Physical habitat below a hydropeaking dam: Examining progressive downstream change

by

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B.Sc. (Hons), McGill University, 2010

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Science

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Geography)

The University of British Columbia

(Vancouver)

August 2015

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Abstract

This study examines the short-term physical habitat conditions at four sites on the Kananaskis River, Alberta, where a hydropeaking dam was installed in 1955. This dam imposes both the approximate pre-dam minimum flow, and the pre-dam flood (from a small flood year) on a daily basis. The purpose of this study was to examine the extent of daily changes in physical habitat conditions that organisms in the stream would have to endure, and the extent to which these fluctuations might be reduced downstream due to distance from the dam and unregulated tributary influence. Physical habitat conditions monitored over low flow and high flow dam releases were: velocity; depth; bed mobility; ramping rates; and total suspended solids. River2D was used to calculate weighted usable area and potential habitat for Brown Trout (fry, juveniles and adults) and Mountain Whitefish (fry, juveniles and adults) at the low and high flow conditions. Of the factors examined, only ramping rates and total suspended solids showed signs of downstream attenuation. Differences in depth, velocity, weighted usable area, and potential habitat between low flow and high flow dam releases were variable, and showed no downstream pattern. Between low and high flow releases, significant (p = 0.05) changes in depth were observed at all sites, and significant changes (p = 0.05) in velocity were observed at all but the second site. The second site also saw the smallest changes in measures of habitat between low flow and high flow dam releases; however, all other sites saw median differences of 48.1% to 170.9%. Percent differences in habitat between low and high flow dam releases ranged from 2.6% (second downstream site, juvenile Brown Trout) to 193.3% (third downstream site, adult Mountain Whitefish). These habitat changes happen more often than before the dam was installed (many times weekly vs. about once a year during the spring freshet) and they oc-
cur more rapidly. Because these changes happen at times of the year that are out of
synchronization with the biota of the river, and as these changes are extreme, this
implies challenging physical habitat conditions for indigenous stream biota.
Preface

B. Eaton, M. Lapointe and the HydroNet research group selected the river and dam for study. B. Eaton assisted with designing field and data analysis methods. All other work was completed by the Author, L. Winterhalt.
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### Glossary

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<th>Description</th>
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<td>ADCP</td>
<td>acoustic doppler current profiler</td>
</tr>
<tr>
<td>PVC</td>
<td>polyvinyl chloride</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>median grain size</td>
</tr>
<tr>
<td>TSS</td>
<td>total suspended solids</td>
</tr>
<tr>
<td>SDC</td>
<td>serial discontinuity concept</td>
</tr>
<tr>
<td>IHA</td>
<td>indicators of hydrologic alteration</td>
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<tr>
<td>WUA</td>
<td>weighted usable area</td>
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<tr>
<td>IFIM</td>
<td>instream flow incremental methodology</td>
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<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
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<tr>
<td>HSI</td>
<td>habitat suitability index</td>
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<tr>
<td>PHABSIM</td>
<td>physical habitat simulation</td>
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Acknowledgments

Firstly, I would like to thank Dr. Brett Eaton for his endless support. His technical expertise, generosity with his time, and encouragement made him an excellent mentor, without whom this project would not have been possible. Thanks also to committee member Dr. John Richardson, whose advice, comments and guidance helped bring important ideas and direction to this project.

Thanks are due to field and lab assistants Aaron Tamminga, Tyler McDivitt Vandermolen, Alistair Davis and Byeong Kim; and the rest of Brett Eaton’s lab group, Dan McParland, Holly Buehler and Sarah Davidson for their help along the way. I would like to acknowledge the rest of the UBC Geography cohort who provided much needed technical R, Matlab and LaTex help, and Shreejoy Tripathy for the statistics crash course.

I would also like to acknowledge friends and family for their emotional support. My parents, for high expectations and raising me in an environment that valued and encouraged higher education. Paul and Elaine for providing me with a beautiful place to write. Alyssa Stryker, Alyssa Salaciak, Lauren Boivin, and Andrea Reid for commiserating with, and encouraging me. Sara Hopkins for help during the final stages. Ilana Klinghoffer, for helping me in every way that you possibly could, through every single stage of this project. And finally to Tyler, for the infinite patience, love, encouragement and perspective - thanks for never giving up on me.

Funding for this project was provided by the HydroNet Consortium NSERC research network.
Chapter 1

Introduction

Fish living downstream of hydropeaking dams are affected by dam operations. Hydropeaking dams (dams with rapidly varied flow, adjusted to meet consumer energy demands) change the flow regime of a river drastically, modifying the magnitude, frequency, duration, timing and rate of change of flows. Physical habitat is altered, and the relationship between fish population fitness and available habitat has been well studied. To date, the study of hydropeaking power has been overwhelmingly centered on the biological responses, with less study on how short-scale temporal variations in flow may influence habitat. Further, how progressive downstream unregulated tributary inflow may alter fish habitat under hydropeaking regimes, can help to understand how organisms respond to regulated rivers at increasing distances downstream.

1.1 Hydropeaking flows

The discharge fluctuations observed below hydropeaking dams are extreme, and when dealing with river restoration efforts, it is common to focus on reducing the extent of hydropeaking. However, at present, direct empirical support of its effectiveness is limited (Korman and Campana, 2009). Hydropeaking dams affect each aspect of the natural flow regime. On average, they: (1) reduce the volume of the highest, and possibly the lowest, discharge events; (2) increase the frequency while decreasing the duration of extreme flows; (3) obscure the seasonal timing of key
flow rates; and (4) increase the incidence of rapid rates of change to a near-daily occurrence. The following will review the effects of highly varied flow on fish and aquatic invertebrates.

Many studies have examined the effects of rapidly varying flow on fish populations. Many of these have specifically examined fish below hydropeaking dams (e.g., Heggenes, 1988; Bunt et al., 1999; Korman and Campana, 2009) while others have examined flood flows (e.g., Seegrist and Gard, 1972; Erman et al., 1988). All these studies examining small, young fish found that they were more susceptible to large, rapidly varying flows, and often sought refuge in woody debris or the substrate. Generally, detrimental effects of hydropeaking dams were more noticeable directly below the dam, with effects diminishing downstream. When examining physical habitat features in relation to fish populations, depth was the most commonly studied feature, while cover type, wetted area, velocity, and substrate size were also commonly investigated features. Physical habitat made reference to hydraulic geometry relationships between discharge, depth, velocity and wetted perimeter. However, most studies did not make mention of other geomorphologic properties, mainly sediment transport and entrainment of bed material under highly varied flows. An exception to this is the Erman et al. (1988) study that linked mobility of the bed to the mechanical crushing of age-0 fish. Table 1.1 provides a summary of the results of selected studies.
**Table 1.1:** Summary of the effects of rapidly varying flow on fish.

<table>
<thead>
<tr>
<th>Methods and habitat variables</th>
<th>Relevant results</th>
<th>Study</th>
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</thead>
<tbody>
<tr>
<td>Measure near shore habitat use</td>
<td>1. Age-0 rainbow trout did not maintain their position within immediate shoreline areas when flows were high.</td>
<td>Korman and Campana (2009)</td>
</tr>
<tr>
<td>Rainbow trout (age-0)</td>
<td>2. Catch rates 2 to 4 times higher at daily minimum flow compared to daily maximum flow in nearshore areas.</td>
<td></td>
</tr>
<tr>
<td>Reviewed 326 articles on flow, fish and fish habitat</td>
<td>3. Otolith growth larger on Sundays, where low flows allowed fish to be near shore areas with higher water temperatures and lower velocities.</td>
<td></td>
</tr>
<tr>
<td>Examined use of (1) cover, (2) pools</td>
<td>1. Use of cover and pools increased as flow increased.</td>
<td>Bunt et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>2. Similar depths were used at high and low flow (63 cm).</td>
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<th>Methods and habitat variables</th>
<th>Relevant results</th>
<th>Study</th>
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</thead>
<tbody>
<tr>
<td>(3) wetted area and depth by Brown Trout</td>
<td>3. Used lower surface water velocities at high than low flow. 4. Woody debris and roots used more during high flows. 5. Woody debris most common cover type, and appears to provide refuge from large fluctuating flows.</td>
<td></td>
</tr>
<tr>
<td>Reference conditions: Hydropeaking (1992, year prior to treatment). Treatment: reduction in extent of hydropeaking (measured two years post, in 1994).</td>
<td>1. Fish no more common after reductions in extremes from hydropeaking. The lack of a significant difference in fish numbers may be due to the relatively short study period.</td>
<td>Cowx et al. (1998)</td>
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<th>Relevant results</th>
<th>Study</th>
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<td>community structure as a function of: (1) Water depth (2) Current velocity (3) Substrate coarseness (4) Substrate heterogeneity</td>
<td>2. Species using broad range of habitat higher in density in regulated vs control system.</td>
<td></td>
</tr>
<tr>
<td>Examined effects of (1) Depth</td>
<td>1. Hydraulic refugia from high flows crucial. 2. WUA does not follow strict relationship with discharge.</td>
<td>Valentin et al. (1996)</td>
</tr>
<tr>
<td>Methods and habitat variables</td>
<td>Relevant results</td>
<td>Study</td>
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<tr>
<td>(2) Velocity</td>
<td>Varies greatly spatially and temporally under hydropoeaking dams.</td>
<td></td>
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<tr>
<td>(3) Weighted usable area on Brown Trout</td>
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| Observed fish fauna composition immediately below a dam (a few km) and further downstream (20-40 km) | 1. Fewer fish immediately downstream of dam (within first few km).  
2. Fish numbers low further downstream (20-40 km) but not as severely reduced, however fewer than reference stream.  
3. Increasing discharge range corresponded with significant decrease in fish population. | Moog (1993) |
<p>| Examined effect of winter floods on Brook Trout and Paiute Sculpin age-0 class. (Not hydropoeaking, but | 1. Brook Trout and Paiute Sculpin age-0 individuals killed during winter floods due to mobility of bed causing mechanical grinding or crushing. | Erman et al. (1988) |</p>
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<tr>
<th>Methods and habitat variables</th>
<th>Relevant results</th>
<th>Study</th>
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<tbody>
<tr>
<td>Examined effects of winter floods on Rainbow and Brook Trout. (Not hydropeaking, but large, rapid change in flow)</td>
<td>1. Winter floods decimated developing eggs of fall spawning Brook Trout. 2. Spring floods destroyed spring-spawned Rainbow Trout eggs. 3. Influence of floods on adults less pronounced and predictable.</td>
<td>Seegrist and Gard (1972)</td>
</tr>
<tr>
<td>Review articles on effects of rapidly varying flow</td>
<td>1. More than 10 studies reviewed observed organism (fish or invertebrates) stranded as water levels drop. Subsequently, organisms may die due to dewatering of pools, lack of food, low DO, high temperatures, and predation. 2. Fish eggs may be in dewatered areas, and may perish due to thermal stress, insufficient oxygen or desiccation. 3. Cushman highlights need to know channel morphometry</td>
<td>Cushman (1985)</td>
</tr>
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<th>Study</th>
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<td>so that velocity, depth, width and wetted perimeter can be determined.</td>
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<tr>
<td></td>
<td>4. Discusses need to understand channel composition so</td>
<td></td>
</tr>
<tr>
<td></td>
<td>that erosion and sediment potential can be made. Also</td>
<td></td>
</tr>
<tr>
<td></td>
<td>discusses bank erosion.</td>
<td></td>
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<tr>
<td>Examined effect of flash flood on structural fish assemblages</td>
<td>1. Fish more resilient to flash floods with increased hydraulic complexity.</td>
<td>Pearsons et al. (1992).</td>
</tr>
<tr>
<td></td>
<td>2. Fish may be washed out under flood flows.</td>
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</table>
Prior to the 1980s, little focus was given to the importance of channel morphology in determining the ecological integrity of riverine systems (Nowell and Jumars, 1984). Recently, more research has been conducted in this area, in a shift towards more holistic and environmentally sensitive river management (Maddock, 1999). Studies have attempted to determine the effect of geomorphology on fish, with descriptors of geomorphology including such factors as elevation, channel slope, wetted width, depth, proportion of reach with deep-pool habitat, and percent composition of various substrate materials (e.g. Bain et al., 1988; Valentin et al., 1996; Bunt et al., 1999; Quist et al., 2004). While the effects of many geomorphic factors on fish have been studied, there are discrepancies in terms of the relative importance of such factors when different fish, rivers, and experimental methods are considered. However, of the geomorphic factors considered, the most commonly examined and agreed upon aspects are the velocity, depth, substrate material, and access/proximity to cover.

Relationships between depth, velocity, substrate and discharge have been largely studied, and while these interactions are still not perfectly understood, models are being developed to help to quantify these relationships (e.g. Eaton and Church, 2007; McParland et al. in press). Furthering these models is useful for predicting fish habitat, the relative role of dams and the quantity and quality of available habitat.

In addition to factors previously discussed, flow alterations from a dam can affect nearly all aspects of a river. Those that are often studied include: temperature (e.g. Camargo and Voelz, 1998; Cereghino et al., 2002; Paller and Saul, 1996; Preece and Jones, 2002; Saltveit et al., 1994); physicochemical properties (e.g. Byren and Davies, 1989; Storey et al., 1991; O’Keeffe et al., 1990); algae, invertebrate and fish abundance and species composition (e.g. Rehn, 2009; Cereghino et al., 2002; Patterson and Smokorowski, 2011; Jones, 2013; Cortes et al., 2002).

1.2 Hydraulic modelling

While the uses of freshwater resources span a large spectrum in Canada, two pervasive and conflicting goals are to maximize power generation profits for economic benefit and to maintain the ecological integrity of a system for biological and soci-
etal good. In order to balance these goals, managers have sought tools which enable them to quantify habitat preservation at different flows in order to decide the minimum flow necessary for the ecosystem, and then to quantify the ‘surplus’ water that can be used for economic activities. Largely, the instream flow incremental methodology (IFIM) and hydraulic habitat modelling are used to set minimum biological flow requirements. As this method is one of the most commonly applied, it is important to understand the methodology, along with shortcomings, if these methods are used to make important water management decisions. This section will examine the IFIM and hydraulic modelling methodologies.

Implemented 1970, the American National Environmental Policy Act forced regulators to go beyond the previous minimum flow requirements in regulated rivers, and instead examine the relationship between discharge and life-stage-specific habitat needs (Stalnaker et al., 1995). The IFIM was subsequently developed by the U.S Fish and Wildlife Service as a framework for quantifying this relationship. The ultimate goal of the IFIM was to make more informed management decisions in terms of the allocation of water resources among different users. Like all models, IFIM simplifies true conditions, and as such certain assumptions are made in order for the model to be applicable. One important assumption is that physical habitat is the key limiting factor for fish, and that any changes in physical habitat are solely related to changes in flow (Maughan and Barrett, 1992). This premise facilitates the further study of physical habitat, which is divided into macro- and micro-habitat variables. Under IFIM, the micro-habitat variables measured are: water velocity; water depths; instream objects such as cover; and bottom substrate materials (Bovee, 1982). The important macro-habitat variables are: water temperature; dissolved oxygen; total alkalinity; turbidity; and light penetration through the water column (Bovee, 1982). Both macro- and micro- habitat variables are influenced by discharge, and these changes can be assessed through modelling. According to United States Geological Survey (USGS) guidelines for IFIM, the amount of usable habitat is determined by a) the length of usable stream habitat (length of stream fitting required macro-habitat variables) and b) the habitat area per stream length (as determined by micro-habitat variables). IFIM does not provide a method to assess micro-habitat, but rather establishes the framework for precise modelling tools to be employed. It is often hydraulic models that are used to investigate macro-habitat
elements as a function of discharge (Bovee 1982).

### 1.2.1 Hydraulic models and habitat suitability indices

Hydraulic models are a logical second step following IFIM. They allow physical channel characteristics (depth, velocity, substrate) to be calculated as a function of discharge. However, modelling these characteristics alone does not allow a manager to determine the available aquatic habitat. To do so, physical hydraulic models must be combined with biological indicators of acceptable physical habitat. A habitat suitability index (HSI) is often used to link these biological needs with physical habitat. HSI measures range from 0 for unsuitable habitat to 1 for ideal habitat conditions. Each fish species and life stage usually have different physical habitat needs, and therefore will have their own specific HSI.

A HSI may be developed using one of three different methods: a review of the literature; empirical frequency analyses; or habitat preference curves (Stier and Crance 1985). Literature reviews will examine peer-reviewed articles pertaining to the target species at the target life stage. Ideally, HSIs developed from literature reviews will preferentially use case studies from areas near that of interest, as different populations within the same species may exhibit different habitat preferences. Reviews often seek to identify important habitat variables in relation to (1) where the target species was found, (2) where it was in highest densities and (3) where it grew the fastest (Stier and Crance 1985). This method assumes that more suitable habitat will have target fish present, support higher densities and support higher growth rates.

The second method, empirical frequency analyses, involves investigating the frequency of fish observed at sites within the stream of interest and may be preferential to literature reviews. This method indicates the habitat that is chosen when given other habitat options (while literature reviews may not make mention of other available habitats). Empirical frequency analyses may also be referred to as utilization curves. The third method, which is to develop preference curves, is similar to empirical frequency analysis. However, corrections are made for environmental biases. This is done by taking into account not only a species’ preference for a given habitat type, but also the availability of that habitat in the environment. For exam-
ple, if a river is composed of 5% pools by volume, and target species are sighted in pools 50% of the time, preference curves would correct for the low percentage of pools. A simple frequency analysis of this situation might indicate that there is no preference for pools (50% in pools versus 50% not in pools). However, the rare occurrence of pools in the stream would indicate that there is a strong preference for this habitat type, and a HSI developed based on a preference curve corrects for this.

Different hydraulic models exist to map suitable habitat and determine overall weighted usable area (WUA). Most common in the United States is the physical habitat simulation (PHABSIM) model, developed in conjunction with IFIM. This model is also commonly used in Canada, Europe and New Zealand (e.g. Ghanem et al., 1996; Moir et al., 2005; Hudson et al., 2003). While developed to work alongside IFIM, PHABSIM models often focus solely on the implementation of HSIs relating to preferences in depth, velocity and substrate while ignoring macrohabitat variables (Spence and Hickley, 2000).

1.3 Downstream trends on impounded rivers

Below hydropeaking facilities, there exists a range of physical habitat conditions, as peak discharge pulses progressively disperse downstream and unregulated tributaries play increasing roles. Downstream variability in invertebrate drift and fish populations below hydropeaking facilities have been examined. For example, longitudinal changes in fish communities, from bottom-dwelling fish in fast-flowing waters to more generalist species downstream have been observed (Vehanen et al., 2005). In contrast, a 9-fold increase in drift with 7-fold increase in flow was observed 250 m downstream from a hydropeaking dam, with similar drift levels 8 km downstream (Bruno et al., 2010). However, little research has been conducted to quantify a gradient of physical habitat downstream, particularly in reference to unregulated tributary influence. A study by Valentin et al. (1996) refers to the importance of specific site morphology in terms of predictions of changes in physical habitat, but this study does not address spatial distribution of morphologic differences.
1.4 Research objectives

The first goal of this research is to quantify the scope of physical changes in the river, as defined by depth, velocity, bed mobility and total suspended solids (TSS) between low and high flow pulses from a hydropower dam and how progressive distance downstream from the dam may alter these changes. The second goal of this research is to quantify changes in WUA between the low and high flow conditions for specific fish species, with increasing distance below a hydropower dam and increasing unregulated tributary inputs. This research will help to understand the mechanisms by which organisms are affected by hydropower operation strategies, and if distance downstream and unregulated tributaries decrease variations in physical habitat conditions between low flow and high flow dam releases.
Chapter 2

Study area

2.1 Kananaskis River

2.1.1 Dams on Kananaskis River

The section of Kananaskis River between Pocaterra Dam and Barrier Reservoir is the subject of this study. Kananaskis River flows 74 km in length from its headwater lakes in the Rocky Mountains to its confluence with Bow River in the foothills, upstream of Calgary, Alberta. There are four dams that impact the Kananaskis System: the Interlakes Dam (1955) between the Upper and Lower Kananaskis Lakes; Pocaterra Dam (1956) downstream of the Lower Kananaskis Lake and at the beginning of the Kananaskis River; Barrier Dam (1947); and Kananaskis Dam (1913) which dams the Bow River immediately downstream of its confluence with the Kananaskis. The Pocaterra hydro plant is capable of producing 15 MW of power, and produces 29,000 megawatt hours per year (TransAlta, 2014). Releases from the Pocaterra Dam are 0.5 m$^3$/s at base flow and 20 to 23.6 m$^3$/s during releases.

2.1.2 Geography

The Kananaskis catchment is very mountainous, with many features evident of past glaciation, including cirques, U-shaped valleys, and moraines. While small, a few glaciers currently remain in the basin. The rock type is predominantly limestone,
with large thrust faults as occur elsewhere in the Canadian Rockies. The Lower Kananaskis Lake, from which the Kananaskis River begins, sits at an elevation of 1680 m asl. Towards the lower end of the river, Barrier Lake is at an elevation of 1380 m asl, and the mouth of the river is at 1280 m asl. Mountain Peaks in the catchment can reach elevations of 3000 m asl. The Kananaskis River varies in sinuosity through its course from tortuous meanders to irregular sinuosity. On occasion it is confined by debris fans or bedrock, but also has large sections of wider valley with wetlands immediately adjacent to the river. The valley bottom consists mostly of forest, while high elevation areas are largely exposed alpine rock, with some alpine meadows above treeline. The Kananaskis River has a drainage basin area of 933 km$^2$, of which 899 km$^2$ lies above the Barrier Dam, and with 362 km$^2$ accounted for above Pocaterra Dam.

Figure 2.1: Upper (right) and Lower (left) Kananaskis Lakes, with the Inter-lakes Dam between the two.
2.1.3 Climate

Climatic variables are measured near the Pocaterra Dam at the Environment Canada weather station Kananaskis Pocaterra (ID 3053604). The climate station is located at 50° 42’ 45.020” N, 115° 07’ 12.060” W at 1610 m asl. This climate station provides information on valley bottom conditions. The average minimum daily temperature for the month of January, the coldest month of the year, is -16.5 °C. The average maximum daily temperature for July, the hottest month of the year, is 20.6°C (see Fig. 2.2). Average annual precipitation is 568 mm, with 255 mm of that falling as snow (Environment Canada, 2015). In the winter, more snowfall is recorded at higher elevations than in the valley bottom, so annual precipitation for the entire basin is somewhat higher.

Figure 2.2: Average monthly air temperature and precipitation values for Kananaskis Pocaterra weather station, 1981-2007. Precipitation means represented by dark blue bars. Monthly maximums, means and minimums represented by red, green and blue lines respectively.
2.1.4 Flow regime

River regulation by hydroelectric dams can have profound effects on the physical and biological components of aquatic ecosystems. One mechanism by which these changes are induced is the flow regime. The flow regime consists of five key elements: the magnitude; timing; duration; frequency; and rate of change. Each of these five aspects has important implications for the physical structure and biota of a river ecosystem. For example, high flows are important for flushing fine grain sediment from spawning habitat of fish (Beschta and Jackson, 1979) and the timing of these high flows may also be an important biological cue for spawning (Montgomery et al., 1983) and egg hatching (Naesje et al., 1995). Poff et al. (1997) provides a summary of the multitude of ecological responses to the five aspects of the flow regime.

Richter et al. (1996) identified five groups of indicators of hydrologic alteration (IHA). These five groups are: (1) Magnitude of monthly water condition; (2) magnitude and duration of annual extreme water conditions; (3) timing of annual extreme water conditions; (4) frequency and duration of high and low pulses; and (5) rate and frequency of water condition changes.

Pre- and post-Pocaterra Dam

IHA were used to assess changes on the Kananaskis River below Pocaterra Dam. Mean daily discharge data was acquired online from the Water Survey of Canada for the Pocaterra gauging station (station ID 05BF003). Discharge data covers a pre-dam period (1931-1955) and a post-dam period (1975-2009) with a 20-year gap following the construction of the dam. Because data are averaged daily, groups 4 (frequency and duration of high and low pulses) and 5 (rate and frequency of water condition changes) of the IHA are not used for this assessment. Due to the hydropeaking operation of the Pocaterra Dam, daily mean data are not sensitive enough for all suggested analyses.

The operation of the Pocaterra hydropeaking dam has had significant effects to the hydrologic regime of the Kananaskis River. A summary of the results of the IHA is found in Table 2.1. Differences from pre- to post- dam conditions ranged from -183% (1-day minimum discharge) to 67% (mean March discharge). Of IHA
Table 2.1: Indicators of hydrologic alteration for Kananaskis River following flow regulation.

<table>
<thead>
<tr>
<th></th>
<th>Streamflow m3/s Pre-dam</th>
<th>Post-dam</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group 1: Monthly magnitude</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>7.75</td>
<td>12.08</td>
<td>44%</td>
</tr>
<tr>
<td>February</td>
<td>6.76</td>
<td>11.35</td>
<td>51%</td>
</tr>
<tr>
<td>March</td>
<td>4.91</td>
<td>9.88</td>
<td>67%</td>
</tr>
<tr>
<td>April</td>
<td>3.34</td>
<td>5.91</td>
<td>65%</td>
</tr>
<tr>
<td>May</td>
<td>6.53</td>
<td>3.29</td>
<td>-66%</td>
</tr>
<tr>
<td>June</td>
<td>14.06</td>
<td>2.51</td>
<td>-139%</td>
</tr>
<tr>
<td>July</td>
<td>13.61</td>
<td>3.70</td>
<td>-115%</td>
</tr>
<tr>
<td>August</td>
<td>9.14</td>
<td>5.16</td>
<td>-56%</td>
</tr>
<tr>
<td>September</td>
<td>5.99</td>
<td>5.29</td>
<td>-12%</td>
</tr>
<tr>
<td>October</td>
<td>3.93</td>
<td>6.23</td>
<td>45%</td>
</tr>
<tr>
<td>November</td>
<td>7.19</td>
<td>8.80</td>
<td>20%</td>
</tr>
<tr>
<td>December</td>
<td>8.87</td>
<td>10.95</td>
<td>21%</td>
</tr>
<tr>
<td><strong>Group 2: Magnitude and duration of annual extremes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-day minimum</td>
<td>1.39</td>
<td>0.07</td>
<td>-183%</td>
</tr>
<tr>
<td>3-day minimum</td>
<td>1.41</td>
<td>0.08</td>
<td>-180%</td>
</tr>
<tr>
<td>7-day minimum</td>
<td>1.5</td>
<td>0.23</td>
<td>-146%</td>
</tr>
<tr>
<td>30-day minimum</td>
<td>2.22</td>
<td>0.51</td>
<td>-125%</td>
</tr>
<tr>
<td>90-day minimum</td>
<td>4.07</td>
<td>2.24</td>
<td>-58%</td>
</tr>
<tr>
<td>1-day maximum</td>
<td>24.78</td>
<td>20.29</td>
<td>-20%</td>
</tr>
<tr>
<td>3-day maximum</td>
<td>23.05</td>
<td>18.94</td>
<td>-20%</td>
</tr>
<tr>
<td>7-day maximum</td>
<td>20.81</td>
<td>16.66</td>
<td>-22%</td>
</tr>
<tr>
<td>30-day maximum</td>
<td>17.1</td>
<td>14.14</td>
<td>-19%</td>
</tr>
<tr>
<td>90-day maximum</td>
<td>11.8</td>
<td>11.87</td>
<td>1%</td>
</tr>
</tbody>
</table>

that were calculated, all but the 90-day maximum showed a significant difference (p = 0.05) in pre-and post- dam states. Statistics from the monthly magnitudes showed a marked shift in seasonality. Seasonality was drastically changed. April through October showed increased discharge from 20% to 67% after damming and September through May experienced markedly decreased discharge from -12% to
-139% after damming. This shift in seasonality is depicted in Fig. 2.3 and Fig. 2.4 depicts the change in seasonality.

The average annual 1-, 3-, 7-, and 30- day minimum and maximum discharges were all significantly lower after the installation of the Pocaterra Dam, with decreases between 19% and 183% (see Table 2.1). The mean 1-day maximum flow event after damming is below the mean prior to damming, however all values fall within 1-standard deviation of the pre-dam data (see Fig. 2.5). This range is suggested by Richter et al. (1997) to be an appropriate initial target for the range of post-dam flows, in order to maintain ecosystem integrity. In contrast, 1-day minimum flows post-dam fall far below the suggested range (see Fig. 2.6).

2.2 Study sites

For this research, there are four study sites on the Kananaskis River (see Fig. 2.7). The first site, called Pocaterra, is at 1.5 km from Pocaterra generating station. Site 2, called Opal, is 20.3 km downstream. Site 3, called Galatea, is 24.9 km downstream. Ribbon, the fourth site, is 35.4 km downstream of the generating station. The inflow end of Barrier Lake (the next downstream reservoir) is 46.0 km downstream of Pocaterra generating station.
Figure 2.4: Daily flows averaged for pre-dam (blue solid line) and post-dam (red solid line) conditions. Dashed blue line represents the mean annual flow prior to dam construction and the dashed red line, the mean annual flow after dam construction.
Figure 2.5: Annual peak discharges for 1931 to 2009. The blue solid line represents annual peak discharge prior to dam construction, with the dashed line representing the mean. The red solid line represents annual peak discharge after dam construction, with the dashed line representing the mean. The dashed black lines represent one standard deviation from the mean pre-dam average.
Figure 2.6: Annual minimum discharges for 1931 to 2009. The blue solid line represents annual minimum discharge prior to dam construction, with the blue dashed line representing the mean. The red solid line represents annual minimum discharge after dam construction, with the red dashed line representing the mean. The dashed black lines represent one standard deviation from the mean pre-dam average.
Figure 2.7: Kananaskis River study sites in relation to the hydropoeaking dam. Flow is northward.
Chapter 3

Changes in physical stream characteristics

3.1 Introduction

Hydroppeaking dams result in significant alterations to the natural flow regime of a river. These alterations can have profound effects on the biota of the aquatic ecosystem and are realized by changes to physical habitat conditions. Understanding and quantifying these physical changes is the first step to understanding the biological changes that result from hydroppeaking dam operation. Additionally, quantifying downstream trends, as compared to examining single sites below dams, aids in the understanding of the geographic extent of these physical habitat changes.

3.1.1 Serial discontinuity concept

Early in the study of regulated rivers, Ward and Stanford (1983) proposed the serial discontinuity concept (SDC), the idea that as distances downstream from dams increase, a river’s ecological properties become more like those of unregulated systems. Fundamental to this theory is the idea that dams act as discontinuities on a river, interrupting natural gradients in properties such as nutrient or thermal regimes. The SDC assumes there should be a downstream recovery of biophysical factors with increasing distance from a dam, due to lateral (e.g. tributary),
and vertical (i.e. hyporheic) inputs, referred to as the recovery distance or zone of influence. While many studies, and even entire journals have been devoted to the study of the effects of dams on rivers (e.g. Regulated Rivers: Research and Management), relatively few studied longitudinal trends and recovery distances, specifically testing the SDC (Stanford and Ward, 2001). Ellis and Jones (2013) and Stanford and Ward (2001) reviewed previous studies in attempts to summarize findings related to the SDC. These review articles found studies that some recovery gradients occur quickly (e.g. within 3.5 km for temperature (Cereghino et al., 2002), within 3 km for nutrient levels (O’Keeffe et al., 1990)), some require much greater distances (e.g. Plecoptera recovering over 80 km (Stanford and Ward, 1989), Trichoptera recovering within 60-80 km (Hauer et al., 1989)) and other variables and river system combinations may show no longitudinal trends of recovery (e.g. invertebrates on 387 km of the Colorado River (Stevens et al., 1997), physicochemical properties over 74 km of study (Byren and Davies, 1989)). The trend towards recovery distances was not necessarily related to the factor studied (for example, sometimes invertebrates showed recovery and other times they did not) and different variables may present different patterns depending on type and operation of the dam and the downstream inputs into the river.

3.1.2 Bed mobility

Interstitial space within the bed of a river is an important habitat area for many aquatic species. Moog (1993) identified the importance of this interstitial space as habitat refugia against high flows for invertebrates, and Liebig et al. (2001) did the same for fish during high-flow events. Erman et al. (1988) linked bed mobility to the mechanical crushing of age-0 fish, and Death and Winterbourn (1995) linked bed instability with decreases in the number of invertebrate species. It is therefore likely that organisms are sensitive to bed mobilization during high-flow events. Grain size distributions, and patterns of degradation and aggradation below dams are common areas of research focus (e.g. Weston, 2013), but the influence of hydropoaking operations on bed mobilization is less commonly studied. Bed mobility was a variable examined by Bruno et al. (2010) below a hydropoaking dam, but in the 8 km studied, no bedload was observed.
3.2 Methods

To assess the range of change in physical properties along the length of the Kananaskis River below the Pocaterra Dam, field measurements were conducted in the summer of 2011 between May 15 and Aug 15. Velocity was measured along cross sections at the four main study sites (see Fig. 2.7). To gain a more complete understanding of depth and velocity characteristics throughout the full lengths of four study reaches, River2D (a 2-dimensional hydraulic modelling program) was used to combine survey data with velocity and discharge data to model depths and velocities throughout the entirety of each site. The following will first describe the instream measurements and secondly, the modelling process in River2D.
3.2.1 Instream measurements

Stream Hydrology

To address the main elements of depth and velocity as habitat variables, multiple field techniques were used. As the physical properties of streams are highly related to stream flow, loggers were installed at various sites downstream of the dam to track depth throughout the summer. Depth data could then be correlated with other, non-continuous data that were collected to extrapolate these data for the entire summer period.

Prior to spring freshet, polyvinyl chloride (PVC) wells were installed into the substrate and Schlumberger Mini-Diver depth loggers were deployed (see Figs. 3.1, 3.2), recording pressure readings on a 15-minute interval. Logger elevation was determined using a Garmin GPSmap 76S by calibrating it at known elevation (1390 m asl) at the University of Calgary Biogeoscience Institute. Another logger was installed in the Kananaskis River valley at the University of Calgary Biogeoscience Institute to act as atmospheric barometric compensation. Instream depth logger pressure data were compensated with the barometric pressure reader using the data compensation feature in the Schlumberger Water Services Diver-Office program 2011.1 (Version 4.0.76.0) given the difference in pressure readings and the given elevations, by the following formula from the diver manual:

\[ P_H = P_0 e^{-\left(MgH\right) / (RT)} \]  

(3.1)

where \( P_H \) is the atmospheric pressure at elevation height \( H \), \( P_0 \) is the atmospheric pressure at the reference height, \( M = 28.8 \times 10^{-3} \text{ kg/mol} \) (molecular mass of air), \( g = 9.81 \text{ m/s}^2 \) (standard gravity), \( H \) = height in metres, \( R = 8.314 \text{ J/mol/K} \) (gas constant), and \( T = \) temperature in Kelvin. Barometric compensation data were unavailable from the period of July 15, 2011 to Aug 15, 2011, therefore instream depth loggers from this period contain a much greater degree of uncertainty due to the range of barometric pressure changes.
Bed topography surveys

The four study reaches were surveyed using a Leica TCR805 total station. Pocaterra, the most upstream study reach was surveyed for a length of approximately 300 m at approximately 1 m intervals. Opal, the second study reach, had six cross sections taken for a reach length of approximately 150 m, with each cross section at approximately one channel width distance downstream of the previous (see Fig. 3.3). Galatea, the third study reach, was surveyed similarly to Opal, but with five cross sections, for a reach length of approximately 100 m. The furthest downstream study reach, Ribbon, was surveyed similarly to the first, over a length of approximately 300 m at 1 m intervals (see Fig. 3.4). When surveying streams for two dimensional (2D) hydraulic modelling, ten cross sections of complete surveys are recommended, and in this regard the middle two reaches have fewer cross sections than recommended. However, for similar 2D hydraulic habitat modelling programs, five cross sections in a stream have been used for habitat modelling purposes (e.g. Rosenfeld et al. 2005). Justification for less intensive surveying relates to the fact that these two reaches had more uniform bed topography.

Velocity

To calculate discharge and measure velocity, an acoustic doppler current profiler (ADCP) was set up at each of the four study sites. The ADCP was used to take vertical velocity profiles at 1 m intervals across the channel (see Fig. 3.5). Exact
Figure 3.3: Surveying stream bed topography at the Opal site.

Figure 3.4: Brett Eaton and Aaron Taminga surveying using a Leica TCR805 total station and survey rod at the Ribbon site.
positioning of the ADCP during recording events was determined using the total station. When ADCP measurements were taken along a cross section, water surface elevation at the cross section and at the depth logger for that site were also recorded. Raw data exported from the ADCP were processed using a script to truncate data at the appropriate depth based on bed topography and water survey elevation, as well as average the forwards and backwards facing beams. The velocity profiles were then integrated over depth and used to calculate discharge and velocity at the given depth at the time of recording.

**Grain size and tracer rocks**

Basic pebble counts of 100 stones were completed at each study reach along cross sections until the requisite number of stones were collected and the cross section was completed. Once the median grain size ($D_{50}$) had been established, $D_{50}$ sized stones were collected and painted blue to be installed as tracer rocks. They were replaced, slightly embedded, along one cross section at each study site. They were re-examined after one flood pulse to determine whether or not the bed had been mobilized during the flood pulse.

**Total suspended solids**

The final element of physical conditions that was examined was the level of TSS. A depth-integrated sampler was used to collect three water samples for each site.
For study sites near tributary creeks (Galatea and Ribbon) samples were taken up-stream and downstream of the tributaries. One additional site named Evan Thomas was added upstream of Ribbon Creek, and samples were taken there immediately upstream of the Evan Thomas Creek. Samples were then filtered using Whatman 934-AH glass fiber filters (particle retention of 1.5 µm), dried and then weighed in the lab to measure TSS.

3.2.2 River2D modelling

Measuring velocity and depth along cross sections provides important information on the physical habitat conditions in a stream; however, this information applies only to the cross section, representing an infinitely small area of the stream channel. To understand the physical conditions experienced by aquatic organisms in the Kananaskis River, channel topography and flow data were used to model the two-dimensional hydraulic conditions over each study reach. Modelling was done using River2D (version 0.95a, January 15, 2010) a 2D hydrodynamic finite element modelling program developed by P. Steffler, A. Ghanem, J. Blackburn, and Z. Yang in conjunction with the University of Alberta, Fisheries and Oceans Canada, and the United States Geological Survey. River2D is capable of outputting 2D maps of hydraulic conditions, including such information as water surface elevation, velocity magnitude, Froude number, depth and shear velocity magnitude. Of interest in this study are 2D maps of depth and velocity.

Model inputs

To run the model, certain physical conditions of the stream, measured in the field, were used as input parameters. First, bed roughness height had to be determined for the study reaches. Detailed roughness characteristics were not recorded in the field, and as such, study reaches were given a single value for bed roughness height. The average reach bed roughness height was determined using the $D_{84}$ for the study site by the following equation (Hey, 1979):

$$K = 3.5 \times D_{84}$$

Secondly, a mesh had to be overlaid onto the study sites. Survey data were
input into River2D, and study sites were defined by external boundaries. Two-dimensional meshes were created by inputting uniform nodes throughout the study reaches. The meshes were then triangulated and smoothed by making alterations to the mesh triangulation, until they had a quality index 0.30 or higher. For each model run, discharge was input along with starting inflow and outflow water surface elevations. River2D was run under steady flow (as opposed to the transient flow option). Inflow and outflow elevations were altered slightly to achieve solution convergence. Solutions were deemed acceptable when the inflow and outflow discharges were equal within plus or minus 5% (often within 1%). For specific model parameters, see Table 3.1.
Table 3.1: River2D model parameters

<table>
<thead>
<tr>
<th>Site</th>
<th>Flow (high or low)</th>
<th>Q inflow (cms)</th>
<th>Q outflow (cms)</th>
<th>Roughness (K)</th>
<th>Mesh spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocaterra Low</td>
<td>1.18</td>
<td>1.18</td>
<td>0.26</td>
<td>2, 3</td>
<td></td>
</tr>
<tr>
<td>Pocaterra High</td>
<td>20.40</td>
<td>20.40</td>
<td>0.26</td>
<td>2, 3</td>
<td></td>
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<tr>
<td>Opal Low</td>
<td>8.24</td>
<td>8.24</td>
<td>0.13</td>
<td>0.3, 1</td>
<td></td>
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<tr>
<td>Opal High</td>
<td>20.60</td>
<td>20.60</td>
<td>0.13</td>
<td>2</td>
<td></td>
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<tr>
<td>Galatea Low</td>
<td>5.52</td>
<td>5.52</td>
<td>0.5</td>
<td>0.5</td>
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<td>Galatea High</td>
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<td>16.80</td>
<td>0.5</td>
<td>0.3</td>
<td></td>
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<tr>
<td>Ribbon Low</td>
<td>3.35</td>
<td>3.27</td>
<td>0.266</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Ribbon High</td>
<td>25.97</td>
<td>25.86</td>
<td>0.266</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Results

3.3.1 Stream hydrology

Depth loggers recorded water level fluctuations in response to environmental flow changes and flow releases from the Pocaterra Dam along the Kananaskis River. Hydrographs for the summer 2011 period are displayed in Fig. 3.7. Each discrete peak represents a high flow release from the Pocaterra Dam. Peak freshet flows occurred in late June, and were most clearly seen at Ribbon. High flows from the dam were released on semi-regular intervals throughout the summer.

The flood hydrograph for single flood events varied between sites. However, the second, third and fourth sites had much more similar characteristics to one another than the most upstream site. A single flood pulse of 10.75 hrs duration on August 5, 2011 was identified as a typical flood, and the hydrographs from each site are depicted in Fig. 3.6. The rising limb of the hydrograph at the Pocaterra site reached its maximum depth in 1 hour at a rate of 57.3 cm/hr, and achieved half of its maximum depth within approximately 16 minutes at a rate of 107.4 cm/hr. At Opal, the maximum depth was achieved within 9.5 hours (the slowest of the four sites) at a rate of 4.0 cm/hr and half of the maximum depth increase occurred within 27 minutes at a rate of 42.6 cm/hr. The next site, Galatea, showed a similar overall up-ramping rate of 3.9 cm/hr requiring 8.5 hours to reach its maximum depth, but with a much slower increase to reach 50% of its maximum depth at a rate of 21.3 cm/hr doing so in approximately 47 minutes. Ribbon, the most downstream site also required 8.5 hours to reach its maximum depth and did so with an up-ramping rate of 2.5 cm/hr. Ribbon obtained half of its depth increase in approximately 23 minutes at a rate of 25.8 cm/hr. Also of importance are down-ramping rates, which were similar, but lower than up-ramping rates (see Tables 3.2 and 3.3). It appears that the flood pulse becomes sufficiently dispersed, that with a 10.75 hr flood, it is only the first site, Pocaterra, that reaches a steady stage. If the peaking release from the dam were to have a duration of greater than 10.75 hrs, it is likely that the Opal, Galatea and Ribbon sites would continue to experience rises in stage and would reach a maximum stage after a greater period of time than described for the 10.75 hr flood. Releases of longer than 10.75 hrs are likely to have minimal effects on
**Figure 3.6:** Hydrograph for each study site of a high flow release from the Pocaterra Dam on August 5-6, 2011.

stage at the Opal site, due to the rapidity with which it attains maximum stage.
Table 3.2: Up-ramping and down-ramping rates for the first 50% of depth increase or decrease during a 10.75 hr high flow release on August 5, 2011.

<table>
<thead>
<tr>
<th>Site</th>
<th>Up-ramping rate (cm/hr)</th>
<th>Down-ramping rate (cm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocaterra</td>
<td>107.4</td>
<td>77.5</td>
</tr>
<tr>
<td>Opal</td>
<td>42.6</td>
<td>15.0</td>
</tr>
<tr>
<td>Galatea</td>
<td>21.3</td>
<td>8.5</td>
</tr>
<tr>
<td>Ribbon</td>
<td>25.8</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 3.3: Up-ramping and down-ramping rates for the entire duration of a 10.75 hr high flow release on August 5, 2011.

<table>
<thead>
<tr>
<th>Site</th>
<th>Up-ramping rate (cm/hr)</th>
<th>Down-ramping rate (cm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocaterra</td>
<td>57.3</td>
<td>43.9</td>
</tr>
<tr>
<td>Opal</td>
<td>4.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Galatea</td>
<td>3.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Ribbon</td>
<td>2.5</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Figure 3.7: Hydrographs for all study sites. The most upstream site is Pocaterra, followed by Opal, Galatea and lastly Ribbon. Red lines represent the date and water level when low flow velocity readings were taken. Blue lines represent the date and water level when high flow velocity readings were taken. Barometric calibration was unavailable from July 15, 2011 to Aug 15, 2011.
Table 3.4: Estimates of bed mobility after one flood cycle. Not all displaced tracer rocks were recovered, and as such, the percentage displaced represents a conservative estimate.

<table>
<thead>
<tr>
<th>Site</th>
<th>Tracer rocks displaced (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocaterra</td>
<td>16</td>
</tr>
<tr>
<td>Opal</td>
<td>31</td>
</tr>
<tr>
<td>Galatea US</td>
<td>20</td>
</tr>
<tr>
<td>Galatea DS</td>
<td>16</td>
</tr>
<tr>
<td>Evan Thomas US</td>
<td>22</td>
</tr>
<tr>
<td>Ribbon US</td>
<td>12</td>
</tr>
<tr>
<td>Ribbon DS</td>
<td>20</td>
</tr>
</tbody>
</table>

3.3.2 Bed mobility

Tracer rocks were installed to determine if the bed was mobile, and not to necessarily precisely measure that mobility. As such, exact distance and number displaced were not recorded. However, a general survey was done to count the displaced rocks. Only rocks that had been displaced and retrieved were counted, so the recorded percentage of displaced rocks is likely to be an underestimate of the total number displaced. The $D_{50}$ from each study site was mobilized after one eight-hour flood flow release from the dam. Tracer rock displacement ranged from 12% to 31%, and after one eight hour flood pulse some tracer rocks were found as far as 9 m downstream from their original placement (see Table 3.4).

3.3.3 Modelled depth and velocity

River2D depth and velocity maps demonstrate the spatial distribution of physical characteristics at low and high flows. Each site had between 1760 and 28500 nodes where depth and velocity were modelled, and used for statistical interpretation. Depth and velocity maps for each study site can be seen in Figs. 3.8 to 3.15. In Fig. 3.8 and Fig. 3.9, the maps of depth and velocity at both low and high flows for the Pocaterra study site can be seen. In this first 300 m section, there is a side channel bar, a point bar and a mid channel bar at a low flow of 1.18 m$^3$/s. When subjected to high flow conditions of 20.4 m$^3$/s, these bars become submerged. The next site, Opal, had somewhat less distinct gravel bars, and as a result, a gen-
Table 3.5: Median grain size for study sites along Kananaskis River

<table>
<thead>
<tr>
<th>Site</th>
<th>$D_{50}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocaterra</td>
<td>44.0</td>
</tr>
<tr>
<td>Opal</td>
<td>19.7</td>
</tr>
<tr>
<td>Galatea US</td>
<td>52.3</td>
</tr>
<tr>
<td>Galatea DS</td>
<td>78.7</td>
</tr>
<tr>
<td>Evan Thomas US</td>
<td>48.3</td>
</tr>
<tr>
<td>Ribbon US</td>
<td>31.3</td>
</tr>
<tr>
<td>Ribbon DS</td>
<td>32.0</td>
</tr>
</tbody>
</table>

eral widening is viewed between the low and high flow conditions (Fig. 3.10 and Fig. 3.11). At the Opal site at low flow, the regions of high velocity occurred over riffles. At high flow, the pools and riffles became less distinguishable as the water surface slope became more even over the site, accounting for the lower velocities seen at high flow.

At the Galatea site, the stream has little influx of sediment, and as a result has a large $D_{50}$ and the channel is somewhat incised (see Table 3.5). It is relatively straight, with few exposed bars at low flow. This site experienced the smallest change in depth of all the sites, which may be attributed to the higher channel slope. The Galatea site also experienced the smallest range in changes (see Fig. 3.12 and Fig. 3.13), likely due to the uniformity of the channel.

Ribbon, the furthest downstream site, experienced flooding of the side and mid channel bars at high flow, with an especially large point bar at the left side of the channel becoming submerged at high flow (Fig. 3.14 and Fig. 3.15). The highest depths were observed towards the left bank mid-way along the study section, where a large pool was found.
Figure 3.8: 2D velocity map for the Pocaterra study site. (a) Low flow release from dam. (b) High flow release from dam.
Figure 3.9: 2D depth map for the Pocaterra study site. (a) Low flow release from dam. (b) High flow release from dam.
Figure 3.10: 2D velocity map for the Opal study site. (a) Low flow release from dam. (b) High flow release from dam.
Figure 3.11: 2D depth map for the Opal study site. (a) Low flow release from dam. (b) High flow release from dam.
Figure 3.12: 2D velocity map for the Galatea study site. (a) Low flow release from dam. (b) High flow release from dam.
Figure 3.13: 2D depth map for the Galatea study site. (a) Low flow release from dam. (b) High flow release from dam.
Figure 3.14: 2D velocity map for the Ribbon study site. (a) Low flow release from dam. (b) High flow release from dam.
Figure 3.15: 2D depth map for the Ribbon study site. (a) Low flow release from dam. (b) High flow release from dam.
Depth and velocity data were not normally distributed, and as such, a non-parametric test was performed. Samples were assumed independent for statistical purposes, but may not be truly independent; they can be approximated as such given that discharge had nearly doubled between samples and depth (velocity) is commonly considered dependent on discharge, velocity (depth), channel slope and frictional forces. The non-parametric test showed a significant ($p=0.05$) difference between depth at the high and low flow conditions at all sites. Increases in depth at high flow ranged from 0.29 m at the Galatea site (the third downstream) up to 0.53 m at the Pocaterra site (the most upstream site), which correspond to increases in discharge of 11.2 m$^3$/s and 19.2 m$^3$/s respectively (see Fig. 3.16 and Fig. 3.17).

Velocities at three of the four sites showed significant increases from the low to the high flow conditions. However, the second site, Opal, experienced no statistically significant change in velocity between low and high flow events (see Fig. 3.18 and Fig. 3.19).

### 3.3.4 Total suspended solids

TSS changed between low and high flow dam releases (see Fig. 3.20). At all but two sites, TSS were found to be significantly higher during high flow releases from the dam, using a t-test with a corresponding $p$ value of less than 0.05 (three samples per site, per flow condition). The highest TSS at high flow were found at the Pocaterra site (42 mg/L) and were more than eight times higher than levels seen at high flow at any other site. At Evan Thomas Creek, 32 km from the dam, there was no statistically significant difference in TSS between low and high flow. However, the average TSS were higher at low flow at this site. Unlike high levels of TSS observed elsewhere, the higher sediment load at low flow at Evan Thomas was associated with a few large suspended grains (1 to 2 mm); whereas elsewhere, suspended solids were much finer (less than 1/4 mm) and uniform throughout the water samples. As water samples were taken during one day, it is likely that these few large grains were indicative of a small localized event, and not representative of regular levels of suspended solids at low flow. This is further supported by the fact that high flow had lower levels of TSS. This site experienced higher discharge rates and greater depths at high flow. Sediment transport theory would anticipate
higher shear stresses at higher discharge rates and therefore greater, not less, levels of suspended solids. This is why it is suspected that the large grains present in the sample were from a small, local disturbance. Ribbon Creek is one of the largest tributaries over this stretch of the Kananaskis River. Downstream of this creek, no statistical difference was observed between the levels of TSS at high and low flow.

3.4 Discussion

3.4.1 Ramping rates

In this study, rates of flow change rapidly due to the hydropoeaking nature of the dam. Most of the literature on the effects of ramping focuses on the rate of fish stranding in rapidly dewatering areas. Scientific studies have also been conducted on the effects of flow fluctuations on fish growth, and have concluded slight posi-
Figure 3.17: Boxplot of the changes in depth between low and high flow at the four study sites. The distribution represents the changes that occurred at individual locations throughout the study site, over an evenly spaced grid.
Figure 3.18: Boxplot of velocities at high (teal) and low (beige) flow for the four study sites.

tive (Smokorowski et al., 2011; Crisp et al., 1983), neutral (Almodovar and Nicola, 1999) and negative effects (Baran et al., 1995; de Crespin de Billy et al., 2002; Weyers et al., 2003). It is unknown if fish stranding occurs on the Kananaskis River. Preliminary fish surveys completed in the summer of 2012 do indicate that fewer fish are located upstream where ramping rates are highest, compared to downstream sites on the Kananaskis River (Macnaughton, 2013, pers. comm.). A study using an artificial stream by Halleraker et al. (2003) showed that stranding of juvenile Brown Trout was significantly decreased by reducing down-ramping rates from 60 cm/hr to 10 cm/hr. Pocaterra, 2 km downstream from the dam experienced the greatest down ramping rates of the study sites, of up to 77.5 cm/hr. With large bars at low flow that then become submerged at high flow, the Pocaterra site has potential to experience fish stranding. Down-ramping rates at the other three sites ranged from 3.8 to 15.0 cm/hr. Potential for stranding is present at these sites, especially when the down-ramping rate exceeds 10 cm/hr (Halleraker et al.)
Figure 3.19: Boxplot of the changes in velocity between low and high flow at the four study sites. The distribution represents the changes that occurred at individual locations throughout the study site, over an evenly spaced grid.
Figure 3.20: Total suspended solids at all study sites, at high and low flow.

Saltveit et al. (2001), and occurs during daylight hours (Halleraker et al., 2003) (as is often the case for the Kananaskis). Stranding potential is likely higher on the Kananaskis River, as down-ramping continues until minimum flow levels are achieved. Where down-ramping occurs rapidly, but to a moderate flow level, stranding is less likely (Tuhtan et al., 2012).

3.4.2 Bed mobility

A thorough analysis of bed mobility is not possible here, due to limitations from sampling procedures whereby not all rocks were recovered as they were not fitted with tracer magnets. As a result, percentages of rocks displaced are underestimated. The 12% to 31% + of tracer rocks that were mobilized at high flow indicate
that the $D_{50}$ is mobile at all sites at high flow. The percentage of displaced rocks was approximately within one order of magnitude across sites, indicating that similar levels of bed mobility are observed throughout the Kananaskis River during high flow events.

3.4.3 Depth and velocity

Fluctuations in depth and velocity were extreme at most sites between high and low flow. Changes in velocities and depths were shown to modify some salmonid behaviour, potentially with energetic costs (e.g. Korman and Campana, 2009; Geist et al., 2005; Scruton et al., 2003, 2005). However, it is difficult to determine the net effect, as other studies have shown positive growth with hydropoeaking. At Opal, there was a wide range of change in velocities at any specific point in the site; however, an average of these changes actually resulted in a decrease in velocity (although this change was not statistically significant). This is partly explained by high water surface slope riffles becoming flooded at high flow, resulting in a decrease in slope and therefore decrease in velocity over the riffles. This behaviour, while reasonable given the morphology, is odd as generally depths and velocities increase with increasing discharge.

3.4.4 Total suspended solids

Ignoring the anomaly at Evan Thomas where a few large grains increased the TSS, differences in TSS between low and high flows were seen only at Pocaterra, the first site within 1.5 km of the dam. When high levels of TSS are seen, it suggests that shear stresses are high enough to erode banks during flood flows immediately downstream of the dam. Suspended load originates largely as erosion of the banks and from overland flow. Because climatic conditions were fairly dry when the samples were taken, all suspended solids in the stream are likely to have originated from within the channel.

The flood wave is likely responsible for the increased erosion at Pocaterra resulting in higher TSS. Downstream, while depths and velocities (and therefore shear stress) were high at high flow releases, there was a much reduced level of solids in suspension, indicating that the rapid up-ramping rate and flood wave ex-
experienced upstream may be responsible for the solids in the water. Slight over
topping of the banks at high flow between the first and second study sites could
result in deposition of suspended particles, and in part, explain lower levels of sus-
pended solids observed at high flow at the downstream sites. TSS concentrations
may also be decreased progressively downstream by the influx of clearer water
from tributaries and groundwater flow.

In a summary report on the effects of suspended solids on salmonids, sus-
pended solids were reported to cause physiological (more acute) and behavioural
(more long-term) changes (Bash et al., 2001). Low level thresholds leading to be-
havioural changes were usually measured in hundreds of mg/L, which is more than
double the highest level recorded on the Kananaskis. Levels as low as 1.5 mg/L
resulted in adverse health conditions in some Chinook Salmon fry (Newcombe and
MacDonald, 1991). It is possible then that TSS at high flow on Kananaskis River
have some adverse effects on fish, with sites between 5.1 mg/L and 6.8 mg/L (ex-
cept Pocaterra’s high of 42.3 mg/L).

3.5 Conclusions

Most of the results of the changes in physical condition point to the idea that longi-
tudinal position has little influence on how a site is affected by the upstream dam.
The dominant driving factor as to how physical characteristics will change between
high and low flow seems to be site-specific morphology. Of indicators measured,
only ramping and TSS relate to distance from the dam. TSS were high 1.5 km
downstream of the dam and appeared to reach an equilibrium by the second study
site, 20.3 km from the dam. This equilibrium, however, is above the level of TSS
observed at low flow.
Chapter 4

Downstream fish habitat

4.1 Introduction

How ecosystems respond to river regulation plays a large role in how dams are operated. Environmental needs are considered along with human needs (hydropower, flood control, etc.) when regulators decide how a dam may be operated. While entire ecosystems are affected by river regulation, it is riverine species that are most affected and most often considered in environmental flow needs. As they are generally the most valuable economic and recreational animal in streams, fish are usually given the most consideration. In the provincial instream flow guidelines for British Columbia, two separate guidelines exist: those for fish-bearing streams, and those for non fish-bearing streams (MWLAP, 2004). It is important to have a strong scientific understanding of how fish respond to changes in flow, so that the best management decisions can be made.

Many studies have been conducted below dams to assess how they impact fish. They generally focus on fish, or fish habitat. When examining fish habitat variables, often a single site below a dam is studied (e.g., Garcia et al., 2011). Fish abundance and diversity below dams may be studied at progressive distances below dams, with little quantifiable data on habitat (e.g., Vehanen et al., 2005). Rarely do studies include detailed, progressive longitudinal habitat data, below dams. The study by Valentin et al. (1996) does address habitat at multiple sites below a dam, but this area of study is uncommon. This chapter seeks to examine habitat at four sites...
downstream of a hydropoeaking dam, at the high and low flow releases. It also examines how differences in usable habitat change with increasing distance from the dam and with increasing unregulated tributary influence.

4.2 Methods

To assess changes in fish habitat on the Kananaskis River, field studies were conducted in the summer of 2011. Pressure transducers were installed at four sites along the river downstream of Pocaterra Dam. Sites were located 1.5 km to 35.4 km downstream of the dam (see Fig. 2.7). The next reservoir on the river is 46 km downstream from Pocaterra Dam.

From these sites, stream bed topography, depth, and velocity measurements were taken between May 15 and August 15, 2011. Field data were used as input parameters to model depths and velocities for 100 m to 400 m at each study site at both the low and high flow dam releases. River2D, a 2-dimensional hydrodynamic finite element modelling program, was used. For a detailed explanation of field methods, River2D and model parameters, please refer to the Methods section of Chapter 3.

4.2.1 Habitat modelling

River2D was used to model fish habitat at high and low flow on Kananaskis River below the hydropoeaking Pocaterra Dam. Depth and velocity estimates presented in Chapter 3 of this thesis were combined with habitat preference curves for known fish species in the Kananaskis River to generate 2D WUA estimates. Courtney et al. (1998) conducted an instream flow requirement study for fish in the Kananaskis River; they developed habitat preference curves for Brown Trout and Mountain Whitefish, the two main species in the Kananaskis River. Habitat preference curves for fry, juvenile and adult life stages were used for both Brown Trout and Mountain Whitefish. For measures of WUA in River2D, the minimum suitability given by either depth, velocity or channel index was used. Using surveyed bed topography, ArcGIS 10.3 was used to measure the stream length of each site. WUA data for each life stage, fish species, site, and flow condition were divided by stream length to get a standardized measure of WUA so that sites of different lengths could be

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more easily compared.

4.2.2 Potential habitat

In addition to WUA, this study also looked at potential habitat, which was defined as any portion of the 2D model that had a habitat value greater than zero. This approach attempts to simplify the model in hopes that a binary measure of ‘habitable’ or ‘non-habitable’ may carry a higher degree of confidence, if less detail. All analyses were performed for measures of WUA and potential habitat.

4.2.3 Change in habitat between flow conditions

Each life stage for fish has different habitat requirements. In general, fry fare better in low compared to high flow conditions, with adults having more habitat available at higher flows. As it would be difficult to measure a general increase or decrease in habitat across multiple life stages from the low flow to high flow condition, absolute changes in habitat were measured for each life stage and species. Because both the low and high flow condition are experienced on multiple occasions per week, the minimum habitat (experienced at either high flow or low flow) is assumed to be a limiting factor. Percent differences of habitat were calculated between the optimal and limiting flow conditions for each site, life stage and species, in order to determine the extent that the hydropoeaking flows limit habitat.

4.3 Results

WUA ranged from a low of 0 m$^2$/m stream length (adult Mountain Whitefish at Galatea during low flow) to 17.7 m$^2$/m stream length (Mountain Whitefish fry at Opal during low flow). Potential habitat varied from 1.0 m$^2$/m stream length (adult Mountain Whitefish at Ribbon during low flow) to 31.9 m$^2$/m stream length (adult Brown Trout at Pocaterra during high flow).

Mountain Whitefish adults had the least amount of habitat compared to other life stages as measured by WUA and potential habitat (at 14 site/flow/habitat combinations of 16), except for potential habitat at the Galatea and Ribbon sites at high flow. For Mountain Whitefish, fry commonly had the most WUA and potential habitat (in 10 of 16 cases). When considering potential habitat, Brown Trout adults
had the most available habitat. For WUA, Brown Trout adults had the most habitat at high flow, whereas juveniles had the most WUA at low flow.

Comparing across species, fry of Mountain Whitefish always had more habitat (WUA and potential) than Brown Trout. The opposite is true of adults, where Brown Trout had more available habitat. For juvenile life stages, no one species consistently had more available habitat. For a full summary of potential habitat and WUA, see Figs. 4.1, 4.2, 4.3, and 4.4.

When examining the percent difference between the high and low habitat condition, a consistent trend is visible across both species by measures of WUA and potential habitat (see Fig. 4.5). The smallest difference in available habitat between the two flow conditions occurs at Opal for both Brown Trout and Mountain
Figure 4.3: Potential habitat per m stream length - Brown Trout.

Figure 4.4: WUA per m stream length - Brown Trout.

Whitefish. Downstream of Opal, this difference increases at the Galatea site, and increases further at the Ribbon site. At Pocaterra, the most upstream site, the difference between the two flow conditions is similar to that at the Ribbon site.
4.4 Discussion

4.4.1 Habitat reductions

Winter habitat has been identified as a bottleneck for salmonids (Cunjak, 1996; Huusko et al., 2007). In a stream restoration study in Norway by Koljonen et al. (2013), it was determined that while restoration efforts increased summer habitat by 20%, they had no significant effect on winter habitat. This high interannual
variability in discharge and WUA negated restoration efforts and resulted in no increase in salmonid numbers. While this study notes the wintertime low in habitat as a bottleneck to salmonid numbers, we speculate that in the hydropeaking Kananaskis River, daily low habitat values (occurring at the high or low flow dam release) observed year round are likely habitat bottlenecks.

Habitat bottlenecks on Kananaskis River for different life stages, species, sites and habitat measures have between a 2.6% (juvenile Brown Trout at the Opal site, potential habitat) and 193% (adult Mountain Whitefish at the Galatea site, WUA as habitat measure) difference in habitat between the two extreme flow conditions. On average, looking at all variables, there is an 84% difference between the flow condition with the most and least habitat. This suggests that the current hydropeaking flow regime is having severe effects on fish in the river.

4.4.2 Serial discontinuity concept

The SDC presents the idea that dams on regulated rivers interrupt theoretical continuous gradients of natural flowing systems (Ward and Stanford, 1983). Natural downstream gradients include biotic (eg. periphyton, invertebrate species compositions) and abiotic (eg. temperature, velocity) factors. Frequently, the SDC examines recovery distances, referring to the distance downstream of a dam that is influenced by the dam. Beyond the recovery distance, the river is thought to behave as if the dam were not there, or where downstream changes have equalized.

Throughout the 35 km of of Kananaskis River examined in this study, there is no apparent recovery. Fluctuations in habitat availability were as extreme immediately below the dam as they were a further 35 km downstream. Along with the lack of recovery, there is no downstream trend in how habitat varied between high and low flow conditions. Rather, extreme fluctuations were seen for most life stages at most sites. These findings contrast those of Vehanen et al. (2005) where downstream gradients of physical conditions and fish assemblages were observed. The Vehanen et al. (2005) study examined a much shorter section of river (8.7 km) and the downstream reach included the impounded area immediately above a dam, perhaps explaining the differences in results.

Due to the strong range of flow conditions under the hydropeaking regime, it
is likely that no true recovery can occur between the Pocaterra Dam and where it is dammed a further 51 km downstream, as this distance is too short.

4.5 Conclusion

Changes in habitat between high and low flow dam releases were extreme. These changes happen regularly, and pose challenges to fish. The Scruton et al. (2003) study of the movement of Atlantic salmon and trout experiencing hydropeaking flows, showed that fish did not move large distances, and usually stayed within the study reach. In this study, trout moved more during peaking events than at steady flows. This increased movement is likely displayed by fish on the Kananaskis River as well, and has energetic costs associated with almost daily peaking events. It is noteworthy that no discernible downstream trend was noticed in habitat. However, this may relate more to site morphology, as the most upstream and most downstream sites were more heterogeneous than the two intermediary sites.
Changes in flow, ramping rates, bed mobility, TSS, depth, velocity, and habitat (potential and WUA) were investigated for this study. These factors were examined for changes between high flow (23 m$^3$/s) and low flow (0.5 m$^3$/s) dam releases, which both occur every week of the year. Changes between the high and low flow conditions were then examined for downstream trends. Of the factors measured, few showed any sign of downstream attenuation, in either absolute terms or in differences between the high and low flow conditions. A review article on longitudinal trends in regulated river by Ellis and Jones (2013) describes how studies often identify changes caused by dams, but more rarely report on any longitudinal changes.

5.1 Observed longitudinal trends

Hydrologic characteristics (including flood pulse attenuation and ramping rates) and TSS were two examined factors that demonstrated a longitudinal trend downstream of the Pocaterra Dam on the Kananaskis River. The downstream attenuation of the flood pulse was described in Chapter 3. This information is an important addition to discussions on longitudinal patterns below dams, as it is rarely reported (Ellis and Jones, 2013). Ramping rates were highest immediately below the dam, and attenuated with increasing distance downstream. Ramping rates were also subject to local site morphology, as demonstrated by the lowest ramping rates oc-
curing at the third, and not fourth site. This is likely related to the high slope at the Galatea site, with more of the additional discharge being accommodated by increased velocities as opposed to increased depth. TSS appears to somewhat follow the predictions of the SDC. At the first site 1.5 km below the dam, TSS were high (42 mg/L) at the peaking discharge. At all other downstream sites, the high flow value appears relatively constant. It appears then, that a steady state is reached at a distance between Pocaterra at 1.5 km and Opal at 20.3 km. However, this steady state does not imply a full recovery, as TSS levels at low flow were, on average, at 1.0 mg/L (excluding the outlier Evan Thomas site) compared to 6.1 mg/L for high flow (excluding the outlier Pocaterra site).

5.2 Elements not displaying downstream longitudinal trends

The $D_{50}$ was mobile at all sites, but not enough precision was employed in the field methods to determine any downstream trend. A future study of longitudinal patterns of bed mobility below a hydropoaking dam would benefit from an examination of multiple size classes and a proper recovery of tracer rocks. Resources did not permit for such an indepth procedure for this study, and therefore only a binary mobile or non-mobile test was completed.

Depth, velocity, and habitat did not display a downstream longitudinal trend. Neither did the changes in these factors between low and high flow. According to the SDC, the relative change in these factors between the two flow releases should diminish downstream, as more tributaries flow into the river, supposedly dampening the flood signal.

5.3 River recovery

Stream characteristics downstream of hydropoaking dams have been greatly studied, and to a lesser extent, the longitudinal trends below these dams. Longitudinal trends commonly examined are temperature (Camargo and Voelz, 1998; Cereghino et al., 2002; Paller and Saul, 1996; Preece and Jones, 2002; Saltveit et al., 1994), invertebrates (Rehn, 2009; Cereghino et al., 2002; Patterson and Smokorowski, 2011; Jones, 2013; Cortes et al., 2002), and periphyton (Rader and Ward, 1988;
Recovery distances for habitat features (either fish or invertebrate) are less commonly studied than animal abundances or diversity. Katano et al. (2009) found that the influence of a tributary downstream of the dam helped in recovering the river from the influence of the dam, which counters what was found in this study, where tributaries and downstream distance did little to reduce the effects from the dam. It is possible that due to the extreme fluctuations in flow on Kananaskis River, the distance between Pocaterra Dam and the subsequent impoundment is too short for recovery to occur.
Bibliography


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