

University of Lethbridge Research Repository

OPUS

<http://opus.uleth.ca>

Theses

Arts and Science, Faculty of

2007

Response of riparian cottonwoods to experimental flows along the lower Bridge River, British Columbia

Hall, Alexis Anne

Lethbridge, Alta. : University of Lethbridge, Faculty of Arts and Science, 2007

<http://hdl.handle.net/10133/624>

Downloaded from University of Lethbridge Research Repository, OPUS

**RESPONSE OF RIPARIAN COTTONWOODS
TO EXPERIMENTAL FLOWS ALONG THE LOWER BRIDGE RIVER,
BRITISH COLUMBIA**

ALEXIS ANNE HALL
Bachelor of Science, University of Lethbridge, 2004

A Thesis
Submitted to the School of Graduate Studies of the
University of Lethbridge in Partial fulfilment
of the requirements for the Degree

MASTER OF SCIENCE

Department of Biological Sciences
University of Lethbridge
LETHBRIDGE, ALBERTA, CANADA

© Alexis A. Hall, 2007

Abstract

The Bridge River drains the east slope of the Coast Mountain Range and is a major tributary of the Fraser River in southwestern British Columbia. The lower Bridge River has been regulated since the installation of Terzaghi Dam in 1948, which left a section of dry riverbed for an interval of 52 years prior to 2000. An out-of-court settlement between BC Hydro and Federal and Provincial Fisheries regulatory agencies resulted in the required experimental discharge of 3 m³/s below Terzaghi Dam in 2000. This study investigated growth of black cottonwood (*Populus trichocarpa*) trees in response to the experimental discharges. Mature trees did not show a significant response in radial trunk growth or branch elongation. In contrast, the juvenile trees displayed an increased growth response, and the successful establishment of saplings provided a dramatic response to the new flow regime. Thus, I conclude that cottonwoods have benefited from the experimental flow regime of the lower Bridge River.

Preface – Thesis Structure

This research-based MSc. thesis has two chapters and five appendices.

Chapter 1 provides an introduction to the Bridge River valley, with a historic look at hydroelectric power generation, mining and a brief description of vegetation and wildlife.

Chapter 2 is a stand-alone research paper summing up my research, which includes field samples from 2003-2007 used to analyze the growth and recruitment of riparian cottonwood trees along the lower Bridge River, British Columbia.

Appendix 1: Yalakom River regression analysis

Appendix 2: Vegetation Index

Appendix 3: Birds and Mammals Index

Appendix 4: Fishes Index

Appendix 5: T-test results for Figure 2.12.

Acknowledgements

I would like to extend my heartfelt thanks to Dr. Stewart Rood, for all the years of encouragement and support he has given me throughout. His endless enthusiasm fuelled my studies of the wonders of riparian zones and rivers.

I would like to thank Paul Higgins for his wealth of knowledge about the Bridge River, data and insight. Thank you to David Pearce for spending days upon days helping me determine the best possible way to measure basal area, and having the patience to try all of them. Thank you to my committee members: Hester Jiskoot and Joseph Rasmussen, for supporting me throughout.

I would like to thank the girls in the lab: Colleen, Karen and Julie (the cottonwood team) for their help, encouragement and hours of thoughtful contemplation. I would like to thank Colleen for sitting beside me and putting up with me every day, all day, and night for two years. Thank you to Karen for teaching me hydrology more than once, and to Julie for helping with editing.

I could not have collected all the data I did without all the support from my trusty field assistants: Breanne Patterson, Steven Hall, Brett Weisser, and Riley Hall, along with the faithful hounds Otter, Max and Kismet.

The Bridge River is a river that I will think about for many years to come.

Table of contents

Signature page	ii
Abstract.....	iii
Preface.....	iv
Acknowledgements	v
Table of Contents.....	vi
List of Tables	viii
List of Figures	ix
Abbreviations	xii

Chapter 1: River damming and hydroelectric power production in the Bridge River valley

1.1 Introduction	1
1.2 Natural History	9
1.3 Geography	13
1.4 Human History	15
1.5 BC Hydro controlled flow experiment	16
1.6 The Bridge River today.....	17
1.7 My thesis research.....	18
1.8 Conclusion	19

Chapter 2: Response of riparian cottonwoods to experimental flows along the lower Bridge River, British Columbia.	20
2.1 Introduction	20
2.1.1 Life history and ecophysiology of black cottonwoods	23
2.1.2 The lower Bridge River	25
2.1.3 The Bridge River today	26
2.1.4 This study	30
2.2 Methods	31
2.2.1 Hydrology	31
2.2.2 Mature trees	35
2.2.3 Juveniles	39
2.2.4 Saplings	43
2.3 Results	44
2.3.1 Hydrology	44
2.3.2 Riparian cottonwoods	51
2.3.3 Mature trees	53
2.3.4 Juveniles	59
2.3.5 Saplings	67
2.4 Discussion	71
2.5 Conclusion and Management Implications.....	75
2.6 Literature Cited	76
Appendix 1: Yalakom River regression.....	84
Appendix 2: Vegetation	85
Appendix 3: Birds and mammals.....	86
Appendix 4: Fishes	87
Appendix 5: One-way ANOVA test for Figure 2.10.....	88
Appendix 6: Independent samples test results for Figure 2.12.....	89

List of Tables

Table 1.1. Time line of hydroelectric infrastructure, installation along the Bridge-Seton system (Conlin et al. 2000).	7
Table 1.2. Water Survey of Canada (WSC) historic and current, hydrometric gauging stations in the Bridge River basin, sequenced from upstream to downstream.	8
Table 2.1. Experimental flow releases below Terzaghi Dam (Failing et al. 2004).	29
Table 2.2. Research components used to analyze impacts of flow regulation on the growth of riparian cottonwoods along the Bridge River system, British Columbia.	36
Table 2.3. Characteristics of historic flow rates of the lower Bridge River below Terzaghi Dam separated into three intervals: pre-dam, pre-flow and post-flow. Q_{max} = annual maximum mean daily discharge.	50
Table 2.4. Wilcoxon signed-rank test results of mature Bridge River cottonwood trees, with mean radial increment growth, displayed in three-year combined averages from 1997 to 1999 (pre-flow) versus 2001 to 2003 (post-flow).	57
Table 2.5. Kruskal-Wallis test (a non-parametric approach for analysis of variance) results from three groups of juvenile cottonwood trees along the lower Bridge River Reach 4 as shown in Figure 2.10.	61
Table 2.6. Mann-Whitney test (non-parametric paired-comparisons) results for juvenile cottonwoods separated into pre-flow, transition and post-flow groups along the lower Bridge River, as shown in Figure 2.10.	62

List of Figures:

Figure 1.1. Map of the Bridge River System in southwestern British Columbia, WSC = Water survey of Canada hydrometric gauging stations. 2

Figure 1.2. The Bridge Glacier September 1, 2006 (Photo - Joe Shea). 3

Figure 1.3. The upper Bridge River Valley, at the inflow delta of Downton Reservoir, November 6, 2004. Note the standing dead timber. 3

Figure 1.4. The middle Bridge River, upstream of the Hurley River inflow May 23, 2004. 4

Figure 1.5. Carpenter Reservoir August 17, 2005. 4

Figure 1.6. Elevational profile of the Bridge River. Bridge Glacier to the confluence of the Bridge and Fraser Rivers..... 10

Figure 1.7. The lower Bridge River Reach 4, 0 m³/s discharge September 1992 (Photo - Paul Higgins). 14

Figure 1.8. The lower Bridge River Reach 4, 3m³/s discharge July 25, 2006. 14

Figure 2.1. The Yalakom River, July 28, 2006 (left) and January 2, 2007 (right) facing upstream from the bridge that crosses road 40. The sample site was on river left (picture right). 34

Figure 2.2. A cross-section of a black cottonwood trunk, showing the anatomy and measurements taken. The increment core represents a sample of wood extracted from the tree. 38

Figure 2.3. Hydrograph showing daily discharge of the free-flowing lower Bridge River (Water Survey of Canada (WSC)) from 1944 to 1948, immediately prior to damming at hydrometric station 08ME001.	46
Figure 2.4. Peak flow recurrence analysis for pre-dam flows along the lower Bridge River, for the interval from 1913 to 1948, at WSC station 08ME001. .	47
Figure 2.5. Daily discharge of the lower Bridge River below Terzaghi Dam (top), and an extended scale for the experimental flow releases that began in August of 2000.	48
Figure 2.6. Total monthly precipitation for the meteorological station: Lillooet Seton BC Hydro Power Authority (BCHPA) active from 1971 to 2001 and station Lillooet active from 1997 to 2004, with zero values representing data gaps (Environment Canada).	49
Figure 2.7. Lower Bridge River daily discharges by year for 1945 to 1948 and 1984 to 2004.	52
Figure 2.8. Mature Bridge River cottonwood tree growth, displayed in mean (\pm s.d.) annual radial increment growth, versus year, displaying changes in growth patterns before and after experimental flow releases in 2000.	56
Figure 2.9. Branch growth from seven mature cottonwoods, along the lower Bridge River, Reach 4, represented by mean yearly (\pm s.d.) branch increments (top) and basal area increments (bottom).	58
Figure 2.10. Mean radial increments for the first four years of growth of juvenile cottonwood trees along lower Bridge River Reach 4. Data are displayed in groups of trees according to year of establishment, either during the pre-flow, transition	

or post-flow, time periods. Groupings associated with different letters (a, b) differ significantly, while the ab group is a combination of both (Table 2.6). Mean values are indicated by dashed lines for the pre-flow and post flow groups. The apparent trend is shown for the transition group and thus could link the two means. 60

Figure 2.11. Juvenile cottonwoods from the regulated lower Bridge River Reach 4 and the free-flowing Yalakom River: number of individuals versus age. 64

Figure 2.12. Average (\pm s.d.) annual basal area increments (BAI) of juvenile trees from the lower Bridge River Reach 4 and Yalakom River during pre and post-flow conditions. *, ** = indicate significance of ($p < 0.05$, $p < 0.01$ respectively), differences in basal area increment as detected by t- tests. 65

Figure 2.13. Juvenile cottonwood trees along the lower Bridge River Reach 4, and Yalakom River, trunk diameter versus age. 66

Figure 2.14. Establishment years of cottonwood saplings that were studied and harvested from the lower Bridge River Reach 4. Age was determined using annual bud scar counting done in the field compared to basal cross-section ring verification done in the lab. 69

Figure 2.15. Lower Bridge River Reach 4, left bank with new band of saplings in the foreground with juvenile cottonwoods midway up the bank and mature trees higher up, July 28, 2006, top, December 31, 2006, bottom. The black arrows indicate the same juvenile tree. 70

Abbreviations

BAI	basal area increment
BCRP	Bridge-Coastal Fish and Wildlife Restoration Plan
df	degrees of freedom
ha	hectare
km	kilometres
LBR	lower Bridge River
MBR	middle Bridge River
m	meters
m ³ /s	cubic meters per second
n	number of specimens in a sample
Q	discharge
Q_{annual}	mean annual discharge
Q_d	daily discharge
Q_{max}	maximum mean daily discharge
RI	radial increment
r	correlation coefficient
r ²	coefficient of determination
UBR	upper Bridge River
WSC	Water Survey Canada
WUP	water use plan

Chapter 1: River damming and hydroelectric power production in the Bridge River valley

1.1 Introduction

The Bridge River is located in southwestern British Columbia and drains the east-slope of the Pacific Coast mountain range (Figure 1.1). It is a major tributary of the Fraser River, with their confluence situated just north of Lillooet. The Bridge River system has been extensively manipulated to accommodate a sequence of hydroelectric power generating and diversion structures along its length. With the affiliated reservoirs, the Bridge River is separated into three major sections, the upper, middle, and lower Bridge River. From its headwaters, draining the Bridge River Glacier (Figure 1.2), the upper section of the Bridge River carries large amounts of glacial silt year-round. This silt colors the turbid green water of Downton Reservoir (Figure 1.3) and, below the middle Bridge River (Figure 1.4) the lighter silty blue of Carpenter Reservoir (Figure 1.5).

The Bridge River system involves two dams and onstream reservoirs along the Bridge River, and a diversion tunnel system which diverts water from Carpenter Reservoir into an on-stream reservoir along the adjacent Seton River (Figure 1.1). With these three dams and another, lower hydroelectric power plant, Bridge River water passes through four hydro-electric generating stations before reaching the Fraser River.

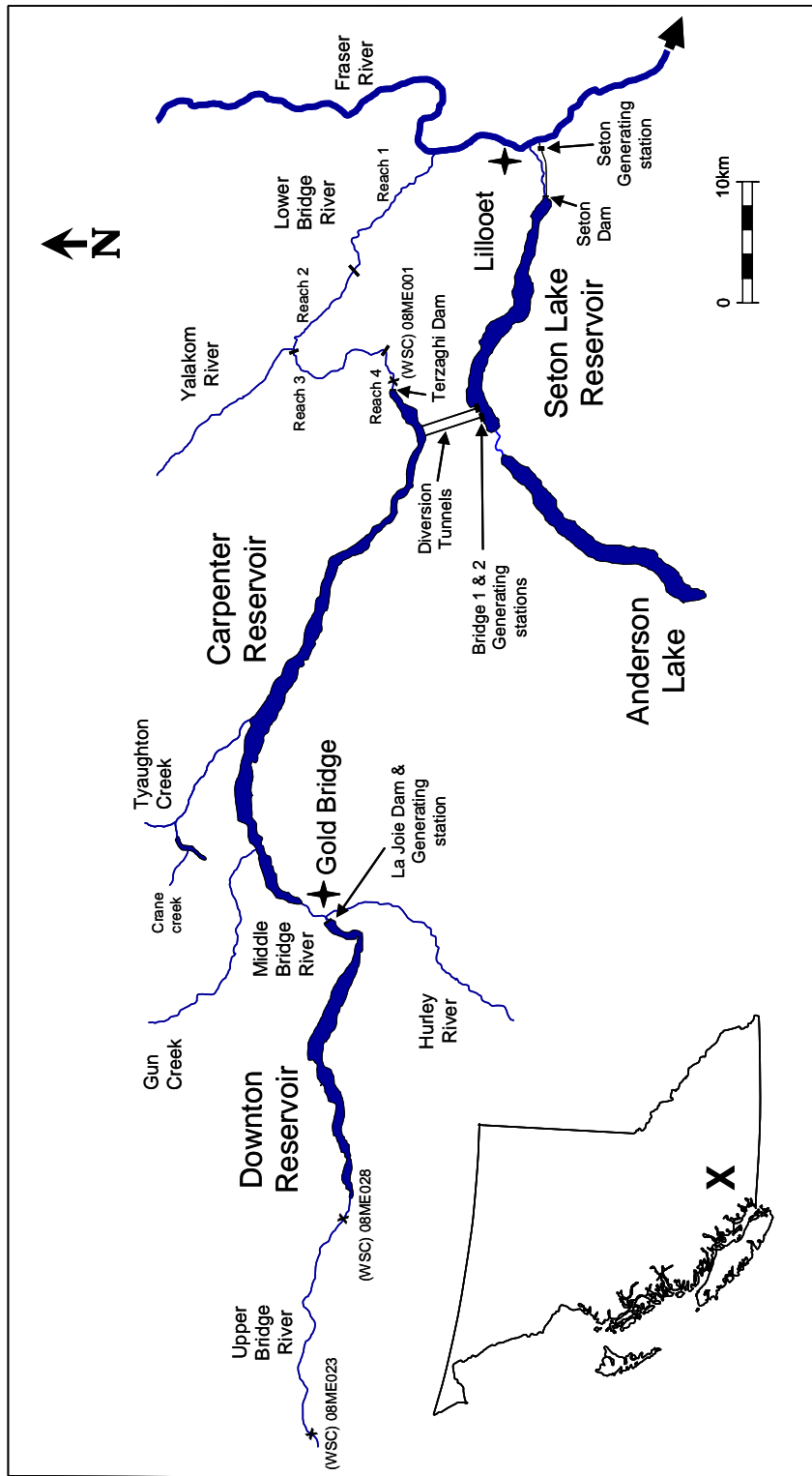


Figure 1.1. Map of the Bridge River System in southwestern British Columbia, WSC
 = Water survey of Canada hydrometric gauging stations.



Figure 1.2. The Bridge Glacier, September 1, 2006 (Photo-Joe Shea).



Figure 1.3. The upper Bridge River Valley, at the inflow delta of Downton Reservoir, November 6, 2004. Note the standing dead timber.



Figure 1.4. The middle Bridge River, upstream of the Hurley River inflow May 23, 2004.



Figure 1.5. Carpenter Reservoir August 17, 2005.

The Bridge River is first impounded by La Joie Dam, which creates Downton Reservoir (Figure 1.3) above the town of Gold Bridge. La Joie Dam was constructed in 1948 and updated in 1957 at the site of historic La Joie Falls (Table 1.1; Conlin et al. 2000). The positioning of La Joie Dam was strategic for two reasons, the first being the topography, with the narrowing of the valley to reduce the dam width. The second was that there used to be the major La Joie Falls, which provided a natural barrier to migrating salmon, and there was no record of anadromous salmon or steelhead advancing upstream past this point (Conlin et al. 2000). Electricity is generated at the La Joie generating station at the dam's outflow and below this, the Hurley River, the only major tributary of the middle Bridge River, Figure 1.4, flows into the Bridge River before it empties into Carpenter Reservoir.

In 1948, the Water Survey of Canada (WSC) hydrometric gauging station 00ME001, along the lower Bridge River was removed with the construction of Mission Dam, which created Carpenter Reservoir (Table 1.1). Terzaghi Dam was built in 1960 on the same site, incorporating Mission Dam into the upstream toe (Conlin et al. 2000). The lower Bridge River stretches 40 km from Terzaghi Dam to the confluence with the Fraser River, just north of Lillooet. Within this section, the river has been separated, for research purposes, into four different reaches starting at the mouth and working upstream (Figure 1.1).

Directly below Terzaghi Dam there are 4 kilometers (Reach 4) of riverbed that were dry for most of 52 years since the river was first dammed in 1948 (Figure 1.6, Conlin

et al. 2000). Further downstream, Reach 3 had limited river flow that arose from seeping groundwater, springs and the inflow from five small tributaries before the major inflow from the unregulated Yalakom River (Higgins and Bradford 1996, Bradford and Higgins 2001). Fifteen kilometers below the dam, the Yalakom River joins the Bridge River to supply the lower reaches with approximately 70 percent of the river's perennial flow. Before 2000 no water was released from Terzaghi Dam as it does not generate electricity, but instead stores and elevates water. This water is gravitationally fed by two large diversion tunnels through Mission Mountain and into Bridge No.1 and No. 2 powerhouses along the shore of Seton Lake Reservoir.

Seton Lake Reservoir was a natural lake prior to the 1956 installation of Seton Dam, which raised the lake level by approximately two meters, flooding 27 ha of land, creating Seton Lake Reservoir (Conlin et al. 2000). At Seton Dam, the water flow is split. Some water is diverted into the Seton Canal and the rest flows down Seton River into the Fraser River. This mixture of Bridge and Seton River water that flows through the Seton Canal is directed through the final hydroelectric generating station in the system before flowing into the Fraser River below Lillooet.

Table 1.1. Time line of hydroelectric infrastructure installation along the Bridge-Seton system (Conlin et al. 2000).

Year of construction	Infrastructure	Event
1948	La Joie Dam and generating station constructed	Upper Bridge River Valley flooded - Downton Reservoir formed
1948	Terzaghi Dam constructed	Middle Bridge River Valley flooded - Carpenter Reservoir formed
1956-57	La Joie Dam reconstructed	
1960	Terzaghi Dam reconstructed	
1956	Seton Infrastructure	Level of Seton lake raised to form Seton Lake reservoir Diversion tunnels through Mission Mountain Bridge 1 and 2 generating stations Seton generating station Seton canal Seton Dam

Table 1.2. Water Survey of Canada (WSC) historic and current, hydrometric gauging stations in the Bridge River basin, sequenced from upstream to downstream.

Station #	Station Name	Location		Drainage area (km ²)	Years active
08ME0	BRIDGE RIVER (SOUTH BRANCH) BELOW BRIDGE GLACIER	50°51'	123°2		1978-
23		22" N	7'1" W		2007
08ME0	BRIDGE RIVER ABOVE DOWNTON LAKE	50°49'	123°1		1996-
28		17" N	2'6" W		2007
			122°5		
08ME0	BRIDGE RIVER AT LA JOIE FALLS	50°50'	1'24"		1924-
04		15" N	W	956	1948
			122°5		
08ME0	BRIDGE RIVER NEAR GOLD BRIDGE	50°51'	0'45"		1924-
05		4" N	W	1650	1941
			122°3		
08ME0	BRIDGE RIVER BELOW TYAUGHTON CREEK	50°53'	7'30"		1929-
14		25" N	W	3190	1941
			122°1		
08ME0	BRIDGE RIVER NEAR SHALALTH	50°47'	3'30"		1913-
01		15" N	W	3650	1948
			122°1		
08ME0	YALAKOM RIVER ABOVE ORE CREEK	50°54'	4'14"		1983-
25		45" N	W	575	2007

1.2 Natural History

The Bridge River Valley is located in the rain-shadow of the eastern slopes of the Coast Mountain range and therefore the Bridge River system is located within the transition zone between coastal and interior vegetation types (Parish et al. 1996). The lower half of the watershed is located in the much drier Okanagan/Thompson plateau zone and there is a large transition zone along the elevational gradient from the upper to lower sections of the Bridge River system. The upper Bridge River valley experiences a moist, cooler climate that supports mesic tree species such as western red cedar (*Thuja plicata*) and Pacific silver fir (*Abies amabilis*). This section of river lies within an elevational range of about 1500 m to 700 meters above sea level with glacier-fed creeks and mountain snow-fields that remain into the summer.

The middle Bridge River (Figure 1.4) encompasses a heavily forested valley, with many small and some large tributaries, including the Hurley River, that drain into Carpenter Reservoir. The upper delta of Carpenter Reservoir is home to many species of waterfowl such as Canadian geese (*Branta canadensis*), trumpeter swans (*Cygnus buccinator*) and common mergansers. This area of the reservoir is seldom completely inundated and consequently, it supports a valley-bottom covered with short grasses, horsetail (*Equisetum spp.*), and a few flood tolerant shrubs.

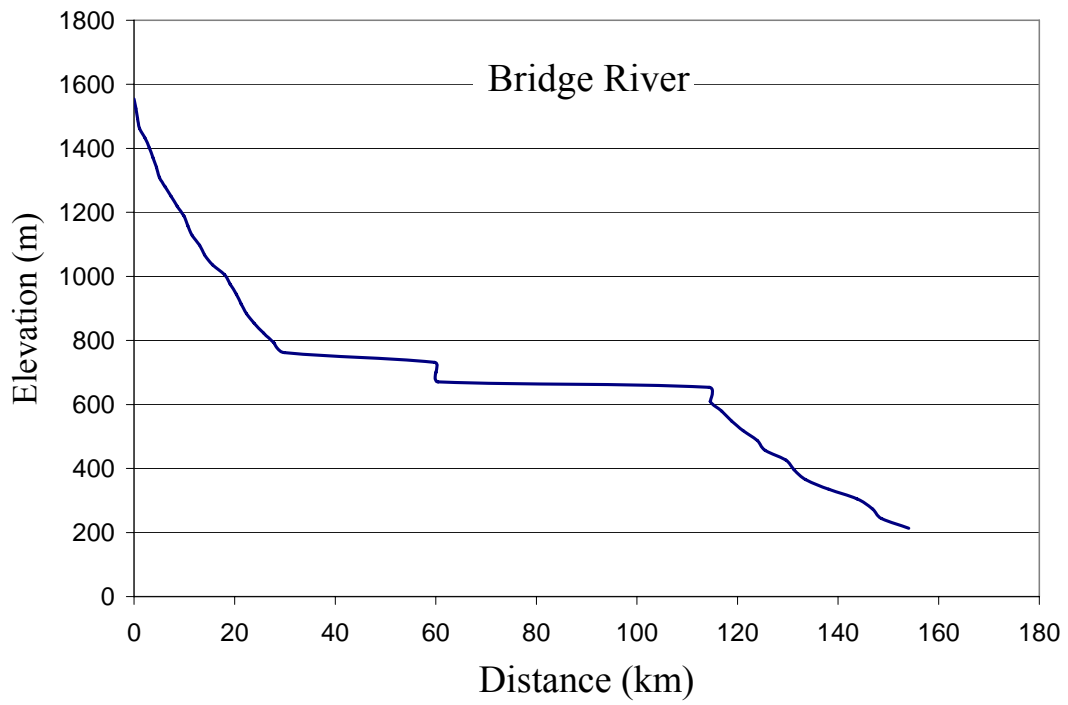


Figure 1.6. Elevational profile of the Bridge River. Bridge Glacier to the confluence of the Bridge and Fraser Rivers.

The greening of the dry reservoir bottom in early spring makes it a favorite place for black bears (*Ursus americanus*) emerging from hibernation, this area is also home to resident Canada geese. The valley surrounding the middle section of the Bridge River has an elevation range from 750 meters at the summit of Mount Truax down to 650 m at the surface of Carpenter Reservoir (Figure 1.5). This provides a steep, narrow valley, surrounded by mountain slopes thick with coniferous forests that support many species of wildlife ranging from bighorn sheep (*Ovis canadensis*) to cougars (*Puma concolor*) (S. Hall pers. comm. 2007).

The Bridge River supports a small harlequin duck (*Histrionicus histrionicus*) population which has been studied for many years along the Bridge River. The lower Bridge River provides breeding and rearing habitat for harlequins, which then migrate to the west coast for the remainder of the season (Hill and Wright 2000). The filling of Carpenter Reservoir flooded 92 km of mainstem channel habitat and an additional 55 km of tributary channel habitat, plus valuable riparian areas (Figure 1.5, Conlin et al. 2000). These riparian areas were significant wildlife habitats that supported populations of moose (*Alces alces*) in the winter months and provided excellent forage areas for grizzly (*Ursus horribilis*) and black bears, especially in the spring (Conlin et al. 2000). These feeding grounds are an important source of habitat for moose and deer during the winter months because higher elevation forage areas are less accessible due to deep winter snows.

Since the complete flooding of the Bridge River valley in 1960, the inundation of these riparian areas has limited the moose populations (Lemke 2000). The south-facing slopes on the north side of Carpenter Reservoir support dry open forests of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) with Saskatoon (*Amelanchier alnifolia*) and mixed grasses. These south-facing slopes are very dry, receiving limited snow-fall in the winter. Redstem ceanothus (*Ceanothus sanguineus*) provides dominate evergreen winter browse for mule deer (*Odocoileus hemionus*) and bighorn sheep (*Ovis canadensis*) (S. Hall pers. comm. 2007).

Historically, the Bridge River supported five different species of anadromous salmonids, chinook (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), sockeye salmon (*Oncorhynchus nerka*), and pink salmon (*Oncorhynchus gorbuscha*) and steelhead (*Oncorhynchus mykiss*) anadromous rainbow trout (Woo 1998, Higgins and Bradford 1996). There were also many resident freshwater species including rainbow trout (*Oncorhynchus mykiss*), bull trout (*Salvelinus confluentus*), bridgelip suckers (*Catostomus columbianus*), three different species of sculpin (*Cottus spp.*), Pacific lamprey (*Lampetra tridentata*), and mountain whitefish (*Prosopium williamsoni*) (Bradford and Higgins 2001, McPhail and Carveth 1993). Most of these species persist today, but in reduced numbers compared to historical accounts. Historic pre-dam spawning areas included Tyaughton Creek, Gun Creek and others (Figure 1.1, Conlin et al. 2000).

1.3 Geography

The topography of the lower section of the Bridge River valley changes dramatically. As the elevation decreases, there is an increase in temperatures as you move easterly down the valley. In the valley bottom, the lower river flows through a large alluvial cobble-boulder matrix, with few areas that support standing pools or wetland habitat. Black cottonwoods (*Populus trichocarpa*), mountain alder (*Alnus incana*), Sitka willow (*Salix sitchensis*), paper birch (*Betula papyrifera*), and trembling aspen (*Populus tremuloides*) trees are common riparian species in this region.

In the area below Terzaghi Dam commonly known as the Bridge Canyon, some of the precipitation that falls on the surrounding hillslopes as snow or rain flows as groundwater into the river, thus defining the Bridge River as a gaining or effluent river system (Gordon et al. 2005). Gaining river systems are common among mountain streams, especially when they are located in narrow bedrock canyons that also have moist and cool climates with upland forested zones (Rood et al. 2003, Polzin and Rood 2006). Terzaghi Dam is located at a nick point in the physical landscape of the Bridge River Valley. This area is a transition zone that changes from an open valley to a narrow, extremely steep, channelized canyon. The canyon walls are steep yet heavily forested with coniferous stands, predominantly Douglas-fir (*Pseudotsuga menziesii*) forests. These forests periodically give way to deciduous clumps of mountain alder Sitka willow and black cottonwood that grow in the adjacent, spring fed tributary drainages.



Figure 1.7. Reach 4 of the lower Bridge River, 0 m³/s discharge September 1992, (Photo-Paul Higgins).



Figure 1.8. The lower Bridge River Reach 4, 3m³/s discharge July 25, 2006.

1.4 Human History

The Bridge River valley has historically supported a sequence of boom and bust cycles that encouraged the establishment of small mining towns affiliated with gold first found in alluvial deposits along the river and its tributaries. The town of Gold Bridge is situated between Carpenter and Downton Reservoirs along the middle section of the Bridge River and currently supports a population of only 43 residents. This town was historically much larger at times when the gold rush fever swept through the valley. Gold was first discovered by placer miners along Gun Creek in 1859 and along lower Tyaughton Creek in 1866 (Church 1996). In 1882, gold was found at the mouth of the Hurley River, adjacent to the present town of Gold Bridge. More than 1000 ounces of coarse gold were taken out of this area; hence the name (Church 1996).

In the area now submerged by Carpenter Reservoir, historically the Wayside, Congress, and Minto mines all produced gold and silver throughout the valley, with Minto being the most productive (Church 1996). The size and longevity of the Minto mine prompted its own town at the confluence of Gun Creek and the Bridge River. This mining town was established in 1920 and supported up to 300 residents at its peak (Church 1996). With the reservoir flooding in 1960, the residents of Minto city were forced to relocate, and many moved to the nearby, town of Gold Bridge. In the Bridge River Valley today there are many recreational opportunities in the valley, especially with two large reservoirs so accessible year round. Unfortunately, the

majority of water-based recreation occurs on the natural lakes in the watershed, rather than on the two large reservoirs that inundate the valley bottom. Because the valley bottoms were flooded without complete or even partial timber harvesting, boating on the reservoirs is dangerous due to abundant stumps, standing-dead timber, and fallen trunks throughout the shallow waters (Figure 1.3).

1.5 BC Hydro controlled flow experiment

In 1991, spring snowmelt and heavy rains throughout the summer, filled Carpenter Reservoir. Subsequent late summer rains forced dam operators to allow water to free-spill over Terzaghi Dam. This created considerable channel and bank erosion resulting in the degradation of fish spawning and rearing habitats below Terzaghi Dam (Clark 2006). This resulted in a law-suit by the federal Department of Fisheries and Oceans and Provincial fisheries agencies against BC Hydro. Because they were required to comply with the $3\text{m}^3/\text{s}$ flow release, BC Hydro also designed and implemented an experiment to test the theory that the release of water should provide habitat restoration along the lower section of Bridge River. Affiliated with this experiment, instream flow assessment studies were undertaken in 1993 by BC Hydro to help define instream flow needs and water management issues (Failing et al. 2004).

In 1996, a 16-year study commenced with an initial four year period of baseline data collection. During this time the lower Bridge River flows remained at $0\text{ m}^3/\text{s}$ (Figure 1.6, Table 2.1). Fish population characteristics were analyzed to document use by

resident and anadromous fish. Sampling of periphyton and drift sampling were also carried out along the three final reaches of the lower Bridge River, excluding the upper Reach 4 which remained dry (S. Hall pers. comm. 2007). Beginning in August of 2000, BC Hydro began releasing an average of 3 m³/s of water from Terzaghi Dam (Figure 1.7), with annual flows following a seasonal hydrograph, with flows fluctuating between 5 m³/s and 2 m³/s throughout the year (as presented in Chapter 2). This flow pattern was scheduled to last for a four year period. Thereafter, flows would be reduced to 1 m³/s for another four year period. Finally, the flow regime would be increased to provide a mean flow of 6 m³/s for four years. This would complete the 16-year study that involved an initial four years of baseline data collection, and then three different 4-year flow regimes.

1.6 The Bridge River today

Today, the Bridge River is managed within the Bridge-Coastal Fish and Wildlife Restoration Plan (BCRP), which was designed as a joint initiative between BC Hydro, the Government of BC and the Government of Canada (Conlin et al. 2000). This plan incorporated the needs of many different interest groups while creating the Bridge-Seton Water Use Plan (WUP), which is instrumental, in determining flows along the lower Bridge River (Conlin et al. 2000). The WUP reflects inputs from many different interest groups including fisheries scientists, land-use managers, local groups and First Nations groups that contributed to a decision-making process by working together to design and implement the experimental flow regimes (Failing et

al. 2004). During the WUP process there were different approaches used in determining the flow levels that were selected and implemented. Initially, due to the out-of-court settlement BC Hydro was required to release a permanent base flow of 3 m³/s to the lower Bridge River. This was incorporated into the 16-year flow experiment currently underway (Failing et al. 2004).

1.7 My thesis research

The experimental flow releases below Terzaghi Dam have increased fish access to aquatic habitat by re-watering the 4 kilometers of Reach 4 that were previously dewatered. BC Hydro has been analyzing the impacts of the partial rewatering on fish and the aquatic ecosystem. This M.Sc thesis analyzes responses of the riparian ecosystem. My primary hypothesis was that this provision of modest, but perennial flow would promote the growth of the riparian vegetation, specifically black cottonwood trees, which are the dominant woody plant along the lower Bridge River.

Reach 4 of the lower section of the Bridge River was my focus, because this zone had experienced the most severe dewatering since the installation of Terzaghi Dam. It was expected that benefits of the flow release would be most apparent here. To test this hypothesis, riparian cottonwoods trees along Reach 4 were measured to determine if their rate of growth had increased following the recent flow release from Terzaghi Dam. Incorporation of other reaches along the lower, middle and upper Bridge River and the Yalakom River provided an appropriate reference system,

enabling further analysis of the prospective correspondence between historic instream flows and growth (Rood et al. 2003).

1.8 Conclusion

The flow experiment along the lower Bridge River provides an internationally-significant case study opportunity. There have been numerous studies associated with reduction in instream flow but the Bridge River situation is relatively unique in that instream flow is being increased. The recent flow regime does not restore the natural flow magnitude but the change from, 0 m³/s to 3 m³/s is dramatic. The implementation of a seasonal flow regime that mimics the natural flow pattern is also noteworthy. As described in the subsequent Chapter 2, the prominent question arises, ‘has the return of flowing water to the Bridge River provided measurable benefit for riparian cottonwoods?’

Chapter 2: Response of riparian cottonwoods to experimental flows along the lower Bridge River, British Columbia

2.1 Introduction

Rivers support rich aquatic (instream) and riparian (streamside) ecosystems. Despite our crucial dependence on rivers, humans have spent generations damming, diverting and degrading rivers around the world. In 2006, there were approximately 2500 dams of varying sizes in operation throughout British Columbia (Ministry of Environment 2007). With steep, mountainous landscapes and abundant precipitation, rivers in British Columbia, have been dammed primarily to generate hydroelectric power. This involves a broad range of alterations to natural systems by developing various types of dams and diversions to capture and transport water to drive hydroelectric turbines. These varied hydrologic alterations have produced a broad range of negative environmental impacts that have been studied mainly with regard to aquatic resources and particularly anadromous fish, especially salmon (Failing et al. 2000, Higgins and Bradford 1996).

In British Columbia salmon are one of the most commercially valuable resources and the focus of many research projects regarding rivers has been on salmon. With the knowledge of undesirable historical management decisions regarding river flows and salmon access to historic spawning grounds, BC Hydro has responded to the charges laid against them with increased research and funding. This aided in the facilitation of

Provincial water use plans which strive to find common ground between the natural ecosystem and the needs of the human population.

Riparian research is adding to the significant base of aquatic research regarding the disappearing salmon. By working together and investigating the fragile connection between the streamside communities and the aquatic ecosystem humans can attempt to restore some of the damaged rivers that we rely on every day. The dams and diversions of the Pacific Northwest have greatly impacted riparian woodlands, which has initiated many studies that focus on the health and stability of riparian cottonwoods and willows (Dykaar and Wigington 2000, Polzin and Rood 2000, Polzin and Rood 2006, Braatne et al. 2007). For both the aquatic and riparian ecosystems, previous studies have primarily investigated historic consequences of river damming and instream flow alterations, particularly investigating the impacts from alteration in seasonal flow regime or from water removal, and in extreme cases, impacts from river channel dewatering (Rood et al. 2003a).

There is hope for the future. The value and vulnerabilities of native river ecosystems have been increasingly recognized, which has initiated a change in river resource management in western North America (Gordon et al. 2005). As the period of construction of large river dams has generally ended and the focus of environmental impact analysis has been redirected towards dam operation and instream flow management, restoration of existing systems has become the new focus (Gillilan and Brown 1997, Instream Flow Council 2002, Shafroth et al. 2002).

Environmental restoration may provide the best proof of ecological understanding of a river system. Thus, cases in which instream flows and/or natural flow regimes are restored should provide novel study opportunities. As a general hypothesis, it would be expected that the restoration of instream flows should reverse the ecological consequences from the prior water withdrawal or change to the seasonal flow regime. There are, however, complexities in that some systems may indeed be altered with rewatering, but the outcome may involve a different state than that prior to the original river flow alteration. Additionally, for both restorations towards the prior condition or with change to a new condition, the time frame is very uncertain. Each river system responds differently and the restoration response may not be the simple inverse of the degradation pathway.

In the present study, we recognized a unique opportunity to investigate the associations between instream flows and riparian woodlands. A major tributary of the Fraser River, the Bridge River, is located in southwestern British Columbia and drains the east-slope of the Coast Mountain Range. The river begins as melt-water from the Bridge Glacier, and with contributions from groundwater, numerous creeks and a few tributary rivers, it flows south-easterly toward its confluence with the Fraser River, north of Lillooet (Figure 1.1).

The Bridge River has been extensively dammed and diverted for hydroelectric power generation. This has resulted in a variety of hydrologic alterations along its length, including the complete elimination of flow release from the lower dam on the river.

Following a court case associated with instream flow management, instream flow was returned to the previously dry reach. This study investigated environmental impacts on the riparian woodland which is dominated by black cottonwood (*Populus trichocarpa* Torr. & Gray) in response to the change from a dry river bed to one with seasonal flow.

2.1.1 Life history and ecophysiology of black cottonwoods

Black cottonwoods are a common poplar in riparian or streamside zones in the Pacific drainages of western North America (Brayshaw 1965, Farrar 1995, Dykaar and Wigington 2000, Polzin and Rood 2006, Braatne et al. 2007). Riparian zones represent the transitional areas between aquatic and terrestrial ecosystems that surround river, lakes, ponds, and swamps (Naiman et al. 2005). Riparian zones have abundant fresh water providing biologically rich ecosystems that occur as linear features along creeks, streams and rivers (Naiman and Decamps 1997). Black cottonwood and other cottonwood species thrive in riparian zones where there is a constant recharge of alluvial groundwater flow from upland zones or with infiltration from the adjacent stream (Rood et al. 1994, Amlin and Rood 2003, Rood et al. 2003a). Black cottonwoods are the largest native broad-leaf trees found west of the Rocky Mountains in British Columbia and the largest of the three section *Tacamahaca* 'balsam poplars' native to Canada (Farrar 1995). In southwestern British Columbia, black cottonwoods are the dominant riparian trees in the Fraser River Basin, particularly along the Bridge River and its tributaries.

Cottonwoods are diploid, dioecious, and deciduous trees whose dominant form of reproduction is through seed dispersal by wind and water. Subsequent seedling establishment requires moist and barren substrates for success (Karrenberg et al. 2002). Like other section *Tacamahaca* poplars, black cottonwoods can also reproduce clonally from branch fragments that may be sheared by wind, snow or rain, or following the toppling and tumbling of trees with floods (Rood et al. 2003b). The branch fragments float downstream to be deposited in moist sediment, enabling dispersive, clonal propagation after adventitious rooting establishes new growth. Black cottonwoods are adapted to the cool and moist climates dominantly found in western British Columbia, and along the hydrologically gaining rivers that are most common in these areas. These gaining rivers receive water contribution originating from riparian groundwater, which ensures a constant alluvial water supply and reduces the dependence of black cottonwood on stream flow (Rood et al. 2003b, Gordon et al. 2004, Polzin and Rood 2006).

Cottonwoods are an ecological pioneering species that initially colonize barren riparian areas, which leads to evolving forest dynamics as the riparian forests age and secondary, successional species follow (Nanson and Beach 1977, Polzin and Rood 2006). Riparian forest structure progressively changes and community diversity often increases over time with additions of shrubs and herbaceous plants. Riparian ecosystems provides habitat for a variety of mammals, birds, reptiles, amphibians,

aquatic and terrestrial invertebrates. Their associated trophic interactions further alter the ecosystem dynamics compounding the biological interactions. Physical disturbances from floods and drought are continuously changing the hydrologic regime and the fluvial geomorphic dynamics of the riparian zones in which the cottonwoods thrive.

Within the riparian forest ecosystem, cottonwoods (Parish et al. 1996) provide a foundation for the overall health of riverine systems. Cottonwood trees also provide shade, bank stabilization and protection that influence the dynamics of the river channel (Abernethy and Rutherford 2001). Cottonwoods directly provide rich habitat for many bird species, and mammals in the form of aquatic and terrestrial transportation corridors as well as providing an interconnected food web for aquatic invertebrates and vegetation (Naiman et al. 2005).

2.1.2 The lower Bridge River

Downstream from Terzaghi Dam, geomorphology of the lower section of the Bridge River has a dominant boulder and cobble substrate in the channel and banks that are often flanked by steep-walled canyons. These sections are interspersed with barren scree areas and more stable zones with heavily forested riverbanks and valley slopes. The Bridge River was historically a sediment-rich river with fine material derived from glacial melt-water. Today it retains a milky blue color along its entire length. This turbid, turquoise water flows into Downton and Carpenter Reservoirs then as the

system changes from lentic to lotic, glacial sediments settle out and vertically stratify the reservoirs, throughout the seasons. The turn-over (flushing rate) of water retention time in Carpenter Reservoir is 3.8 months, thus allowing settling of all but very fine sediments (Conlin et al. 2000).

Due to this sediment trapping in Carpenter Reservoir, water released to the lower Bridge River is generally 'sediment –starved' or 'hungry water' that has a greater capacity for sediment erosion than deposition (Kondolf 1997). The lack of fine alluvial sediments below Terzaghi Dam has potentially diminished the opportunities for cottonwood seedling recruitment due to lack of fine sediments. Because seeds and seedlings establish on barren sites with fine sediments, they are an integral part of successful establishment. These sites retain moisture and create a semi-saturated capillary fringe that provides the primary zone for fibrous roots and the uptake of water and nutrients (Mahoney and Rood 1998).

2.1.3 The Bridge River Today

The present $3\text{m}^3/\text{s}$ flow release of the lower Bridge River were determined following eight years of litigation and research and an out-of-court settlement reached between BC Hydro, the Ministry of environment in the Province of British Columbia and the Federal Department of Fisheries and Oceans (Failing et al. 2004). This dispute arose over differing opinions regarding the effect that free spills had on the lower Bridge River between 1948 and 2000. During those 52 years, water was only released if the

reservoirs had reached maximum capacity resulting in un-regulated free spills (Figure 2.5). The amount of water that free spilled from Terzaghi in 1991 was not enough to reach pre-dam average yearly flows (Figure 2.3) but it was enough water to alter the generally dry, and severely altered, lower Bridge River.

These flows, that pre-dam would have been channel maintenance flows, were suddenly channel-altering flows that caused significant alterations to the post-dam channel (Leopold 1994, Clark 2006). This included bank erosion, riparian habitat destruction, large amounts of sediment contribution and the flushing of resident fish out into the Fraser River (Clark 2006). As well as complying with the 3 m³/s flow release, BC Hydro designed and implemented an experiment to test the hypothesis that the release of water should provide habitat restoration along the lower section of Bridge River (Table 2.1).

Affiliated with this experiment, instream flow assessments were undertaken in 1993 by BC Hydro to help define instream flow needs and water management issues of the lower Bridge River (Failing et al. 2004). BC Hydro's data collection began in 1993 with four years of baseline data collection on the aquatic ecosystem of the lower Bridge River (Failing et al. 2004). With this project, BC Hydro gathered background information on the system so that biologists, fisheries managers, First Nations groups and other stakeholders could assess the effect of the re-introduction of flow to the lower Bridge River (Failing et al. 2004).

The minimal, yet long anticipated, flow release allows 3 m³/s to be released from Terzaghi Dam, with the flow pattern following a seasonal hydrograph. This flow change has rewatered four kilometers of riverbed that had been predominantly dry for 52 years, since the installation of the initial Mission Dam in 1948 (Conlin et al. 2000).

Table 2.1. Experimental flow releases below Terzaghi Dam (Failing et al. 2004)

Discharge (m ³ /s)	Years	Comments
0	1948-1999	Baseline data collection 1993-1996
3	2000-2006	Out of court settlement
1	4 years	Possible future flow
6 or 9	4 years	Possible future flow

2.1.4 This study

This study involved three major parts to investigate the overall hypothesis that the reestablishment of a perennial, seasonally varying flow regime would increase the growth and reproduction of riparian cottonwoods along the lower Bridge River, British Columbia. The first component investigated the prediction that well established mature cottonwoods would respond to the new flow regime with increased radial trunk growth and increased radial growth and elongation of branches.

Next, it was anticipated that juvenile trees would respond to the increased flow regime with increased basal trunk growth. Basal trunk growth was analyzed for juvenile tree growth along the regulated lower Bridge River and also compared to the growth of juveniles growing along the adjacent, free-flowing Yalakom River. The third research component considered the youngest age group, saplings, for which, we predicted an increase in abundance.

2.2 Methods

2.2.1 Hydrology

The Bridge River system has been extensively altered to accommodate diversion and storage structures and hydroelectric facilities that have the ability to generate electricity at four locations before water reaches the Fraser River at Lillooet. These dams and diversion structures have separated the river into three distinct sections that will be referred to as the upper, middle and lower sections of the Bridge River. The upper Bridge River is free-flowing and substantially glacier-fed, draining an elevational range from 2900 m on the Bridge Glacier down to 760 m at Downton Reservoir.

Lajoie Dam and generating station create Downton Reservoir, providing the first regulation structures along the Bridge River. Below La Joie Dam, the Hurley River joins the middle Bridge River. The middle Bridge River is a short section that flows for approximately three km filling Carpenter Reservoir. This reservoir is created by Terzaghi Dam, which does not generate electricity it strictly stores and elevates water. This water is transferred by two large diversion tunnels, which pass through Mission Mountain, to Bridge 1 and 2 generating stations along the shore of Seton Lake Reservoir (Figure 1.1).

Seton Lake Reservoir was Seton Lake prior to installation of the Seton Dam in 1956, which raised the level by approximately two m and flooded 27 ha of land (Conlin et al. 2000). At Seton Dam, water is split between the Seton Canal and Seton River. Water flows into the Seton Canal, passes through the Seton Generating Station to generate electricity one last time before the combined flows of Bridge River and Seton River empty into the Fraser River (Figure 1.1).

Flow data from the lower Bridge River were accessed from Water Survey of Canada's archived Hydat information for gauging station 08ME001 (Table 1.2) (http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=HydromatD.cfm). This station was operated from 1913 until 1948, when Mission Dam was built at the same location. Thus, the Bridge River was a large free-flowing river until 1948 when the British Columbia Electric Company constructed La Joie Dam at the site of La Joie Falls (Figure 1.1, Conlin et al. 2000). Then, in 1960, the taller and longer Terzaghi Dam was incorporated into the upstream toe of Mission Dam (Conlin et al. 2000).

The installation of Mission Dam and then Terzaghi Dam resulted in four km of the lower Bridge River being an essentially dry riverbed for the majority of 52 years (Conlin et al. 2000). From 1948 to 1999, the 15 km between the Terzaghi Dam and the confluence of the Yalakom River experienced an overall flow reduction of about 99%, although hydrometric records are incomplete (Failing et al. 2004). The lower Bridge River is separated in four reaches beginning at the confluence of the Bridge and Fraser rivers with Reach 1.

Moving up-stream reaches two three and four are organized sequentially, ending with Reach 4 directly below Terzaghi Dam. Reach 3 has limited discharge that arises from inflowing groundwater, as well as from many small springs and five small tributary creeks (Figure 1.1). Marking the transition from Reach 3 to Reach 2, of the lower Bridge River, there is major inflow (Q_{annual} 4.3 m³/s) from the free-flowing Yalakom River (Figure 2.1, Higgins and Bradford 1996, Bradford and Higgins 2001).

The final 28 km of the lower Bridge River extend from the confluence of the Bridge and Yalakom Rivers down to the Fraser River and includes Reaches 2 and 1.

Throughout this section there is some recovery of natural flow and river function, with about 70 to 90% of the discharge originating from the Yalakom River (Higgins and Bradford 1996).



Figure 2.1. The Yalakom River, July 28, 2006. Looking upstream from the road 40 bridge. The sample site was on river left.

2.2.2 Mature Trees

To analyze any impacts of flow regime on riparian cottonwoods, we sampled growth of mature and juvenile trees and the recruitment of saplings (Table 2.2). Mature black cottonwood trees were sampled along the three river sections of the upper, middle and lower Bridge River (Figure 1.1) in autumn 2003 and 2004, and in summer 2005/2006, and winter 2006/2007. Increment cores or basal trunk cross-sections, ‘discs’, were collected to analyze yearly wood growth patterns. Trees were sampled on river right, within 20 m of the main river channel.

All trees sampled were single stemmed, appeared healthy and demonstrated no evidence of beaver browse or major disease. Riparian cottonwood trees in the upper Bridge section were cut down in order to access branches, and take trunk cross-sectional disks. Mature trees in the middle section and lower section had cores and disks taken. Cores were predominantly used in Reach 4 to reduce the risk of increased mortality, due to a minimal population of trees in these sections, but disks were also taken to increase data availability.

Mature black cottonwood trees were defined by a trunk diameter of 10-40 cm in diameter. Core samples were taken by drilling a Suunto, Finland, 40 cm increment borer into each tree at the lowest possible height that permitted auger rotation. The pith was reached for successful age verification. Two cores were taken from each tree from opposite sides, to reveal growth patterns (Figure 2.2).

Table 2.2. Research components used to analyze impacts of flow regulation on the growth of riparian cottonwoods along the Bridge River system, British Columbia.

Growth phase	Locations	Observation	Indication
Mature trees	upper Bridge middle Bridge lower Bridge	Annual growth ring increment analysis: Trunks and branches and branch elongation	Possibility of enhanced growth
Juvenile trees	Reach 4 lower Bridge Yalakom	Annual growth ring increment analysis: Trunks	Possibility of enhanced growth
Saplings	Reach 4 lower Bridge	Annual growth rings for aging Cross-sections and Annual growth scars	Possibility of recruitment response and age of establishment

Cores were stored in plastic straws, at cool temperatures for less than two weeks before mounting to reduce the potential of mold growth. All disks and cores were then further dried and sanded to determine ring counts and radial increment measurements (as below).

Five branches were taken from each mature tree in Reach 4 because prior studies of mature cottonwoods, branch growth has been found to be more responsive than trunk radial increment growth to stream flow and riparian groundwater depletion (Willms et al 1998, Scott et al 1999). Branch elongation was measured from yearly growth scars to determine yearly growth rates. The base of each branch was also cut to produce disks, which were measured using the same procedures as the trunk disks.

All increment core samples were mounted on 1.8 x 8.7 cm grooved boards and then sanded with 400-grit sandpaper until ring clarity was reached. Radial increments were measured with accuracy of 0.002 mm precision using the Measure J2X software program (VoorTech Consulting, Holderness, NH), in conjunction with a Velmex stage attached to an Acu-Rite encoder (Velmex Inc. Bloomfield NY) and dissecting microscope (Willms et al. 2006).

For additional statistical comparison, we combined three-year radial growth increments for the pre-flow versus post-flow years to further determine if there has been any promotion of the growth of these trees. Radial growth increments were thus combined from 1997-1999 versus 2001-2003.

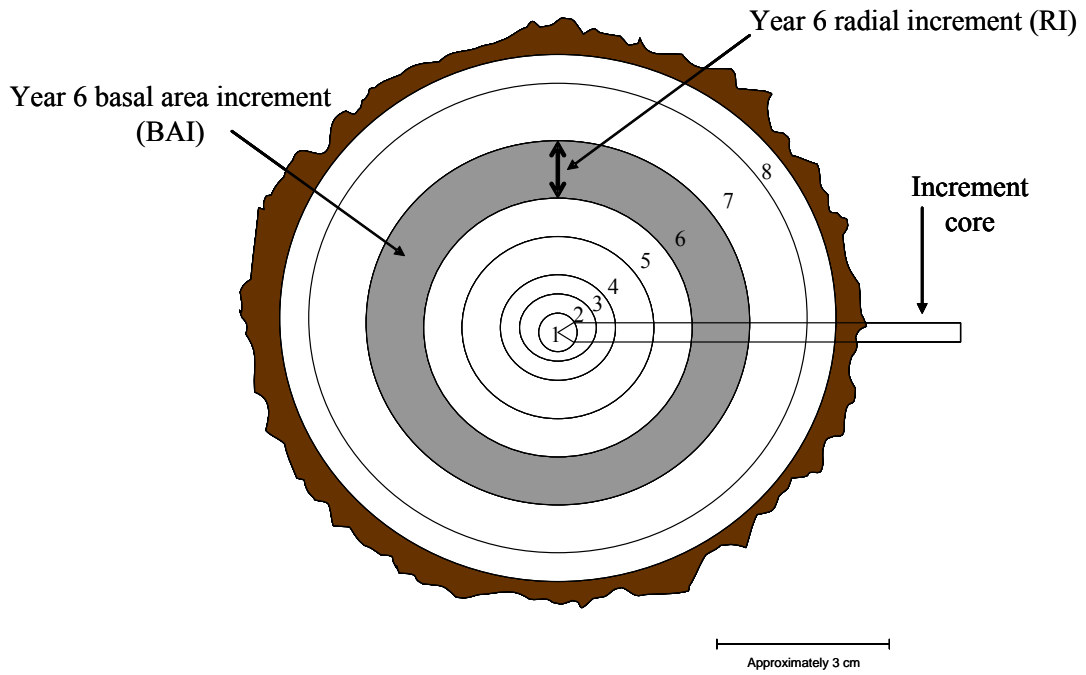


Figure 2.2. A cross-section of a black cottonwood trunk, showing the anatomy and measurements taken. The increment core represents a sample of wood extracted from the tree.

2.2.3 Juveniles

Due to the complacency of trunk growth we found in the mature trees and also in the literature (Willms et al. 1998), we measured juvenile aged cottonwoods to see if they had responded to increased flows. We hypothesized that because the juveniles are younger than the mature trees they have a less established root system and therefore will be more affected by increased stream flow. To determine if juvenile cottonwoods were responding to increased flows, trees were sampled along Reach 4 of the lower Bridge River.

Juvenile cottonwoods were sampled by cutting down the trees and cutting out cross sectional disks from the base or taking increment cores from the tree's trunk. This was done using the same methodology that was used to take increment cores from the mature trees. The population of juvenile aged trees is small in Reach 4, so increment cores were taken as well as cross sectional disks to reduce tree mortality. Cross sectional disks were sanded and dried and increment cores were mounted, sanded and analyzed using the same methodology as the disks and cores from the mature trees (Willms et al. 2006).

We wanted to determine whether juvenile trees that were established before the experimental flow releases began, had been growing more slowly in their first four years of growth than juvenile trees that were established after the flow experiments began. A reference system was needed to do this, so the lower Bridge River and the

Yalakom River were compared to determine if there was a difference in growth rates. The Yalakom River was chosen as a reference system because it has similar geomorphic and hydrologic features as the lower Bridge River. It also lies within a similar geographic location and it has comparable topography.

With the Yalakom as a reference system we could dismiss any local climatic changes that might affect the growth of juveniles along both these rivers. Cross sectional disks were cut for all trees sampled along the Yalakom River due to large availability of trees. Juvenile disks from the Yalakom were mounted, sanded and measured using the same methodology as for the mature and juvenile trees along the lower Bridge River (Willms et al. 2006).

In order to test the Yalakom tree data, juvenile trees were split into two groups separating trees established pre-flow (1996-1998) and post-flow (1999-2004.) A Mann-Whitney test then was used to determine if there were any pre-flow and post-flow differences in the radial increment growth of juvenile cottonwoods. The cross-sectional disks from each juvenile tree were analyzed using five different cross-sectional lines and by measuring the yearly growth of incremental radial and basal area for each tree.

We then averaged the first four years of growth to reduce variation across individual years to determine if trees displayed different early growth patterns during the pre-flow, transition and post-flow time periods. The first four years of growth since

establishment also coincided with the initial four year schedule planned for each flow regime of the BC Hydro flow experiment.

A non-parametric Kruskal-Wallis test was applied to compare the pre-flow, transition and post-flow groups to determine if the three groups were significantly different.

We then used Mann-Whitney tests to determine if there was any significant difference between each pair of groups. We then compared the trees in the pre-flow group versus trees in the transition group. Followed by trees in the pre-flow versus post-flow groups and, finally, we compared post-flow trees to the transition trees. Because our sample sizes were insufficient to confirm that our data was normally distributed we also used a one-way ANOVA, to test for significance.

Juvenile trees from the lower Bridge River and the Yalakom River were similarly compared, again using the average of five lines of measurement for each tree. Data were compiled from 1996 to 2006 to assess yearly growth increments during the pre-flow and post-flow periods. To confirm the significant difference between the lower Bridge River and the Yalakom trees we used an independent samples t-test to determine the significance between the sample means. To back up this data we also used a non-parametric, Mann-Whitney test to compare means of lower Bridge River vs. Yalakom juvenile growth.

All juvenile cottonwoods along the lower Bridge River and Yalakom Rivers had trunk diameters measured at the lowest point on the tree, the same position as where

the tree was cut down. Ages were determined by counting annual growth rings (Figure 2.2) Juvenile riparian cottonwoods were sampled from the free-flowing Yalakom River and from Reach 4 of the lower Bridge River and these two samples resulted in a wide range in tree ages along each river. Therefore the age category was limited to juvenile trees aged 5 to 11 years which incorporated the majority of the samples. The age composition of the trees that were sampled was also compared between the lower Bridge River and the Yalakom River. This same data set was then used to compare trunk diameter versus age of juveniles along the lower Bridge River and the Yalakom River.

2.2.4 Saplings

Saplings were the third age class of riparian black cottonwoods that were sampled. In 2005, test sites were located along the lower Bridge River, and then in 2006 a more in-depth analysis of numbers of individuals and ages was undertaken along Reach 4 of the lower Bridge River. The non-invasive method of yearly growth scar counting was used to determine the age of sapling, in areas where they were less abundant.

In areas of heavy growth sapling were excavated and taken back to the lab for further analysis. Saplings were defined as ≤ 1 m in height, and growing adjacent to the river's edge. Downstream from Terzaghi Dam saplings are scattered for approximately 2 km, with the occasional thick band adjacent to the river.

Along Reach 4 of the lower Bridge River, height, basal diameter and annual growth measurements were taken using annual growth scars from each of 200 saplings. To verify ages, a subset of 59 saplings were excavated, and taken back to the lab for ring interpretation. Laboratory validations were done using a dissecting microscope to clearly separate and count individual rings to determine accurate ages.

2.3 Results

2.3.1 Hydrology

Throughout time, the Bridge River has been greatly altered by nature and by humans. The current sequence of dams along the Bridge River harnesses its energy to change the flow amount and pattern. However, even though there are man-made dams on the Bridge River today, dams and flooding are not new features within the system. Prior to humans damming the river, the upper Bridge River experienced a sequence of moraine dams. Their resulting failures caused flooding near the outflow of the Bridge Glacier (Ryder 1991) during the period 1964 to 1970. An exceptionally large flood occurred during this time but was not documented because it coincided with a time when no discharge records were maintained (Ryder 1991).

There are historical discharge records from the Bridge River that display the magnitude of the seasonal pre-dam flows from 1913 to 1948 (Figure 2.4). Prior to damming the Bridge River had an annual average Q_{max} of 473 m³/s for the period from 1913 to 1948 at station 00ME001, at the current site of Terzaghi Dam. For that same interval, the maximum mean daily discharge (Q_{max}) was 900 m³/s on June 9, 1948 (Figure 2.4, Table 2.3). The four final years of natural flow at station 08ME001 on the lower Bridge River display the natural, seasonal flow pattern of this large river and demonstrate a fairly consistent annual pattern of a snowmelt-dominated

hydrograph (Figure 2.3). From 1983 until 2000 there were no regular flows in the lower Bridge River.

There were only occasional free-spills that produced large peaks (Figure 2.5). The peak on August 21, 1991 was one of the largest post-dam free spills on record with a Q_{max} of 241 m³/s (Figure 2.5). These high discharges followed a wet summer with exceptionally high precipitation in August (Figure 2.6). For the lower Bridge River, this was a flow that the river had not experienced during the 52-year period of no flow releases. It was then followed by another peak on August 8, 1992 and a smaller peak in 1997 (Figure 2.5). The large spill in 1991 prompted the legal action that resulted in the implementation of the experimental flow regime of 3m³/s that was used in this study (Failing et al 2004).

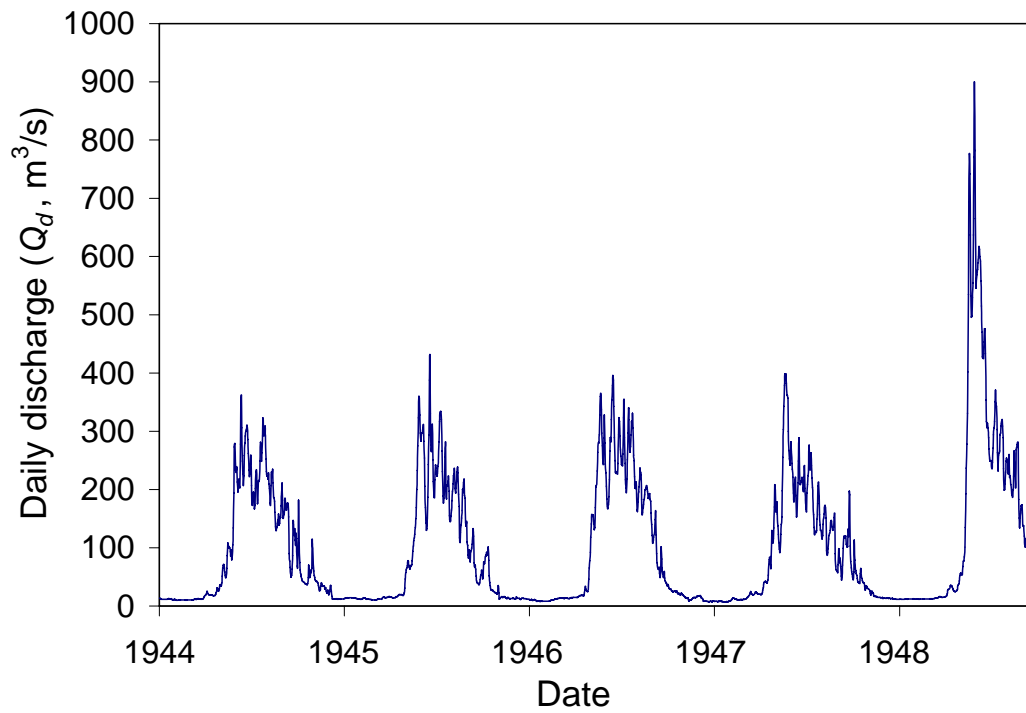


Figure 2.3. Hydrograph showing daily discharge of the free-flowing lower Bridge River (Water Survey of Canada (WSC)) from 1944 to 1948, immediately prior to damming at hydrometric station 08ME001.

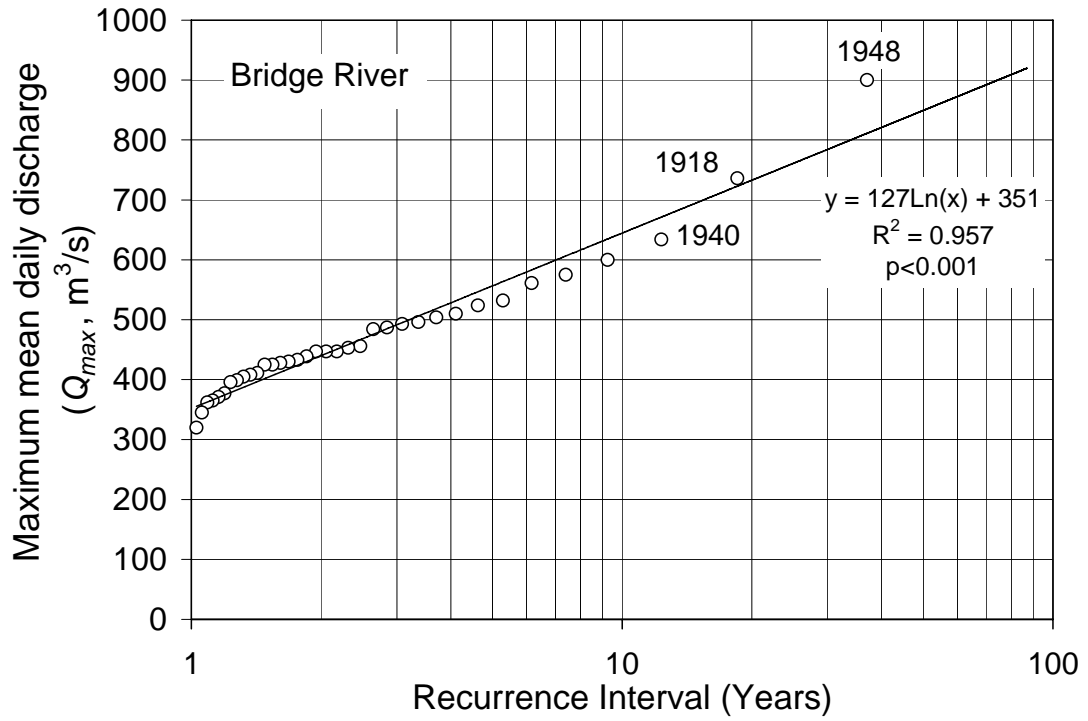


Figure 2.4. Peak flow recurrence analysis for pre-dam flows along the lower Bridge River, for the interval from 1913 to 1948, at WSC station 08ME001.

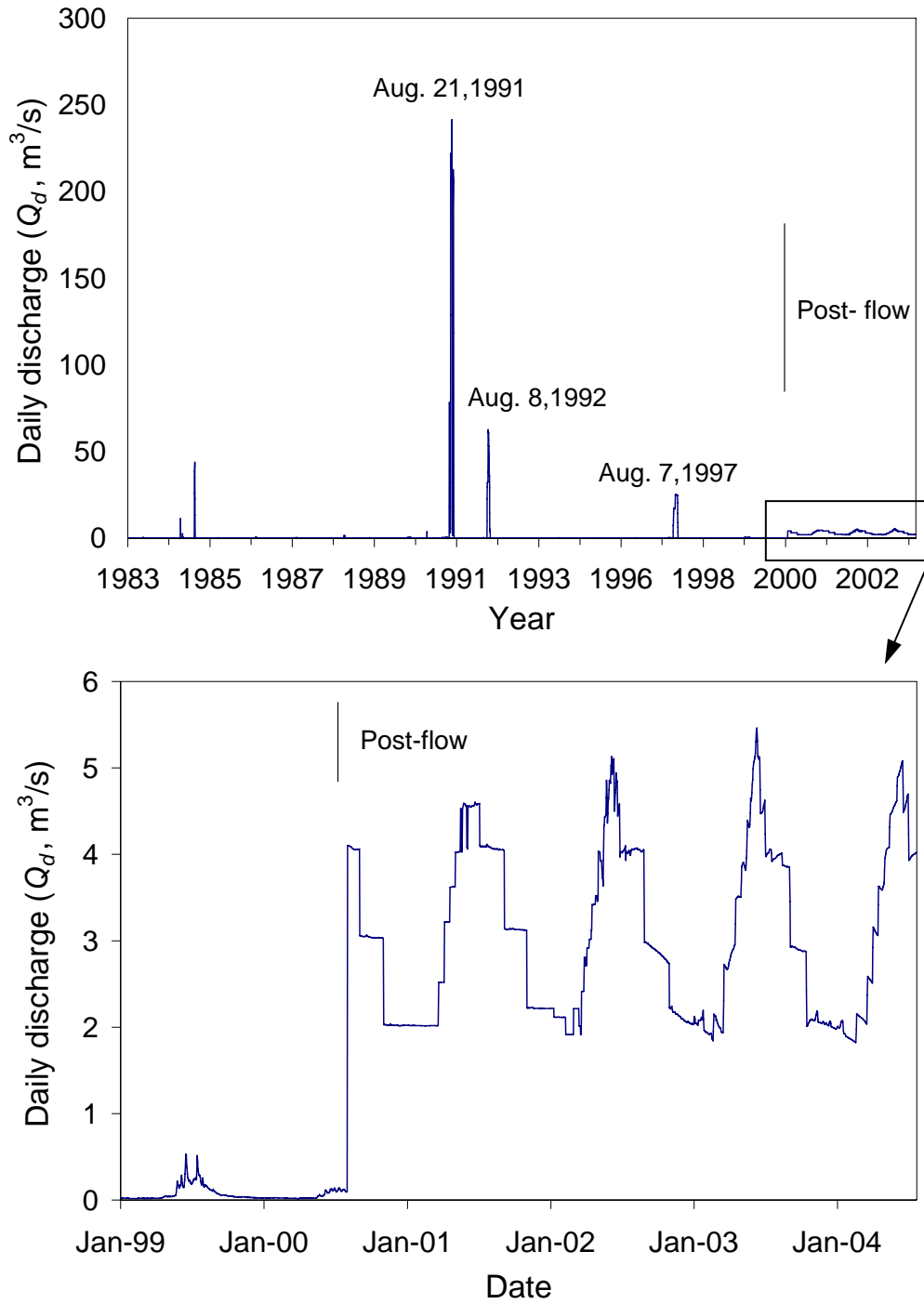


Figure 2.5. Daily discharge of the lower Bridge River below Terzaghi Dam (top), and an extended scale for the experimental flow releases that began in August of 2000.

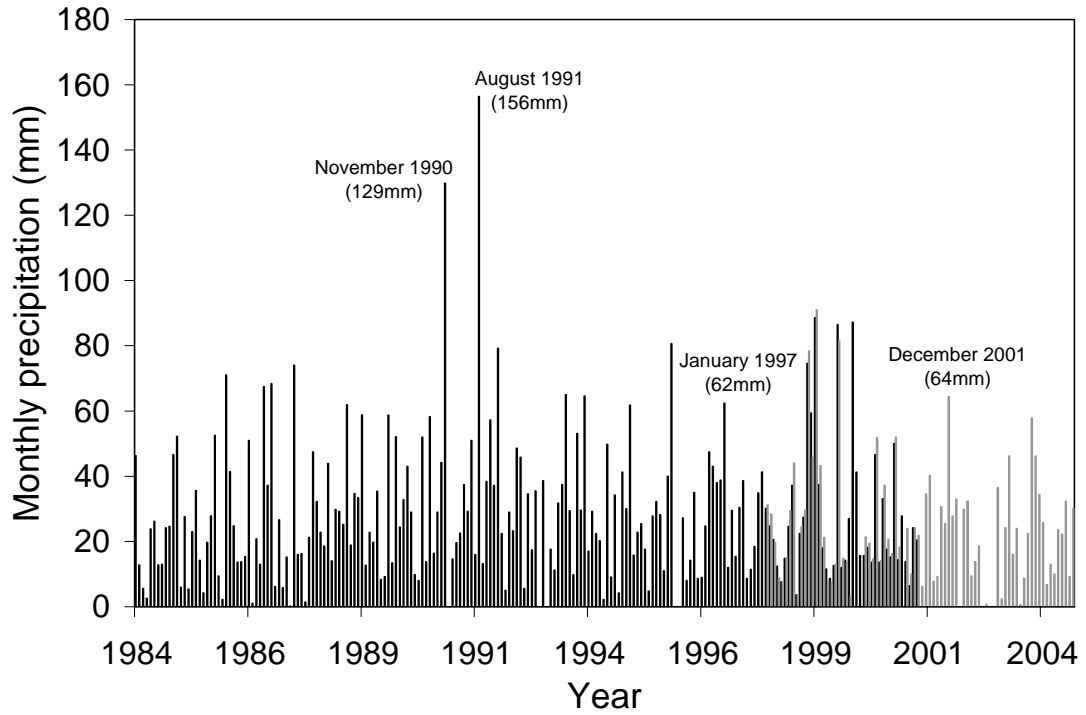


Figure 2.6. Total monthly precipitation for the meteorological station: Lillooet Seton BC Hydro Power Authority (BCHPA) (black bars) active from 1971 to 2001 and station Lillooet (grey bars) active from 1997 to 2004. Zero values represent data gaps (Environment Canada).

Table 2.3. Characteristics of historic flow rates of the lower Bridge River below Terzaghi Dam separated into three intervals: pre-dam, post-dam and post-flow.

Lower Bridge River Flows			
Flow Characteristic (m ³ /s)	Pre-dam (1914-1947) (m ³ /s)	Post-dam (1984-1999) (m ³ /s)	Post-flows (2000-2004) (m ³ /s)
Average Q _{max}	473	23.6	4.73
Highest Q _{max} (highest flow of record interval)	900 (June 9, 1948)	241.25 (August 21, 1991)	5.121 (June 10, 2003)
Q (Mean)	100.89	1.32	2.62

Q_{max} = annual maximum mean daily discharge.

In the late summer of 2000, flow was returned to the lower Bridge at a rate of 3 m³/s to be released from Terzaghi Dam, due to an out of court settlement between BC Hydro and Federal and Provincial fisheries agencies (Failing et al. 2004, Woo 1998). Along with fulfilling this requirement, BC Hydro implemented an experimental flow regime that attempted to resemble a natural seasonal hydrograph for a snowmelt-dominated flow regime (Figure 2.5).

From 2000 through 2004 the average annual flow rate was 2.6 m³/s with an average Q_{max} of 4.7 m³/s for the lower Bridge River below Terzaghi Dam (Table 2.3). Since the implementation of the experimental flows below Terzaghi, the Q_{max} or flow of record that the lower bridge has experienced was 5.1 m³/s on June 10, 2003. This new flow regime for the lower Bridge River introduces a small amount of water to the river system compared to historic flows, but represents a vast increase when compared to the flow of 0 m³/s, which was only rarely exceeded and short lived in the prior 52 years (Figure 2.7).

2.3.2 Riparian cottonwoods

Throughout the study riparian cottonwoods were analyzed by separating them into three age classes. These analyses were undertaken on each age class to analyze the collective patterns of growth and reproduction in relation to water flows in the lower Bridge River.

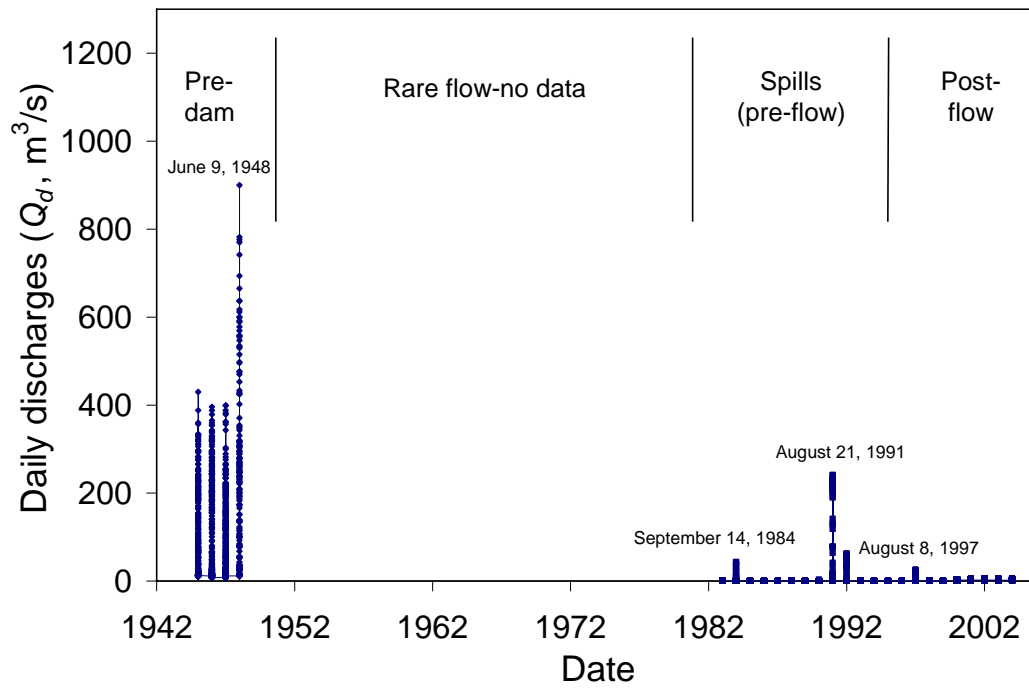


Figure 2.7. Lower Bridge River daily discharges by year for 1945 to 1948 and 1984 to 2004.

2.3.3 Mature trees

Annual radial trunk growth increments were measured from increment cores extracted from 64 mature (greater than ten cm and less than 40 cm diameter at breast height (DBH)) black cottonwoods along the Bridge River (Figure 2.8). Cores were analyzed from ten trees each for the free-flowing upper Bridge River, the flow-attenuated middle Bridge River and Reach 2 of the lower Bridge River. This was the final river segment studied and is below the inflow of the free-flowing Yalakom River (Figure 1.1; Figure 2.8). No mature tree sampling was undertaken along the Yalakom River it was strictly used to sample juveniles. Cores from 14 trees were analyzed from Reach 3 that had received contributions from groundwater and springs and thus demonstrated growth patterns related to perennial surface flows available prior to the flow experiment. Finally 20 trees were sampled from Reach 4, directly downstream from Terzaghi Dam (Figure 1.1).

The annual radial increments for each tree represent the mean of two measurements from increment cores extracted from opposing sides of each tree. These yearly values corresponded satisfactorily across the two cores with mean correspondence (r^2) of 57% for mature trees growing in the middle Bridge River section. Mature trees along the lower Bridge River demonstrated more variation within and across trees, as shown by the large standard deviation bars in Figure 2.8, which also display more variation within trees with a mean correspondence (r^2) of 35%. The annual radial increments were observed to be relatively constant over the study decade for

cottonwoods sampled from the upper Bridge River and the upper segment of the lower Bridge River, Reach 4 (Figure 2.8). Trees along the middle Bridge River and along Reach 3 of the lower Bridge River showed a significant decreasing trend over the past decade (Figure 2.8). This pattern is consistent with prior analyses of narrowleaf and black cottonwoods growing in mountain and foothills regions of southern Alberta (Willms et al. 2006, Berg et al. 2007). Trees growing in forest stands with canopy closure will experience competition between trees and this will reduce the size of annual growth ring widths but still provides constant annual basal area increments (Figure 2.2, Berg et al. 2007).

Our hypothesis was that the implementation of the experimental flow regime should promote cottonwood growth. We anticipated that this would be demonstrated by increased radial growth increments after 2000, especially for trees along Reach 4 and to a lesser extent along Reach 3. The pattern for Reach 4 was ambiguous, with an apparent growth increase in the first three years of the flow restoration. However the data were highly variable and in the fourth year, the apparent trend was reversed (Figure 2.8). For Reach 3, there was little evidence of growth enhancement since annual growth increments declined throughout the study interval (Figure 2.8).

The only river section that experienced experimental flow releases was the lower Bridge River. However we undertook the comparisons for all sections and most reaches to consider general environmental effects such as regional weather, as well as specific effects that could result from the flow experiment (Table 2.4). There was an

apparent trend ($p < 0.1$) for reduced growth along the middle Bridge River that would be consistent with the progressive decline over the study decade. Otherwise, there were no differences in three-year growth increments in the pre- versus post-flow comparisons (Table 2.4). Thus, the study of the mature trees did not demonstrate significant growth enhancement from the experimental flow regime.

We consequently analyzed annual branch increments which can be discriminated by the lengths between annual bud scars rings (Willms et al 1998). Branch data from seven mature trees were sampled along Reach 4 of the lower Bridge River. Each tree had five branches taken mid-canopy, on all sides of the tree. Branch data displayed no significant pattern of growth across the thirteen year interval (Figure 2.9). Similar to the radial increments, the basal area increments did not reveal a statistically significant pattern in the pre-flow versus post-flow interval, however for both measures there was an appropriate trend for increased growth in the first three post-flow years (Figure 2.9).

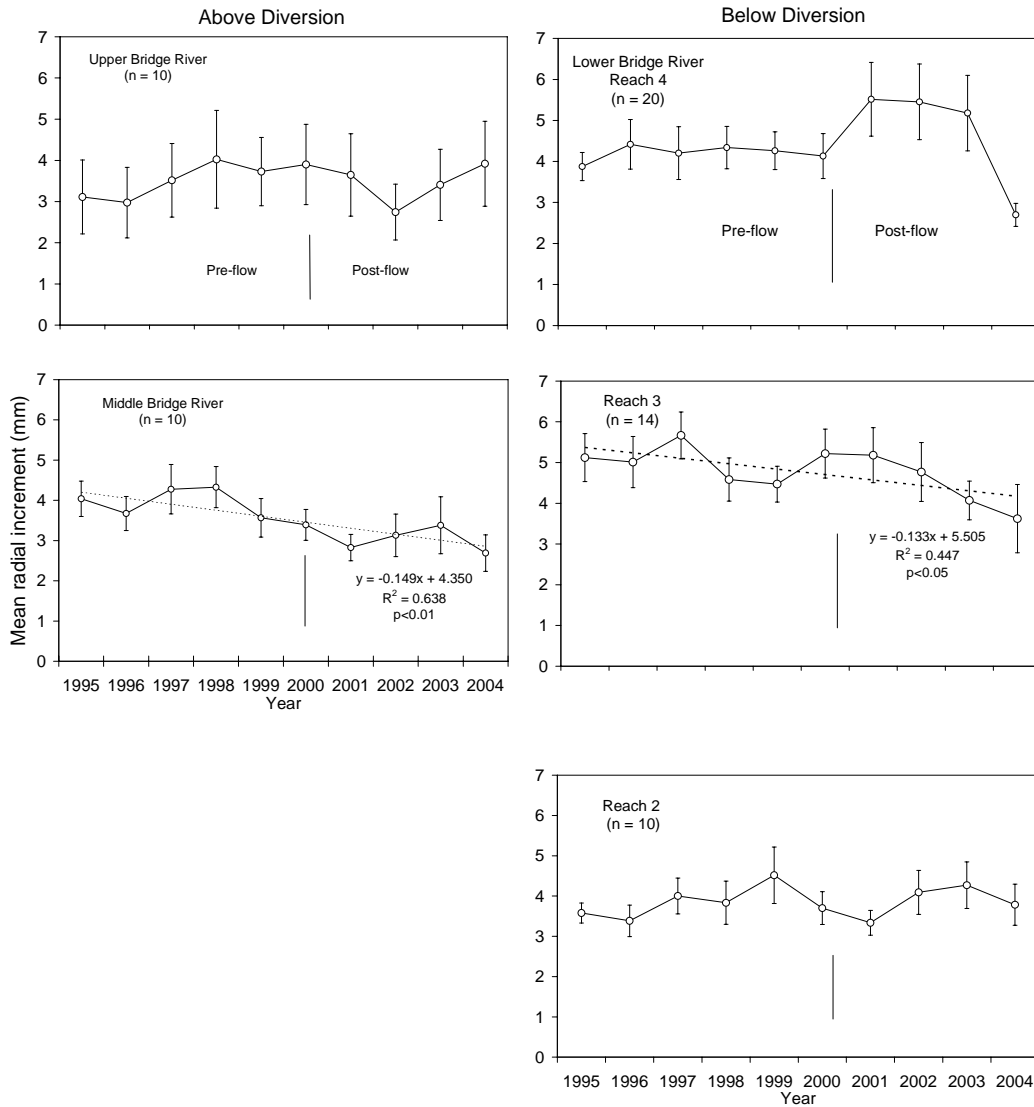


Figure 2.8. Mature Bridge River cottonwood tree growth, displayed in mean (\pm s.d.) annual radial increment growth, versus year, displaying changes in growth patterns before and after experimental flow releases in 2000.

Table 2.4. Wilcoxon signed-rank test results of mature Bridge River cottonwood trees, with mean radial increment growth, displayed in three year combined averages from 1997 to 1999 (pre-flow) versus 2001 to 2003 (post-flow).

River Section	n	z	Probability
Upper Bridge River	10	-1.172	0.241 n.s
Middle Bridge River	10	-1.682	0.093 t
Lower Bridge River, Reach 4	20	-0.261	0.794 n.s.
Lower Bridge River, Reach 3	14	-0.659	0.510 n.s.
Lower Bridge River, Reach 2	10	-0.561	0.575 n.s.

t = P<0.1(trend), n.s. = not significant.

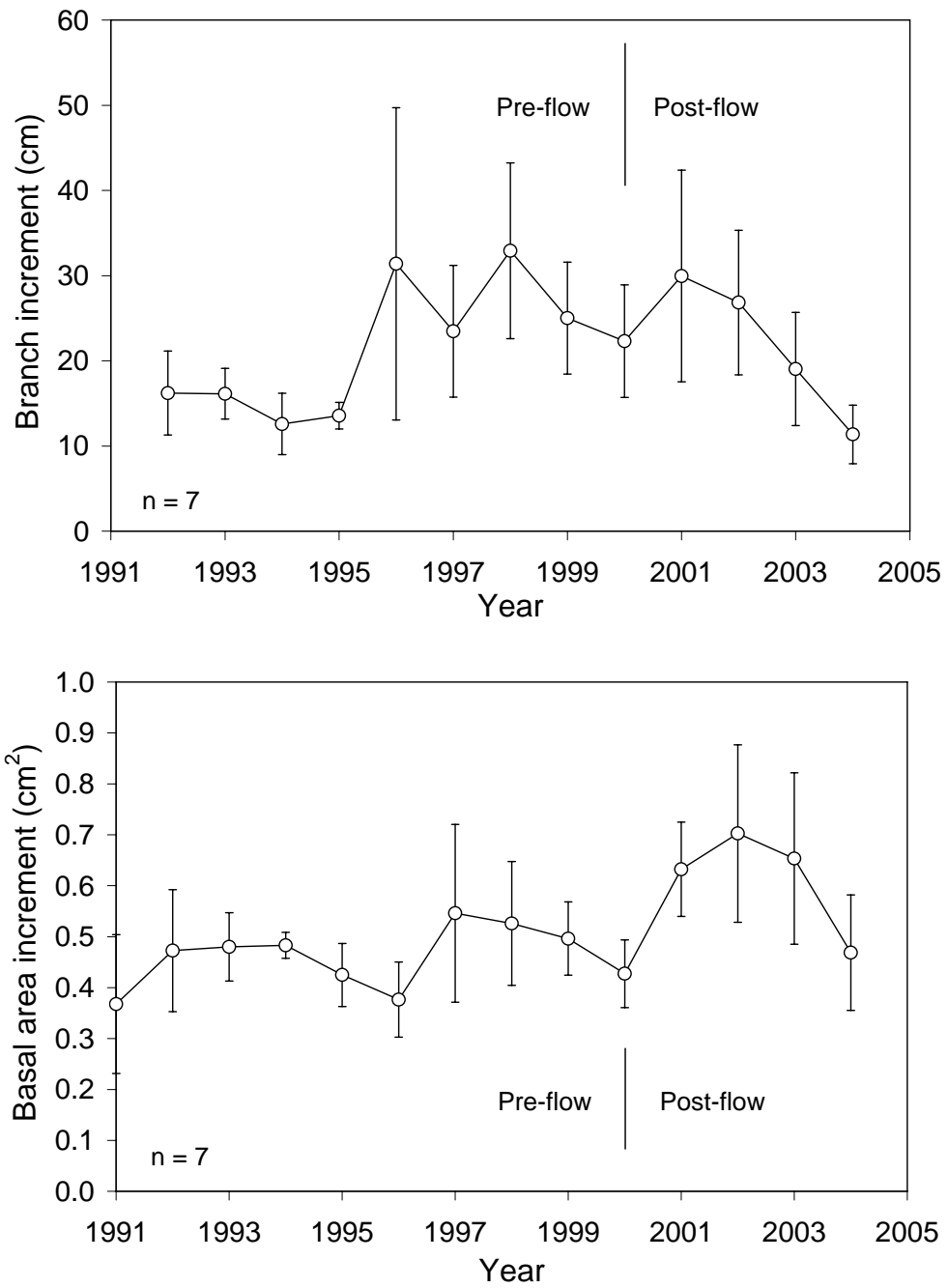


Figure 2.9. Branch growth from seven mature cottonwoods, along the lower Bridge River, Reach 4, represented by mean yearly (\pm s.d.) branch increments (top) and basal area increments (bottom).

2.3.4 Juveniles

To smooth the data and integrate growth over multiple years juvenile tree growth was analyzed in four year averages (Figure 2.10). The pre-flow group of juveniles displayed a reduced average growth relative to the post-flow group (Figure 2.10). The transition group apparently increased through the interval as the trees establishment date moved towards the year 2000, when the experimental flow commenced. This can be explained because most of the growth experienced by these later trees would have been during the flow-release time period, even though their establishment would have been prior to the flow release, thus potentially increasing their growth (Figure 2.10).

The non-parametric Kruskal-Wallis test and the parametric ANOVA test showed that the pre-flow, transition and post-flow groups varied significantly ($p < 0.001$) (Table 2.5, Appendix 6). To determine how the three groups varied we applied Mann-Whitney non-parametric paired-comparisons. These tests indicated that the pre-flow and the transition group probably differed ($p = 0.055$), the pre-flow and the post-flow groups were highly significantly different from each other ($p < 0.001$). While the post-flow and the transition groups ($p = 0.114$, Table 2.6), were not significantly different.

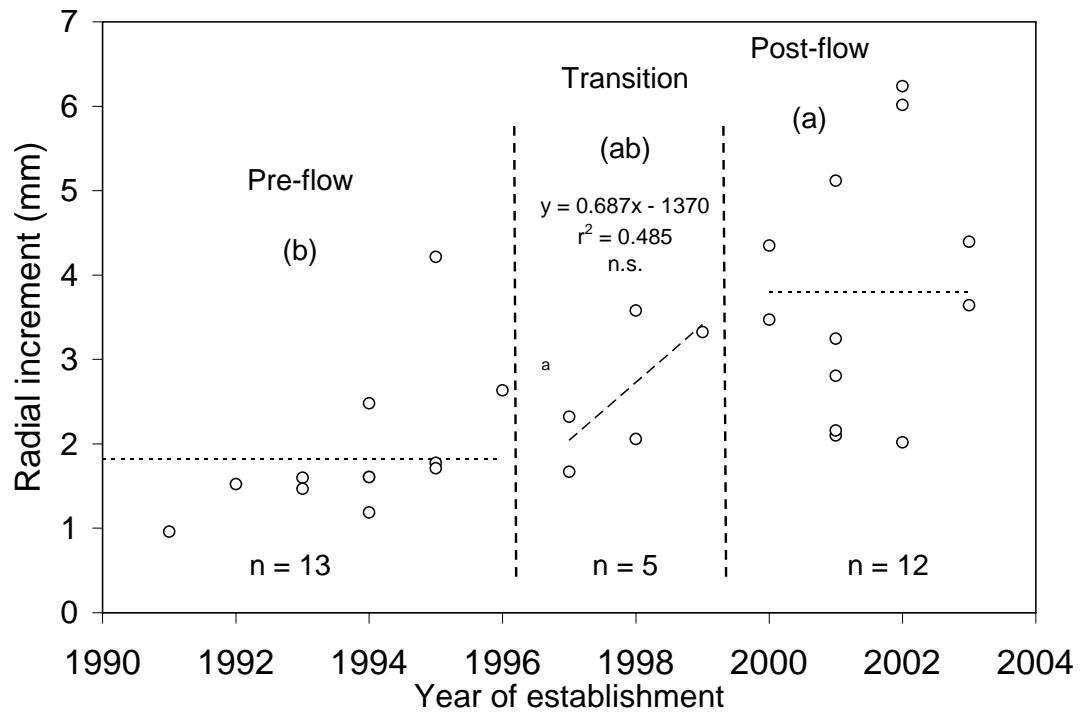


Figure 2.10. Mean radial increments for the first four years of growth of juvenile cottonwood trees along lower Bridge River Reach 4. Data are displayed in groups of trees according to year of establishment, either during the pre-flow, transition or post-flow, time periods. Groupings associated with different letters (a, b) differ significantly, while the ab group is a combination of both. Mean values are indicated by dashed lines for the pre-flow and post flow groups. The apparent trend is shown for the transition group and thus could link the two means.

Table 2.5. Kruskal-Wallis test (a non-parametric approach for analysis of variance), results from three groups of juvenile cottonwood trees along the lower Bridge River Reach 4 as shown in Figure 2.10.

Kruskal-Wallis Test						
Group	N	Mean Rank	χ^2	df	Probability	
Pre-flow	13	9	14.0	2	0.001***	
Transition	5	16.4				
Post-flow	12	22.2				
Total	30					

*** = P<0.001

Table 2.6. Mann-Whitney test (non-parametric paired-comparisons) results for juvenile cottonwoods separated into pre-flow, transition and post-flow groups along the lower Bridge River, as shown in Figure 2.10.

Mann-Whitney Test				
Comparison	n	Mean rank	Z	Probability
Pre-flow vs. Transition	13 + 5	8.0 vs. 13.4	1.92	0.055 t
Pre-flow vs. Post-flow	13 + 12	8.0 vs. 18.4	3.54	0.000 ***
Transition vs. Post-flow	5 + 12	6.0 vs. 10.3	1.58	0.114 n.s.

t = P<0.1; *** = P<0.001; n.s. = not significant

The juvenile trees sampled along the lower Bridge River ranged from 3 to 28 years old with the basal stem diameters ranging from 5 cm to 11 cm (Figure 2.11). These trees were compared to Yalakom River juvenile trees that also ranged from 5 to 11 cm in trunk diameter. The majority of trees sampled along both rivers are within the age range of 5 to 13 years old in the comparison of basal area increments vs. years, displayed in the 10 year comparison (Figure 2.12). Juvenile trees from the lower Bridge River displayed a greater increase in growth after 2000 compared to the juvenile trees growing along the Yalakom River (Figure 2.12). We had insufficient data to determine if the data have a normal distribution. So we used an independent samples t-test (parametric) and a Mann-Whitney test (non-parametric) to compare the means of juvenile growth. Both tests display a significant difference in juvenile growth rates along the lower Bridge River vs. the Yalakom River (Appendix 5).

The trunk diameter of cottonwoods normally increases with increasing age of the tree which can be seen in the juvenile Yalakom data (Figure 2.13). However, the lower Bridge River data did not display the same pattern, as data were more scattered with some trees displaying apparently stagnant growth (Figure 2.13). The Mann-Whitney test was used to determine if there was a difference between the two groups of data. The data was ranked and then tested resulting in the data not being significantly different with an assumptive significance (2 tailed) of 0.164. We also analyzed the growth patterns of the juvenile cottonwoods data set that was used in (Figure 2.11) but without the two oldest samples (Figure 2.13).

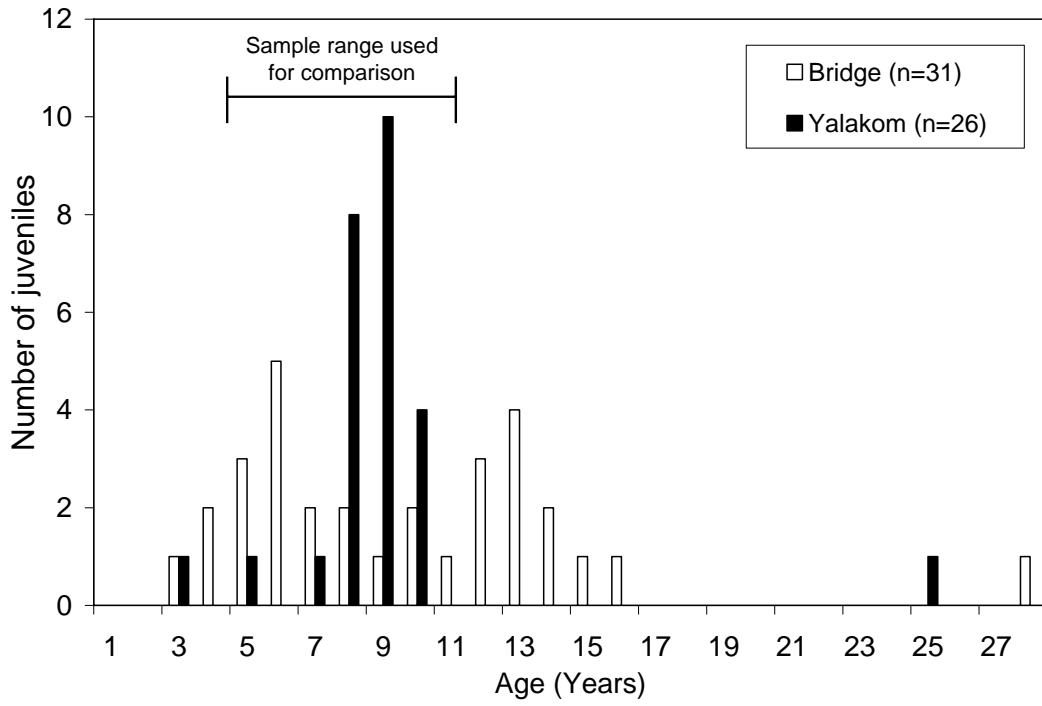


Figure 2.11. Juvenile cottonwoods from the regulated lower Bridge River Reach 4 and the free-flowing Yalakom River: number of individuals versus age.

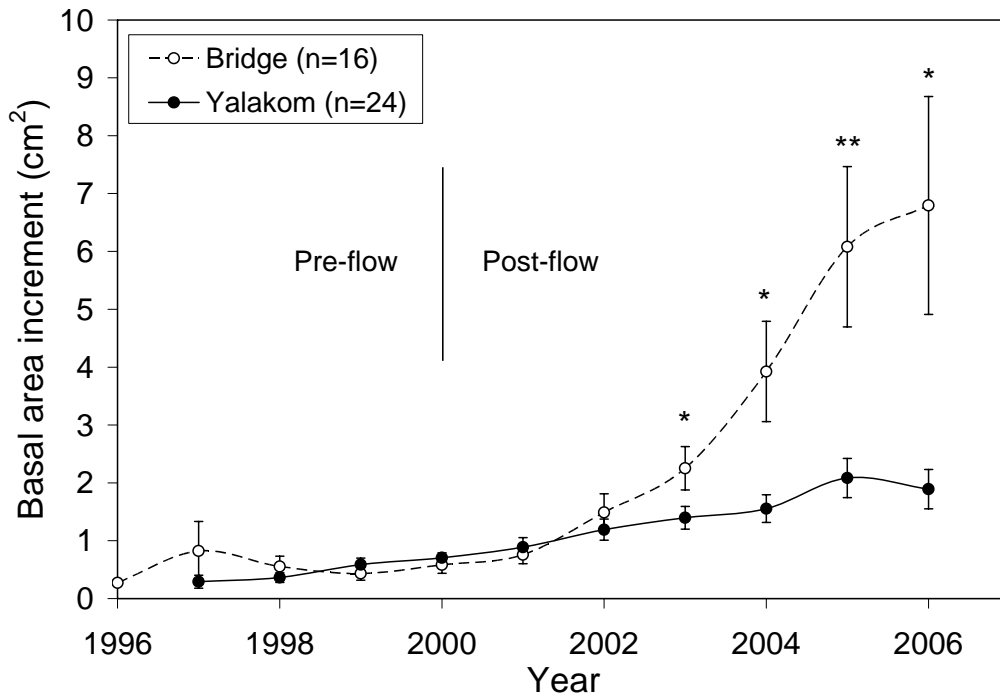


Figure 2.12. Average (\pm s.d.) annual basal area increments (BAI) of juvenile trees from the lower Bridge River Reach 4 and Yalakom River during pre and post-flow conditions. *, ** = indicate significance of ($p < 0.05$, $p < 0.01$ respectively), differences in basal area increment as detected by t- tests.

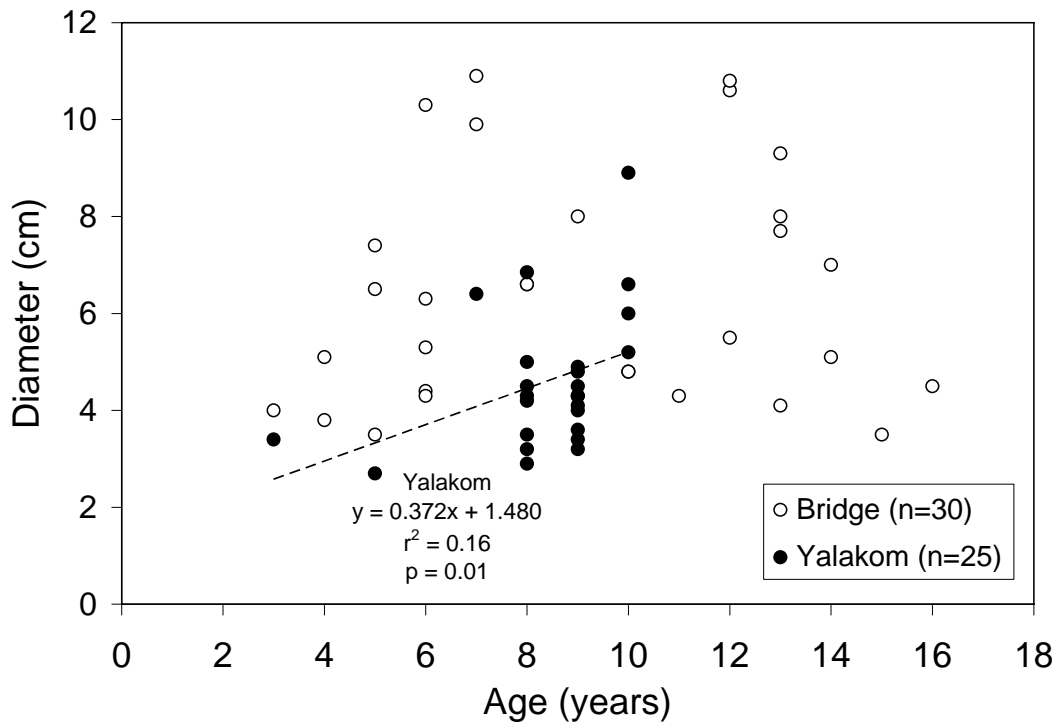


Figure 2.13. Juvenile cottonwood trees along the lower Bridge River Reach 4 and Yalakom River, trunk diameter versus age.

2.3.5 Saplings

The final age class of cottonwoods sampled along the lower Bridge River was included as an afterthought due to the inconspicuous nature and size of the saplings. To determine if experimental flows were affecting the recruitment of sapling-aged cottonwoods in Reach 4, studies were undertaken in 2005 to initially determine, if this age class existed in that specific reach. The entire 4 km of Reach 4 was investigated for saplings with one specific location along Reach 4 providing an excellent band of saplings, in which sampling was focused (Figure 2.15).

When data collection for this study began in 2003 the saplings that were collected in 2006 would have been barely visible as a distinct riparian tree. It was only once these saplings had reached their third year, when rapid growth is likely to occur, that they became readily apparent (Figure 2.15).

Cottonwoods require favorable conditions for recruitment such as barren sites, fine sediments and slowly declining water levels to survive throughout the growing season and the first critical year of growth (Rood et al. 2003a). The experimental flow regime of the lower Bridge River has attempted to mimic a seasonal snow-melt dominated hydrograph. The receding limbs of these hydrographs exhibit steep, sharp declines in water stage in the first few years of operations, but become more gradual in the later years (Figure 2.5).

The majority of saplings aged by bud scar counting indicate that they were established in 2002. The saplings that were aged using ring verification indicate that the majority of establishment occurred in 2003, corresponding with the gradual flow decreases (Figure 2.14).

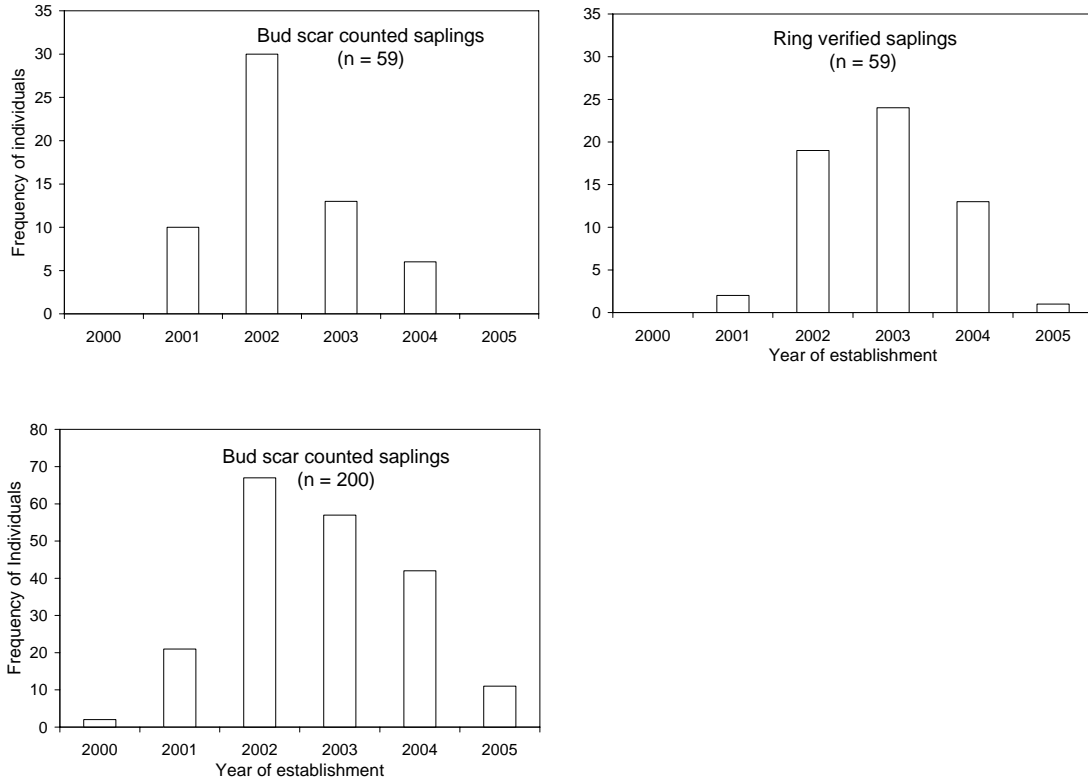


Figure 2.14. Establishment years of cottonwood saplings that were studied and harvested from the lower Bridge River Reach 4. Age was determined using annual bud scar counting done in the field compared to basal cross-section ring counting done in the lab.

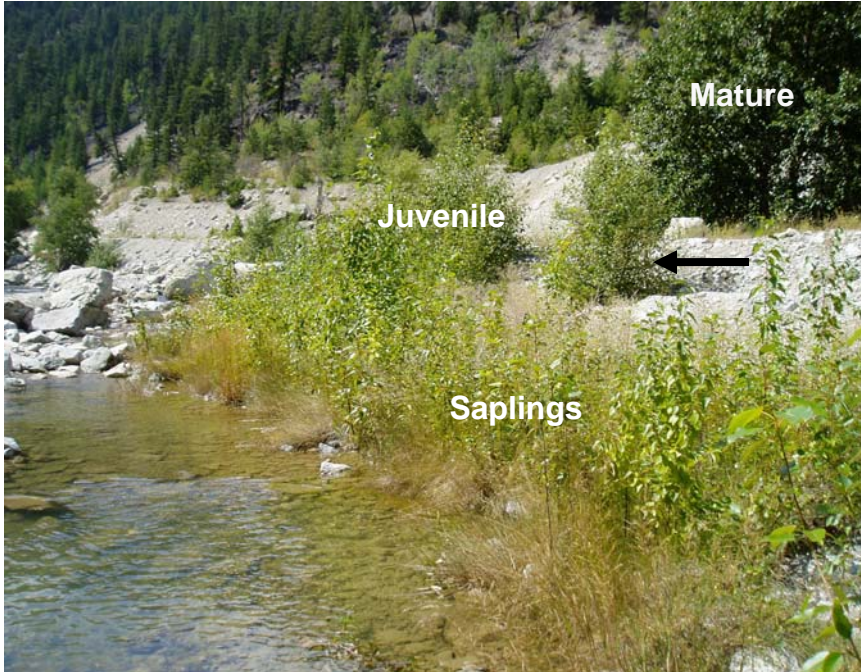


Figure 2.15. Lower Bridge River Reach 4, left bank with new band of saplings in the foreground with juvenile cottonwoods midway up the bank and mature trees higher up, July 28, 2006, top, December 31, 2006, bottom. The black arrows indicate the same juvenile tree.

2.4 Discussion

The results of this study suggest that specific age classes of black cottonwood trees growing along the lower Bridge River in south-western British Columbia have displayed an increase in growth, due to the re-introduction of flow to Reach 4. Since the summer of 2000 the Bridge River has become a different river than it was historically. It is no longer the big river it was in the past, but since the summer of 2000 the lower Bridge River has surface flow once again.

Over the past seven years it has been altered, shaped and modified into a much smaller regulated river with a functioning seasonal hydrograph. The effect that this seasonal hydrograph has had on the riparian cottonwoods can be seen in the increased growth of these trees but predominantly in the recruitment of young cottonwoods. The study investigated three specific age groupings of riparian black cottonwoods growing throughout the watershed in attempts to determine the effects that surface flows have on the trees in this river system.

Mature cottonwoods along Reach 4 of the lower Bridge River did not display a response to the increase in flow. One explanation for this non-response can be explained by their large physical size which also indicates intricate deep rooting systems, making it possible for the mature trees to reach and utilize the groundwater resource (Reily and Johnson 1982). This has also been stated by Stromberg and Patten (1990), in relation to vegetation that could be reliant on a subsurface or

groundwater resource if surface flow is unavailable. Physical size determination would also explain the potential for groundwater to be unavailable to younger and smaller trees, thus indicating that surface water would be more readily available, which suggests that any flow changes in the river would likely affect them.

Although previous studies (Willms et al. 1998) found that branch growth was hydrologically more responsive to water changes than radial trunk increment growth, this was not verified amongst the mature trees along the lower Bridge River. The trunk and branch radial increment growth analysis did not show any significant response to the $3\text{m}^3/\text{s}$ discharge of the lower Bridge River.

Juvenile cottonwoods displayed an increase in growth in regards to annual growth. The location of juveniles was at a lower elevational position on the river bank than the mature trees. Juvenile cottonwoods grow at an increased rate. To compare sample populations from along the lower Bridge and Yalakom Rivers, we ensured that all samples were of the same age and trunk size class. The juvenile trees growing along the lower Bridge River grew consistently faster or with more vigor than the juveniles growing along the Yalakom River during the same time period.

When deciphering tree growth during the pre-flow and post-flow time periods, the lower Bridge River cottonwoods displayed increased growth patterns post-flow (after) the flow releases in 2000. This confirmed our hypothesis that the increase in

surface flow in the lower Bridge River would increase growth among riparian cottonwoods, but only in a particular age class.

The next discovery of cottonwood growth along the lower Bridge River was a gratifying realization that regeneration in the form of establishment was taking place the entire time the study was focused on the mature and juvenile age classes. During the initial years of data collection in 2003, the lower Bridge River cottonwood saplings were growing as an invisible population disguised by the tall grasses and shrubs. It was not until the third year of data collection along the lower Bridge River that the sapling age class revealed itself as a strong recruitment event that was significantly correlated with the seasonal re-introduction of flow in the lower Bridge River.

Saplings were analyzed to determine year of establishment in regards to the increased flow in Reach 4. The 59 ring-verified saplings displayed a different age structure in the lab than compared to age measurements taken in the field. By comparing these two methodologies, we determined that node counting is a reliable way to assess sapling ages in field conditions whereas ring verification of the samples is more accurate. The number of similarly aged saplings in this previously dewatered reach indicates there was a major event that resulted in a large recruitment event.

This initial peak in recruitment is usually followed by a gradual decline in recruitment year by year, which can be explained by looking at patterns of establishment among

cottonwoods that depict a natural decline in numbers of sapling established in years following a large hydrologic event (Rood et al. 2003a). The effective establishment of saplings along the lower Bridge River indicates that the seasonal flow pattern of the Bridge River from 2000 – 2006 has been effective at creating a healthy riparian zone in which cottonwoods are reproducing.

2.5 Conclusion and management implications

In the future, the lower Bridge River should be managed in a way that will enhance and embrace the connectivity of aquatic and riparian systems without compromising the functionality of the hydroelectric operations in the Bridge watershed. This study has shown that it is not necessarily the volume of historic flows that are needed in the lower Bridge River, but the presence of surface water in conjunction with a seasonal flow regime.

The riparian zone response has been documented and displays the increased growth of juveniles and the recruitment of young cottonwoods. These documented increases in cottonwood growth are the beginning of the cycle of riparian forest succession. Such growth is further rejuvenating a previously compromised ecosystem. These findings have led us to view the Bridge River today as a functioning river rather than a river that has been fully restored.

The Bridge River has essentially been re-sized and re-constructed into a different river today than the historical pre-dam version. Today the results from the experimental flows can be regarded as functional flows in that they perform all the necessary tasks of a river but at a vastly reduced scale. Thus, the Bridge River no longer has historic discharge levels but does maintain functional flows that uphold the seasonality of a snowmelt dominated hydrograph, thus reviving Reach 4 of the lower Bridge River.

2.6 Literature cited

Abernethy, B., and I. D. Rutherford. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes*. 15: 63-79.

Annear, T., I.C. Chisholm, H.B. Beecher, A. Locke, P.A. Aarrestad, N. Burkhart, C. Coomer, C. Estes, J. Hunt, R. Jacobson, G. Jobsis, J. Kauffman, J. Marshal, K. Mayes, C. Stalnaker, and R. Wentworth. 2002. Instream flows for riverine resource stewardship. Instream flow council, Cheyenne, Wyoming, USA.

Amlin, N. M. and S. B. Rood. 2003. Drought stress and recovery of riparian cottonwoods due to water table alteration along Willow Creek, Alberta. *Trees*. 17: 351-358.

Berg, K. J., G. M. Samuelson, C. R. Willms, D. W. Pearce, and S. B. Rood. 2007. Consistent growth of black cottonwoods despite temperature variation across elevational ecoregions in the Rocky Mountains. *Trees*. 21: 161-169.

Braatne, J. H., R. Jamieson, K. M. Gill, and S. B. Rood. 2007. Instream flows and the decline of riparian cottonwoods along the Yakima River, Washington, USA. *River Research and Applications*. 23: 247-267.

- Bradford, M. J., and P. S. Higgins. 2001. Habitat-, season-, and size-specific variation in diel activity patterns of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Oncorhynchus mykiss*). *Canadian Journal of Fisheries and Aquatic*. 58: 365-374.
- Brayshaw, T. C. 1965. The status of the black cottonwood (*Populus trichocarpa* Torrey and A. Gray). *The Canadian Field Naturalist*. 79: 91-95.
- Church, B. N. 1996. Bridge River mining camp geology and mineral deposits. Energy and Minerals Division, Geological Survey Branch, British Columbia.
- Clark, J. 2006. Fisheries Act cases involving BC Hydro operation in the Pacific Region. Prairie Provinces Water Board (PPWB) Instream Flow Needs Workshop Report. March 2006, Calgary, Alberta, Canada. 41 pp.
- Conlin, K., C. Lamont, and S. MacFarlane. 2000. BC Hydro: Bridge-Coastal Fish and Wildlife Restoration Program: Strategic Plan, Volume 1 & 2, Ch.10-11.
- Dykaar, B. B., and P. J. Jr. Wigington. 2000. Floodplain formation and cottonwood colonization patterns on the Willamette River, Oregon , USA. *Environmental Management* 25: 87-104.

- Failing, L., G. Horn, and P. S. Higgins. 2004. Using expert judgment and stakeholder values to evaluate Adaptive Management options. *Ecology and Society*. 9 (1): 13.
- Farrar, J. L. 1995. *Trees in Canada*. Fitzhenry & Whiteside Ltd. Markham, Ontario and the Canadian Forest Service Ottawa, Ontario, Canada. pp. 338-339.
- Gadd, B. 1995. *Handbook of the Canadian Rockies, Second Edition*. Corax Press, Jasper Alberta, Canada. 831 pp.
- Gillilan, D. M., and T.C. Brown. 1997. *Instream flow protection: seeking a balance in western water use*. Island Press, Washington DC, USA.
- Gordon, N. D., T. A. McMahon, B. L. Finlayson, C. J. Gippel, and R. J. Nathan. 2005. *Stream Hydrology: An Introduction for Ecologists*. Second edition. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, England. 429 pp.
- Higgins, P. S., and M. J. Bradford. 1996. Evaluation of a large-scale fish salvage to reduce the impacts of controlled flow reduction in a regulated river. *North American Journal of Fisheries Management* 16: 666-673.

- Hill, E. L., and K. G. Wright. 2000. Harlequin duck breeding distribution and hydroelectric operations on the Bridge River, British Columbia. Proceedings of a conference on the biology and management of species at risk, Kamloops BC, 1999. Vol. 1. 490 pp.
- Karrenberg, S., P. J. Edwards, J. Kollman. 2002. The life history of *Salicaceae* living in the active zone of floodplains. *Freshwater Biology* 47: 733–748.
- Kondolf, G. M. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management*. 21: 533-551.
- Lemke, S. L. 2000. Moose winter habitat evaluation and enhancement opportunities in the Bridge River System. BC Hydro Bridge-Coastal Compensation Program Report. BC Hydro. 24 pp.
- Leopold, L. B. 1994. *A View of the River*. Harvard University Press, Cambridge, Massachusetts, USA. 298 pp.
- Mahoney, J. M., and S. B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment - an integrative model. *Wetlands* 18: 634-645.

McPhail, J. D., and R. Carveth. 1993. Field key to the freshwater fishes of British Columbia. Resources Inventory Committee, Queens Printer for British Columbia, Victoria, BC. 239 pp.

Ministry of Environment, Water Stewardship Division. 2007. Dams in BC. Government of British Columbia. Accessed January 10, 2007.
http://www.env.gov.bc.ca/wsd/public_safety/dam_safety/responsible.html#dams

Naiman, R. J., and H. Décamps. 1997. The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics*. 28: 621-658

Naiman, R. J., H. Décamps, and M.E. McClain. 2005. *Riparia: Ecology, Conservation, and Management of Streamside Communities*. Elsevier Academic Press, Amsterdam 430 pp.

Nanson, G. C., and H. F. Beach. 1977. Floodplain succession and sedimentation on a meandering-river floodplain, northeast British Columbia, Canada. *Journal of Biogeography*. 4: 229-251.

Parish, R., R. Coupe, and D. Lloyd. 1996. *Plants of southern interior British Columbia*. Lone Pine Publishing, Vancouver, B.C. 463 pp.

Peterson, R. T., and V.M. Peterson. 1990. A Field Guide to Western Birds. Houghton Mifflin Company, New York, New York. 432 pp.

Polzin, M. L., and S. B. Rood. 2000. Effects of damming and flow stabilization on riparian processes and black cottonwoods along the Kootenay River. *Rivers*. 7: 221-232.

Polzin, M. L., and S. B. Rood. 2006. Effective disturbance: seedling safe sites and patch recruitment of riparian cottonwoods after a major flood of a mountain river. *Wetlands*. 26: 965-980.

Reily, P., and W. Johnson. 1982. The effects of altered hydrologic regime on tree growth along the Missouri River in North Dakota. *Canadian Journal of Botany*. 60: 2410-2423.

Rood, S. B., J. M. Mahoney, D. E. Reid, and L. Zilm. 1994. Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. *Canadian Journal of Botany*. 73: 1250-1260.

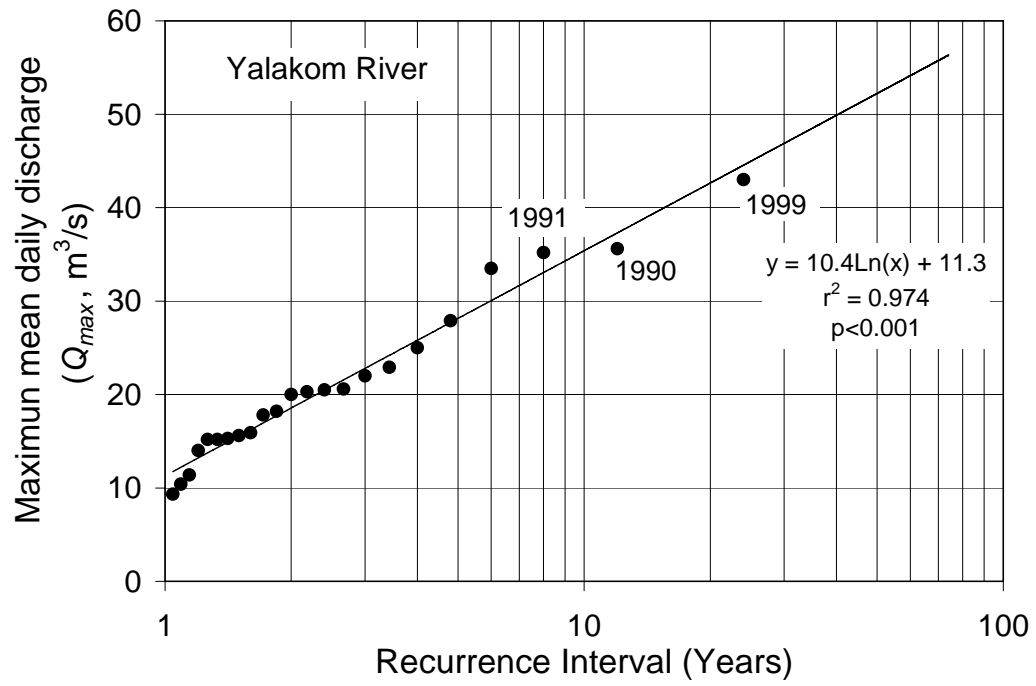
Rood, S. B., J. H. Braatne, and F. M. R. Hughes. 2003a. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology*. 23: 1113-1124.

- Rood, S. B., A. R. Kalischuk, M. L. Polzin, and J. H. Braatne. 2003b. Branch propagation, not cladogenesis, permits dispersive clonal reproduction of riparian cottonwoods. *Forest Ecology and Management*. 186: 227-242.
- Ryder, J. 1991. Geomorphological processes associated with an ice-marginal lake at Bridge Glacier, British Columbia. *Geographie Physique et Quaternaire*. 45: 35-44.
- Scott, M., P. Shafroth, and G. Auble. 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management*. 23: 347-358.
- Shafroth, P., J. Friedman, G. Auble, M. Scott, and J. Braatne. 2002. Potential responses of riparian vegetation to dam removal. *BioScience*. 52: 703-712
- Stromberg, J., and D. Patten. 1990. Riparian vegetation instream flow requirements: a case study from a diverted stream in the Eastern Sierra Nevada, California, USA. *Environmental Management*. 14: 185-194.
- Willms, C. R., D. W. Pearce, and S. B. Rood. 2006. Growth of riparian cottonwoods: a developmental pattern and the influence of geomorphic context. *Trees*. 20: 210-218.

Willms, J., S. B. Rood, W. Willms, and M. Tyree. 1998. Branch growth of riparian cottonwoods: a hydrologically sensitive dendrochronological tool. *Trees*. 12: 215-223.

Woo, E. 1998. BC Hydro and DFO sign \$600,000 agreement resolving fish habitat issues at Bridge River. *Habitat Enforcement Bulletin, Fisheries and Oceans Canada, Pacific Region*. No. 4.

Appendix 1



Appendix 1. Recurrence analysis for the free-flowing Yalakom River 1983-2005 (Station 08ME025) (Water Survey of Canada, accessed 2007).

Appendix 2

Vegetation	
western red cedar	<i>Thuja plicata</i>
Pacific silver fir	<i>Abies amabilis</i>
horsetail	<i>Equisetum spp.</i>
Ponderosa pine	<i>Pinus ponderosa</i>
Douglas-fir	<i>Pseudotsuga menziesii</i>
saskatoon	<i>Amelanchier alnifolia</i>
redstem ceanothus	<i>Ceanothus sanguineus</i>
black cottonwood	<i>Populus trichocarpa</i>
trembling aspen	<i>Populus tremuloides</i>
paper birch	<i>Betula papyrifera</i>
mountain alder	<i>Alnus incana</i>
Sitka willow	<i>Salix sitchensis</i>

(Parish et al. 1996)

Appendix 3

Birds

Canadian geese	<i>Branta canadensis</i>
trumpeter swan	<i>Cygnus buccinator</i>
common merganser	<i>Mergus merganser</i>
harlequin ducks	<i>Histrionicus histrionicus</i>

(Peterson 1990, Hill and Wright 2000)

Mammals

bighorn sheep	<i>Ovis canadensis</i>
moose	<i>Alces alces</i>
grizzly bear	<i>Ursus horribilis</i>
black bear	<i>Ursus americanus</i>
cougar	<i>Puma concolor</i>
mule deer	<i>Odocoileus hemionus</i>

(Gadd 1995)

Appendix 4

Anadromous fishes

chinook	<i>Oncorhynchus tshawytscha</i>
coho salmon	<i>Oncorhynchus kisutch</i>
sockeye salmon	<i>Oncorhynchus nerka</i>
pink salmon	<i>Oncorhynchus gorbuscha</i>
steelhead	<i>Oncorhynchus mykiss</i>
Pacific lamprey	<i>Lampetra tridentata</i>

Resident fishes

rainbow trout	<i>Oncorhynchus mykiss</i>
bull trout	<i>Salvelinus confluentus</i>
bridgelip suckers	<i>Catostomus columbianus</i>
sculpin	<i>Cottus spp.</i>
mountain whitefish	<i>Prosopium williamsoni</i>

(Higgins and Bradford 1996, McPhail and Carveth 1993)

Appendix 5: One-way ANOVA test for Figure 2.10, page 58.

Descriptives

	N	Mean	Std. Dev	Std. Err	95% Confidence Interval for Mean		Min	Max
					Lower Bound	Upper Bound		
1	6	6.06	1.30	0.53	4.70	7.43	3.83	7.15
2	6	8.59	3.95	1.61	4.44	12.7	3.82	15.1
3	6	13.2	4.12	1.68	8.91	17.5	9.84	20.7
Total	18	9.29	4.40	1.04	7.10	11.5	3.82	20.7

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	158	2	79.2	6.94	0.01
Within Groups	171	15	11.4		
Total	330	17			

Appendix 6: Independent samples Test, Mann-Whitney Test, Figure 2.12, p63.

Independent Samples Test		Levene's Test for Equality of Variances		t-test for Equality of Means		
		F	Sig.	t	df	Probability
2003	Equal variances assumed	4.27	0.046	2.21	38	0.03
	Equal variances not assumed			2.03	23.3	0.05
2004	Equal variances assumed	15.4	0.000	3.11	38	0.00
	Equal variances not assumed			2.64	17.3	0.02
2005	Equal variances assumed	20.0	0.000	3.33	38	0.00
	Equal variances not assumed			2.80	16.8	0.01
2006	Equal variances assumed	18.1	0.000	3.09	38	0.00
	Equal variances not assumed			2.56	16.0	0.02

Mann-Whitney Test				
	2003	2004	2005	2006
Mann-Whitney U	124	87	81	75
Z	-1.88	-2.90	-3.06	-3.23
Asymp. Sig. (2-tailed)	0.060	0.004	0.002	0.001