spp. · Chinook salmon · Hydropower · Migration · Fish telemetry

Introduction

River flow is an important factor for the upstream movement of salmonids (Banks 1969). Water levels that are too high or too low can increase energy use, delay migrations and in extreme cases, lead to migration failure. Thus, the management of river flows by hydropower utilities can influence the ability of salmonids to migrate to natal spawning grounds (e.g., Thorstad and Heggberget 1998; Gowans et al. 2003; Thorstad et al. 2003, 2005; Keefer et al. 2004; Tiffan et al. 2009). Upstream movements by salmonids are often impeded by low river flow, exposure to artificial and natural barriers, attraction to artificial river currents (i.e., turbine out flows), and/or the presence of non-optimal environmental conditions (i.e., cold/warm river temperature, supersaturation of dissolved oxygen) (Thorstad and Heggberget 1998; Gowans et al. 2003;

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Thorstad et al. 2003, 2005; Keefer et al. 2004; Tiffan et al. 2009). In addition, many hydropower developments are located in rivers that provide spawning habitat for migratory species like Pacific salmon and, in some instances, declines in population sizes have been noted (Nehlsen et al. 1991). Though loss of connectivity and habitat alteration are often cited as the primary reason for changes to population size in hydropower impacted rivers (e.g., Sheer and Steel 2006), there also are associated changes in fish locomotor activity that may occur due to changes in water flow and local environmental characteristics (Murchie and Smokorowski 2004; Cocherell et al. 2010a). Migratory delays can increase energy use and lead to failed migration, or for fish that successfully reach spawning grounds, delay may cause pre-spawn mortality (Cooke et al. 2006; Crossin et al. 2008; Hasler et al. 2012a).

In regulated rivers, pulse flows (also sometimes referred to as artificial freshets) may facilitate the upstream migration of fish while requiring less water than continuous higher releases of water over the migration period, thus serving to mitigate the consequences of low and stable flows. Pulse flows can simulate a "natural" runoff event that would typically correspond with the upstream migration period of a species. Pulse flows have been used to encourage fish holding in estuaries to move into the river main stem (Huntsman 1948) or to aid upstream movements through fishways (Thorstad and Heggberget 1998; Thorstad et al. 2003), however, clear relationships between pulse flows and movement have not been observed in all cases (Thorstad and Heggberget 1998; Thorstad et al. 2003). Further studies, in particular species- and river-specific studies, are needed to better understand the potential for pulse flow releases to be used for conservation purposes in regulated rivers.

In the Pacific Northwest, hydroelectric utilities and fisheries regulators are challenged to manage river flows to balance competing needs, including power generation, salmon conservation, and recreation. On the Puntledge River on Vancouver Island, BC, Canada, a multi-stakeholder, structured decision-making process reviewed a variety of alternative water management and hydroelectric operational options to understand their potential for meeting objectives for power generation, fisheries resources, recreation, and flood protection (BC Hydro 2003).[1] A key concern was the effect of hydroelectric infrastructure and operations on the migration of adult summer-run Chinook salmon. Returns of summer-run Chinook salmon have declined (Fisheries and Oceans Canada, Puntledge River Hatchery) in-spite of conservation actions by the federal government and the power utility (i.e., BC Hydro), such as enhancing spawning habitat, hatchery propagation, and providing base flows and restrictive flow ramping rates. Previous observations and telemetry investigations highlighted potential migration challenges, including summer-run Chinook salmon holding in the turbine outlet pool, and migration delay and failure at two natural barriers (Stotan and Nib Falls) (Komori Wong Environmental and Bixby 2003; Hasler et al. 2011). For example, Hasler et al. (2011) noted that tagged summer-run Chinook salmon held in the turbine outlet pool for as many as 41 days. In addition, only 74 % of tagged Chinook salmon passed Stotan Falls and those that did took on average 8 days to do so. Of the Chinook salmon that reached Nib Falls, 85 % passed, doing so on average of 3 days.

Given the above, one recommendation by the water-use planning committee was to release pulse flows during the summer-run Chinook salmon migration that mimic, to some extent, natural variation in discharge that would have historically existed (BC Hydro 2003). The aims of the pulse flows were to: (1) facilitate the rate of summer-run Chinook salmon upstream migration, (2) facilitate passage at two natural barriers, and (3) reduce fish residency at the turbine release pool (henceforth called the Powerhouse Pool) by rheostatically stimulating fish to move away from the pool. The frequency, duration, timing and magnitude of the pulses were based largely on professional judgment, previous observations and telemetry studies completed on the river, and trade-offs against the value of foregone power generation from pulse flow releases. Thus, the effectiveness of pulse flows was uncertain.

We completed a 3-year radio-telemetry study to reduce these uncertainties and determine the potential of using pulse flows as a measure to assist in the conservation of Puntledge River summer-run Chinook salmon. Our specific objectives were to assess the effects of pulse flows on (1) migration rates (distance/unit time), (2) passage rate at key obstructions, (3) Powerhouse Pool delay, and (4) locomotor activity as an index of energy expenditure. Locomotor activity level was examined in the fourth objective because increased activity levels to hold position during pulse flows was a potential negative impact that would influence energy expenditure (Murchie and Smokorowski 2004) and potentially affect subsequent survival and spawning.

Materials and methods

Study site

The Puntledge River is located on the east coast of Vancouver Island, Canada (Fig. 1). The river is approximately 16.9 km long and drains Comox Lake into the Comox Estuary. The hydropower facility was constructed in 1912

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[1] http://www.bchydro.com/etc./medialib/internet/documents/environment/pdf/wup_puntledge_river_executive_summary_pdf.Par.0001.File.wup_puntledge_river_executive_summary.pdf.

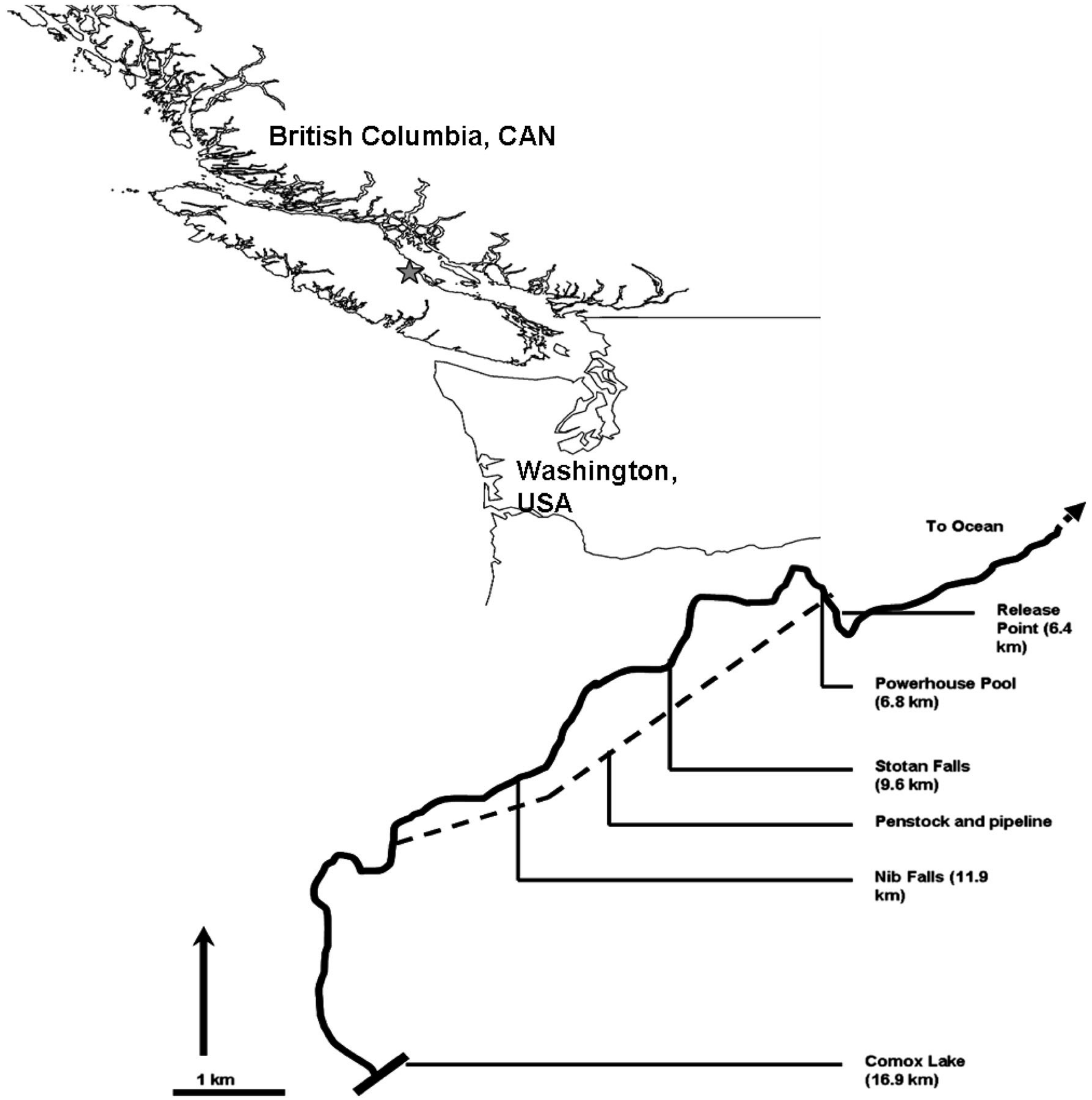

Fig. 1 Map of the location of the Puntledge River on Vancouver Island and a schematic drawing of the study reach. Release point indicates the location of the Lower Hatchery

and consists of a storage dam at the output of Comox Lake, as well as a diversion dam approximately 3.7 river km downstream that diverts water through a penstock that funnels the water to a powerhouse and re-joins the Puntledge River 7.2 km downstream. The diversion results in the river having less water flow between 6.8 river km and 14.0 river km. Within this 7.2 km reach, there are two natural barriers that summer-run Chinook salmon are known to hold below: Stotan and Nib Falls (Komori Wong Environmental and Bixby 2003). Both falls are three-tiered with enhancement to aid in the upstream movement of adult fish (i.e., concrete baffle fishways that resemble steps in the bedrock). Another previous area of concern is the Powerhouse Pool at the power station located at 6.8 river km (Komori Wong Environmental and Bixby 2003). Most summer-run Chinook salmon spawn in the reach between the storage dam and the diversion dam during October each year and, historically, are believed to have held in Comox Lake prior to spawning, as has been previously documented in recent years to influence migratory characteristics (Taylor and Guimond 2004, 2006).

Study design

The overall study approach involved using telemetry to study both longitudinal movements (using manual radio tracking and fixed receiving stations) and energy expenditures during pulse flows (using electromyogram activity radio transmitters). Specifically, we aimed to compare fish responses between control periods and pulse periods with respect to the various objectives. Fish responses to each pulse period (approx. 48 h) were compared to the same period prior to the pulse (called control) and to a period 12 h post-pulse (the reason for the shortened timeframe for the post-pulse period was to capture movements during the ramping down after the pulse flow). It was not possible to replicate the river system, so this experimental design was the most robust approach for addressing the study objectives. By repeating the study over 3 years, we were able to study 13 pulses, although they were not all delivered in the same manner (see below).

Study animals and telemetry methods

Between June 25th and July 20th 2007 and 2008, and in 2009 between June 2nd and June 26th, adult summer-run Chinook salmon were diverted into raceways at the Lower Puntledge River Fish Hatchery (Fisheries and Oceans Canada; Fig. 1) for transmitter implantation [2007: 38 fish, TL = 727 ± 14 mm (SD); 2008: 27 fish, TL = 663 ± 11 mm; 2009: 35 fish, TL = 646 ± 56 mm]. All research efforts focused on males given the status of the stock and the need to retain females for a captive breeding program. Twenty-seven male fish (16 in 2007, and 11 in 2008), assumed to be of wild origin based on the presence of adipose fins (adipose fins are removed in hatchery-reared fish), were implanted with coded electromyogram (EMG) transmitters [CEMG2-R16-25 (2007) and CEMG2-R11-25 (2008)], Lotek Engineering, Inc., Newmarket, ON, Canada; surgical methods outlined in Cooke et al. (2004); and 66 fish (22 in 2007, 15 in 2008, and 29 in 2009) had a conventional radio transmitter (MCFT-3A, Lotek Engineering, Inc., Newmarket, ON, Canada) gastrically inserted with the antenna protruding from the oral cavity, an approach that has high rates of retention in migratory adult Pacific salmon (Ramstad and Woody 2003). Brown et al. (2007) suggested that coded EMG transmitters should be calibrated by swimming tagged fish in a swim tunnel prior to release to enable the determination of energy use and to allow for grouping of coded EMG values from different fish. Due to the conservation status of the Puntledge River summer-run Chinook salmon and the added stress that calibration requires (Cooke et al. 2004), we were unable to calibrate the tags. We have therefore limited our analysis of coded EMG values to coarse-scale locomotor activity and have avoided grouping the data for all fish because of the technical limitation of using these transmitters (see Hasler et al. 2012b for further information).

Transmitters (both conventional and EMG) were manually tracked from shore at least twice a day using a telemetry receiver (SRX-600 or SRX-400, Lotek Engineering, Inc., Newmarket, ON, Canada) and a 3-element Yagi antenna. Transmitter locations (approximate river km) were determined using zero point tracking (a method whereby the gain of the receiver is continuously reduced as the user approaches the fish), as the river is narrow and there are a minimum number of possible locations fish can inhabit, meaning transmitter locations are easily found with a high-degree of accuracy. Transmitters were tracked from June 30 to August 4 in 2007, June 30 to August 3 in 2008 and June 2 to August 7 in 2009. The range of days tracked encompassed the time period that summer-run Chinook salmon enter the river and the end of the period when pulse flows were administered. Three fixed stations consisting of 1–3 Yagi antennas and telemetry receivers with external batteries were used at Stotan, Nib Falls, and the Powerhouse to determine time of ascent at the falls and the time that fish moved away from the Powerhouse Pool. In addition to these three fixed stations, additional single antenna fixed stations were positioned at strategic locations (i.e., where there were reasonable concentrations of tags) along the river to record EMG output values from EMG-tagged fish. Effort was made to maximize the number of fish being recorded during the control, pulse flow, and post-pulse flow periods.

The time when fish passage occurred at Stotan and Nib Falls was determined by analyzing the recorded fixed station data by assessing the antenna that the transmission was being received on and by using the power of the signal (e.g., high signal power on the upstream antenna and low signal strength on the downstream antenna indicated the fish was nearing passage or had passed the falls). Passage was also confirmed during subsequent manual tracking. A fish was considered to be present at each Falls from the time that the fish was first located (by manual tracking or by fixed station recordings) at the lower tier of the Falls until it was last located at the upper tier of the Falls (either by manual tracking or by fixed station recordings).

Pulse flows

Pulse flows were scheduled weekly throughout July and early August in 2007, 2008, and 2009 (Table 1). Minimum flow in the diversion reach during this period was 5.7 $m^3 s^{-1}$. Pulse flows were intended to be 12 $m^3 s^{-1}$ 48 h^{-1} (including ramping time), and water flow was to be greater than the powerhouse output (see BC Hydro 2003 for water-use planning committee rationale and advice for pulse flow releases). The actual magnitude and duration of pulses varied due to operational constraints and hydrologic conditions. Thirteen pulse flows were released. Mean river flow during the peak of the pulses varied from 12.1 to 42.5 $m^3 s^{-1}$ and was at least 6.1 $m^3 s^{-1}$ above base flows (approximately double). Ten

Table 1 Dates and mean flow ($m^3\ s^{-1}$) of each pulse flow implemented in 2007, 2008, and 2009

Pulse flow #	Date	Mean flow ($m^3\ s^{-1}$)
2007		
1	4–5 July	18.1
2	11–26 July	17.2
3	1–2 Aug	13.1
2008		
4	2–3 July	42.5
5	9–10 July	13.0*
6	16–17 July	13.1*
7	23–24 July	13.2
8	30–31 July	13.0*
2009		
9	8–9 July	12.4
10	15–16 July	12.8
11	22–23 July	13.0
12	29–30 July	12.1
13	5–6 Aug	12.2

* Indicate when the pulse flow was not greater than the output at the Powerhouse

of the 13 pulse flows had mean river flow between 12.1 and 13.2 $m^3\ s^{-1}$ and one pulse flow was higher and longer due to increased run-off in the watershed. All but one pulse flow lasted 48 h (pulse flow 2 was 15 days long due to increased spring melt and the subsequent need to spill water). Pulse flow 5, 6, and 8 did not result in the flow at the Powerhouse Pool being less than the flow in the mainstem of the river. Pulse flow 12 and 13 are not included in further analysis because no tagged fish remained in the diversion reach at the time of those pulses. The study design called for all pulses to be delivered in the same manner, therefore the variability that was observed in duration and magnitude of the pulses was not sufficient to enable their use as factors in quantitative analyses (e.g., attempting to correlate magnitude or duration of pulse flow with migration endpoints).

To address our first objective, migration rates (i.e., $m\ h^{-1}$) were determined by summing the distance fish moved during each time period (i.e., control, pulse period, post-pulse period). For objective two, we calculated the passage rate at key obstructions as the proportion of fish that passed an obstruction during a particular time period relative to the total number of fish present. The third objective was addressed by examining whether fish that were residing in the powerhouse pool during the pre-pulse control period left during the pulse flow or post-pulse period (henceforth called power house delay). The final objective was evaluated by comparing the relative EMG activity level of individual fish across the three periods.

Data analysis

The study design (i.e., pre-pulse control, pulse flow, and post-pulse flow) involved repeated measures under different periods, so for all analyses we used repeated measures tests. Because the migration and passage rates were not normally distributed, we used Kruskal–Wallis tests to compare migration rate during the 11 pulse flows; Friedman tests to compare migration and passage rates for the three periods (control, pulse, and post-pulse flow); and Wilcoxon tests to compare migration and passage rates for control and pulse, and control and post-pulse flow. Significance was tested at a Bonferroni corrected significance level ($\alpha = 0.005$).

To further understand the influence of flow on fish ascending Stotan and Nib Falls, we normalized the frequency of discharge at Stotan and Nib Falls when each fish was present at the base of the falls, and the discharge when fish ascended the falls (Fig. 4). We compared the present and ascent frequencies qualitatively/visually.

Because of constraints with using non-calibrated coded EMG transmitters, and the sampling rate of tag transmissions, we compared gross scale relative differences in EMG output values between pulse flow and non-pulse flow conditions for each fish tagged. Specifically, we measured whether mean EMG outputs were increasing or decreasing during non-pulse flow and pulse flow conditions. Data points were generated by calculating the modes of coded EMG values for each fish during the non-pulse flow periods (control period) and the pulse flow periods. Because fish holding in the Powerhouse Pool were less directly exposed to the change in discharge given the physical, geomorphic, and hydraulic characteristics of the pool, we analyzed their coded EMG outputs separately. Fisher's exact tests were used to assess the relative changes (i.e., increase or decrease) of coded EMG output values during control and pulse flow periods.

Results

Migration rates

Mean migration rate per hour did not differ among the 11 pulse flows (Kruskal–Wallis; $\chi^2 = 15.573$; $P = 0.113$; Fig. 2). In addition, there were no statistically significant differences among mean migration rate (per hour) during the pulse flow periods, 12 h after the pulse flow periods, or during the control periods (Table 2; Fig. 2). However, pulse flows 5, 6, and 9 showed significant differences in the mean migration rate during the three periods (Table 2). During pulse flow 9, mean migration rate was significantly higher [i.e., 3.00 (±2.63) $m\ h^{-1}$] during the pulse flow than during

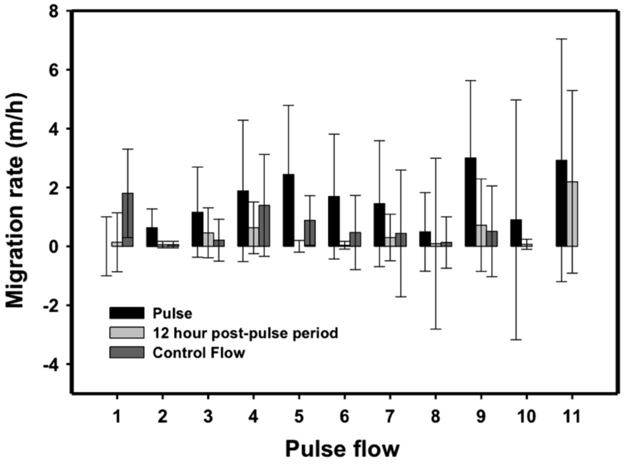

Fig. 2 Mean migration per hour rate of tagged fish during each of the pulse flows. Whiskers represent standard deviation

Table 2 Friedman's results (Chi squared and associated P value) for the tests comparing variables mean migration distance per hour and number of natural barriers ascended per hour of control, pulse and post-pulse periods among the 3 years and 11 pulse flows studied

Year	Pulse number	Number of tagged fish	Migration distance		Natural barriers ascended	
			χ^2	*P*	χ^2	*P*
2007	1	6	0.429	0.807	n/a	
	2	11	1.724	0.422	12.286	0.002*
	3	21	5.134	0.077	8.857	0.012
2008	4	3	0.286	0.867	n/a	
	5	10	8.882	0.012	n/a	
	6	11	6.276	0.043	5.200	0.074
	7	19	3.250	0.197	2.00	0.368
	8	14	0.069	0.966	0.667	0.717
2009	9	15	7.837	0.020	1.600	0.449
	10	6	2.000	0.368	4.000	0.135
	11	2	2.000	0.368	2.000	0.368

* Indicate statistical difference ($\alpha = 0.005$)

the control period [i.e., 0.51 (±1.54) m h^{-1}] but not during the post-pulse period [i.e., 0.72 (±1.57) m h^{-1}; Tables 3, 4; Fig. 2]. In pulse flow 5, fish moved at a greater rate during the control period [i.e., 0.88 (±0.84) m h^{-1}] than during the post-pulse period [i.e., 0.00 (±0.20) m h^{-1}], while fish moved marginally more during the pulse flow [2.44 (±2.35) m h^{-1}]; Tables 2, 4; Fig. 2).

Table 3 Wilcoxon results for test comparing between pulse and control for mean migration rate and natural barriers ascended by Puntledge River summer-run Chinook salmon

Year	Pulse number	Number of radio-tagged Chinook salmon	Mean migration distance per hour		Number of natural barriers ascended per hour	
			χ^2	*P*	χ^2	*P*
2007	1	6	0.287	0.592	n/a	
	2	11	3.965	0.047	9.456	0.002*
	3	21	4.110	0.043	6.173	0.013
2008	4	3	0.196	0.658	n/a	
	5	10	1.549	0.2121	n/a	
	6	11	5.539	0.019	2.224	0.136
	7	19	1.056	0.304	1.000	0.317
	8	14	0.245	0.620	n/a	
2009	9	15	8.540	0.004*	1.115	0.291
	10	6	1.307	0.253	2.200	0.138
	11	2	1.000	0.317	n/a	

* Indicate statistical difference ($\alpha = 0.005$)

Table 4 Wilcoxon test for 12 h post-pulse versus control periods for mean migration rate and natural barriers ascended by Puntledge River summer-run Chinook salmon

Year	Pulse number	Number of radio-tagged Chinook salmon	Mean migration distance per hour		Number of natural barriers ascended per hour	
			χ^2	*P*	χ^2	*P*
2007	1	6	0.030	0.863	n/a	
	2	11	0.201	0.654	1.000	0.317
	3	21	0.723	0.395	1.000	0.317
2008	4	3	0.088	0.767	n/a	
	5	10	8.541	0.004*	n/a	
	6	11	1.159	0.282	1.000	0.317
	7	19	0.216	0.642	0.352	0.553
	8	14	0.132	0.717	0.360	0.549
2009	9	15	0.845	0.358	n/a	
	10	6	1.000	0.317	n/a	
	11	2	1.000	0.317	1.00	0.317

* Indicate statistical difference ($\alpha = 0.005$)

Passage rates

Passage rates at the natural barriers differed among pulse flows (Kruskal–Wallis; $\chi^2 = 32.075$; $P < 0.001$; Fig 3). During pulse flow 2, there was a difference between the rate at which salmon passed the natural barriers (Table 2; Fig. 3). During pulse flow 2, rate of passage past the natural barriers was statistically higher during the pulse flow [i.e., 0.003 (±0.002) barriers h^{-1}] than during the control period [i.e., 0.00 (±0.00) barriers h^{-1}; Table 3; Fig. 3). There were no differences in passage rates during the post-pulse and control periods (Table 4).

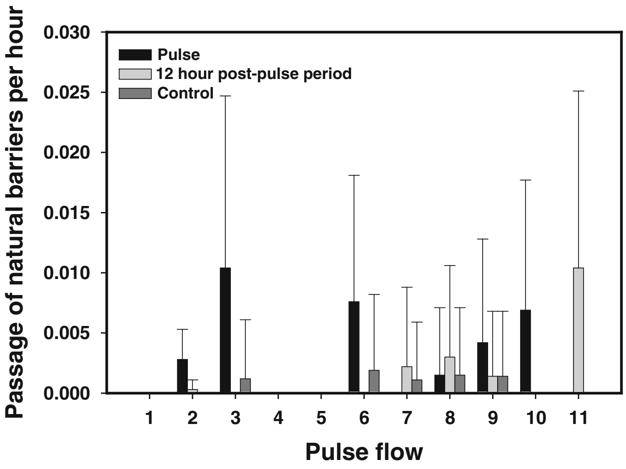

Fig. 3 Mean passage per hour rate of tagged fish during each of the pulse flows. Whiskers represent standard deviation

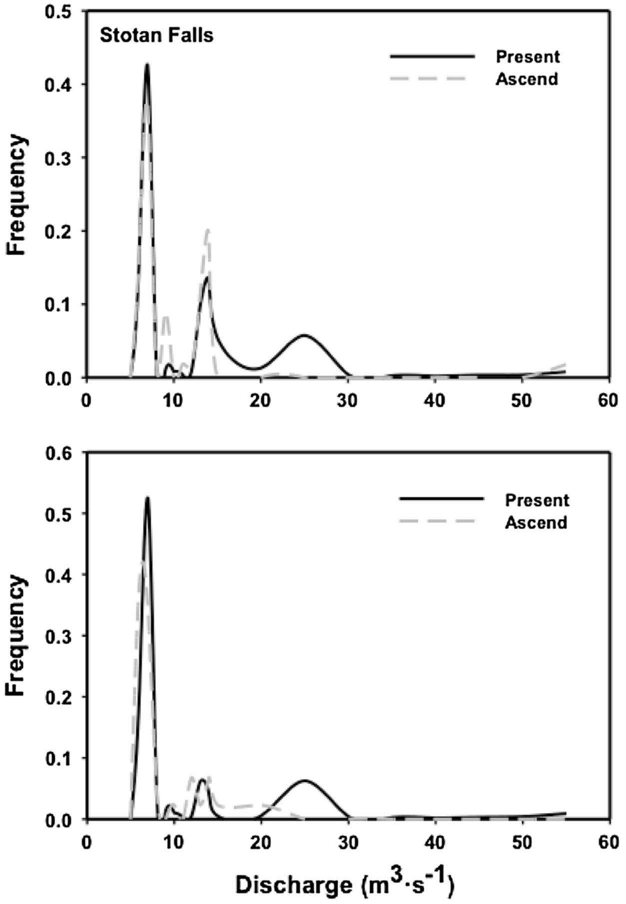

Fig. 4 Flows at Stotan Falls (SF) and Nib Falls (NF) when fish were present (*solid line*) and ascending (*dotted line*)

For Falls, fish typically ascended the barriers during the flow that was most frequent. However, fish ascended the barriers at higher frequency during "transitory" flows than at base flows; i.e., is flows that occur during the ascending or descending period of the pulse flows (Fig. 4). Fish ascended Stotan Falls at relatively high frequency during the peak of the pulse flow (11–13 ms; Fig. 4).

Powerhouse residency

Movements away from the powerhouse pool during pulse flows were observed. When all years and pulse flows were grouped, 45 % of fish were present for some time in the Powerhouse Pool. Eighteen of these fish moved to areas upstream of the Powerhouse Pool during pulse flows and 37 fish moved to upstream areas during non-pulse flows. Compared to a 50:50 likelihood of fish moving away from the pool during pulse flows, the observed difference was not significant (Chi squared test, $\chi^2 = 2.708$, $df = 1$, $P = 0.1$). When the same analysis is done, but assuming a distribution of 2:5 to account for the fact that pulses lasted 2 days while no pulses occurred for 5 days of the week, the result is also not significant (Chi squared test, $\chi^2 = 0.271$, $df = 1$, $P = 0.603$).

Locomotor activity levels

The difference in coded EMG output of fish in the impacted reach during pulse flows was negligible when compared to control flow conditions (Fig. 5). In addition, there was no significant change in EMG output during pulse flows when compared to non-pulse flow conditions for fish holding in the Powerhouse Pool (Fig. 5).

Discussion

Our results regarding the ability of pulse flows to enable upstream movement were equivocal. Summer-run Chinook salmon migrated upstream, left the powerhouse pool, and ascended natural barriers over a range of flows, and no major effect of pulse flows on migration was detected. Statistical evidence of upstream movement was only noted for 3 of 11 pulse flows. However, for all but one pulse flow, the absolute level of upstream movement was higher than control periods suggesting that larger samples sizes, and therefore increased statistical power, may have yielded more statistical clarity. Nonetheless, from a biological significance perspective, the increase in upstream migration rate, even for those three pulses that were statistically significant, was relatively minor. Our findings are consistent with Thorstad and Heggberget (1998) in which no clear relationship between increased water flow and Atlantic salmon (*Salmo salar*) upstream migration was noted. Migration is complex with the triggers for upstream movement involving factors such as flows, weather conditions, water temperature, lunar

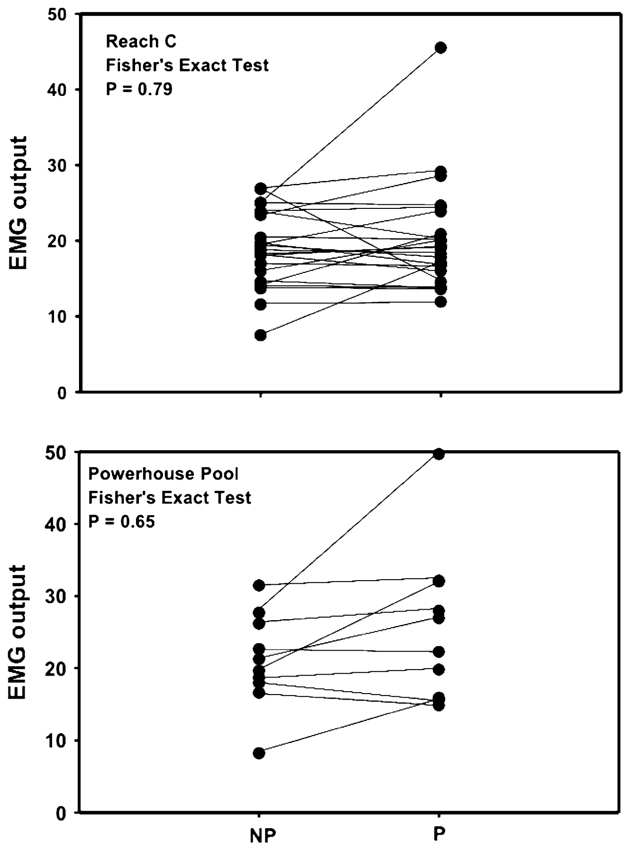

Fig. 5 Paired mean EMG outputs (no units) for each fish during non-pulse flow (NP) and pulse flow (P) conditions when fish were located in Reach C and when fish were located in the Powerhouse Pool

conditions, genetics, endocrine mechanisms, and level of maturation (summarized in Banks 1969; Quinn 2005). Lastly, Young et al. (2011) describe a conceptual model that implies pulse flows should be designed around several characteristics; specifically seasonality, magnitude, frequency, duration, and photophase to ensure positive effects on fish.

The pulse flows may not have been administered at an appropriate flow rate, though previous work on the river suggests that this is not the case. A preliminary study in 2003 found that 18 of 21 fish holding in the Powerhouse Pool moved upstream during a single 48 h pulse flow, indicating that a specific flow rate is important (Komori Wong Environmental and Bixby 2003). Another possibility is the weather conditions at the time of the pulse flows may not have been favourable for upstream migration by salmonids, as Baxter (1961) suggested that precipitation in combination with pulse flows are more effective. In contrast, a study conducted on the nearby Ash River found no relationship between weather (barometric pressure, precipitation) and summer-run Steelhead (*O. mykiss*) movement during pulse flows (Ecofish Research Ltd 2010). Furthermore, telemetry studies completed in the American southwest found no movements associated with pulse releases of water on resident trout (Gido et al. 2000; Cocherell et al. 2010b). The Puntledge River is also popular for recreation and during favourable weather conditions the pools as well as step fishways are used for swimming and lounging such that the presence of humans can physically stop or deter upstream migration. Recreational activity is reduced during pulse flow periods, but it is not known whether upstream migration of summer-run Chinook salmon could be enhanced by managing human recreational activity.

Another possibility is that upstream movement during the pulse flows by the tagged Chinook salmon (all male) in the Puntledge River was not displayed or detected because of inherent stock characteristics. These summer-run fish typically arrive in the river 4–5 months prior to the spawning. We hypothesize that there may be two migratory strategies: (1) Conserve energy by resting in habitat that minimizes energy-use and then move to spawning grounds once sexual maturation has occurred; or (2) move quickly upstream to spawning grounds and spawn when sexual maturation occurs. The trade-off for strategy one is that the fish may no longer have energy to expend on demanding migration during non-optimal flow and environmental conditions. The trade-off for strategy two is that sexual maturation may occur too early or too late if the spawning ground offers unfavourable habitat conditions (i.e., warm water temperatures). Under strategy 1, upstream movement by tagged fish during July and August would not be observed because the fish are resting in localized areas. In 2007 and 2008, fish were likely behaving in this manner, as overall migration rate was relatively slow and fish were not found to move far during pulse flows. Under strategy 2, upstream movement may be occurring irrespective of environmental conditions and at too fast a rate for it to be attributed to the pulse flows. In 2009, fish moved relatively quickly to the upper section of the reach (or through the upper hatchery fish way and out of the study area) and large numbers of fish were only present in the reach during the first two pulse flows. Since the Puntledge River has been altered from its historic condition and a number of barriers have been modified or constructed, fish should likely opt for strategy two, as delaying upstream movement likely would lead to energy deficits during the final upstream migration to the spawning ground. As well, river temperature during July and August may be too high for fish that stay in the river during migration to successfully spawn during historic time frames because of accelerated depletion of somatic energy stores (Hasler et al. 2012a). However, movement rates during pulse flows did not reveal temperature dependence (data not shown). Indeed, without detailed historical information (i.e., pre-regulation) on the behavior of summer-run Chinook salmon in the Puntledge system, it is only possible to speculate on the factors that influenced migration success.

The second goal of the pulse flow was to facilitate fish ascending the two natural barriers (i.e., Stotan and Nib Falls) that are accentuated at low flows. Passage rates did differ significantly across the pulse flows, only pulse flow 2 had a significant increase in passage and it was this pulse flow that lasted an abnormally long time (i.e., 360 h). Thorstad and Heggberget (1998) also found that not all pulse flows were able to stimulate fish to ascend barriers to migration. A number of studies have found that obstructions to migration are difficult for fish to move through under almost any flow conditions (Gowans et al. 2003; Thorstad et al. 2003). In particular, Thorstad et al. (2003) found that the stimulation of fish to ascend barriers during pulse flows was river-specific, and fishways that seemingly appeared to be easy for fish to migrate through had low passage rates.

When the river flow during the time fish were present at each barrier was compared to the river flow at the approximate time that fish passed, it was found that fish typically passed during the flows that occurred the most often (base flows 5–6 m^3 s^{-1}). In addition, fish present at Stotan Falls also tended to ascend relatively more frequently during pulse flows and during transition flows (i.e., river flows present when the pulse flows were either ramping up or ramping down). This tendency was not as prevalent at Nib Falls, possibly due to structural differences between the sites, or the increased likelihood of finding appropriate spawning habitat in the Nib Falls area (compared to Stotan, Nib Falls is a shorter, less inclined water fall complex and potential spawning habitat is more prevalent).

Limiting the residency times of fish to the turbine outflow at the Powerhouse Pool was a goal of the pulse flows. We observed that over one-third of fish that resided at the pool moved away from it (i.e., upstream) during pulse flows. Though this was statistically non-significant, the powerhouse pool could be explored in more detail to understand the rheotactic stimuli at the site and determine if there are possible physical alterations that could be made to reduce residency times at the Powerhouse pool or to eliminate attraction all together. Telemetry results showed that the majority of fish were not attracted to the pool, contrary to visual observations and a previous telemetry investigation (Taylor and Guimond 2006; Komori Wong Environmental and Bixby 2003). Without knowing what side of the river the fish prefer, one may expect a 50–50 likelihood of becoming behaviourally entrained and, in fact, we found that 55 % of fish avoided the pool. In reality, the hydraulic influence of the pool extends across the entire river and all fish were released on one side (the same side as the outflow). There may be merit in comparing the fate of fish released on both sides of the river and in characterizing hydraulic conditions within and downstream of the Powerhouse Pool to identify potential opportunities to reduce delay. For example, managers may be able to decrease residence times at the pool by diverting fish to the opposite side of the river with in-river structures or placing a fishway on the opposite bank.

Though our analysis of the EMG output values was coarse, we should have been able to detect changes in coded EMG output values that would indicate biologically significant changes in locomotor activity patterns. However, we found no change in EMG output values during changes in flow. Fish will seek out habitat that optimizes their energy expenditure (Hinch and Rand 1998). Cocherell et al. (2010a) suggested that fish increased swimming speeds during initial increases in river discharge, but then found suitable habitat that resulted in reduced swimming speeds during periods of near peak flow conditions. It is possible that the sampling rate of the transmitters did not allow for brief and rare burst activity, as the coded EMG tags rectify the muscle contraction activity over a 2 s period (the minimum setting; Cooke et al. 2004). However, such transmitters have been used successfully in several studies to document fine-scale behavioural responses to variation in flow (e.g., Murchie and Smokorowski 2004; Cocherell et al. 2010a; Taylor et al. 2013a, b), suggesting that summer-run Chinook salmon were able to make adjustments in their position such that they did not experience increased focal water velocities during pulse flows. One could surmise that if fish were able to avoid high flows, that the pulse flows themselves may be ineffectual unless we better understand the suite of cues that are needed to stimulate upstream movement.

Management implications

No clear relationship was found between pulse flows administered in the Puntledge River and summer-run Chinook salmon migration. However, we did find some results that suggest that there may be some limited benefit of pulse flows, as several pulse flows stimulated statistically significant upstream movements and all but one pulse yielded absolute increases in upstream movement relative to control periods. What is lacking, however, is an understanding of the biological significance of these relatively small increases in upstream movement. Given the status of the stock, there may be merit in continuing to use pulse flows. We found no evidence that fish holding in the reach during pulse flows were exhibiting increased locomotor activity, suggesting that pulse flows do not have significant negative consequences on summer-run Chinook salmon energy expenditure. Therefore, it may be appropriate to alter pulse flow operations and evaluate longer pulse flows, earlier timing (though timing is based on when fish are returning), and/or using different magnitudes of flows. We also suggest additional research to characterize hydraulic conditions in and downstream of the Powerhouse pool and experimental release of telemetered fish on both river banks. We also suggest experiments to evaluate the influence of recreational activity (i.e., swimming, lounging) on upstream movement of summer-run Chinook salmon given the popularity of the Puntledge River and our belief that fish cannot or would not pass barriers such as Stotan and Nib Falls during periods of heavy recreational use. Managers will need to consider the trade-offs associated with the financial losses that occur during pulse flows and if those funds could be more wisely spent on other mitigation measures or compensative strategies, possibly including stock enhancement, habitat restoration/modification, or even trap and truck transport options to facilitate upstream passage.

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