

**COTTONWOOD EVALUATION FOLLOWING ENVIRONMENTAL FLOW
IMPLEMENTATION ALONG THE WATERTON RIVER, ALBERTA**

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Bachelor of Science, University of Lethbridge, 2013

A Thesis
Submitted to the School of Graduate Studies
of the University of Lethbridge
in Partial Fulfillment of the
Requirements for the Degree

MASTER OF SCIENCE

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

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ABSTRACT

Alberta's Waterton River was dammed in 1964 and to avoid a collapse of downstream riparian woodlands as had occurred along the nearby St. Mary River, an Environmental Flow regime was implemented in 1991. This involved an increase in the minimum flow and flow ramping, gradual recession after spring peaks. This study assessed the consequences on the riparian woodlands by analyzing aerial photographs and assessing hydrological changes. Additionally, field research confirmed the persistence of the cottonwoods and quantified their growth characteristics through analyses of tree rings. Riparian cottonwood area remained relatively unchanged throughout the study interval, indicating survival after damming. There has been progressive colonization after damming, cottonwood growth benefitted from the Environmental Flow regime and analyses indicated that the increase in minimum flow was particularly beneficial.

ACKNOWLEDGEMENTS

Dr. Stewart Rood has provided me with an incredible opportunity to advance my education in a way that I never thought possible, and for that I am truly and deeply grateful. I thank my committee members, Dr. John Mahoney, Dr. Mathew Letts, and Dr. Craig Coburn for their support and feedback throughout my studies. I thank the Lethbridge College and the University of Lethbridge for providing amazing professors whose enthusiasm inspired and drove me to question and learn.

To my family and friends, thank you for your love, support, and patience as I furthered my education. A special thanks to my partner Michelle Mandy, who has been with me all the way. I would not have been able to do this without you.

Thank you to my field assistants Laurens Philipsen and Caitlyn Tracey. Thanks to the entire 'Rood Lab' during my time here, including Karen Zanewich, David Pearce, Kayleigh Nielson, Samuel Woodman, Evan Hillman, Sobadini Kaluthota, and Karen Gill. Your friendship and shared knowledge means a great deal to me.

TABLE OF CONTENTS

Abstract	iii
Acknowledgements	iv
Table of contents	v
List of tables	vii
List of figures	viii
List of abbreviations	x

CHAPTER 1

Overview of Cottonwoods and of the Waterton River

1.1 Importance of Cottonwoods in Southern Alberta	1
1.2 Cottonwood Species in Southern Alberta and Life Strategy Requirements	2
1.3 Southern Alberta's Agriculture – The Irrigation Capital of Canada.....	5
1.4 The Southern Tributaries River Impoundments	7
1.5 Flow Regime Requirements for Cottonwood Health.....	10
1.6 Cottonwood Forests along the Southern Tributaries	12
1.7 Environmental Flow Regime	17
1.8 Focus on the Waterton River	20

CHAPTER 2

River Regulation and Riparian Woodlands: Cottonwood Conservation with an Environmental Flow Regime Along the Waterton River, Alberta

2.1 Summary	21
2.2 Introduction.....	22
2.3 Methods.....	27
2.3.1 Study Area	27
2.3.2 Historic Hydrology	30
2.3.3 Analyses of Riparian Woodlands.....	33
2.4 Results.....	36
2.4.1 Free-Flowing Upstream Reach	36
2.4.2 Regulated Downstream Reach.....	38
2.4.3 Monthly Flow Patterns.....	40
2.4.4 Minimum Flows.....	41
2.4.5 Maximum Flows	43
2.4.6 Forest Dynamics	45
2.5 Discussion	51
2.5.1 Floods.....	52
2.5.2 Low Flows	54
2.5.3 Monthly Means	55
2.5.4 Adjacent Stream Comparison	56
2.6 Conclusion	61

CHAPTER 3

Implementation of an Environmental Flow Regime Promotes Cottonwood Colonization and Growth along the Waterton River, Alberta

3.1	Summary	62
3.2	Introduction	63
3.3	Methods	67
3.3.1	The Waterton River	67
3.3.2	The Historic Hydrometric Record	70
3.3.3	Cottonwood Recruitment Criteria	73
3.3.4	Field Study Sites	75
3.3.5	Statistical Overview	79
3.4	Results	79
3.4.1	Hydrology	79
3.4.2	Field Study Sites	87
3.4.3	Dendrochronology	90
3.4.4	Density and Elevational Profile	95
3.4.5	Floodplain Physical Attributes	98
3.5	Discussion	103
3.6	Conclusion	108
CHAPTER 4		
Conclusion: Suggestions and Future Recommendations		
4.1	Introduction	110
4.2	Thesis Chapters Summary	111
4.3	Methodology Suggestions	113
4.3.1	Aerial Photographs	113
4.3.2	Field Research Sites	114
4.4	The Belly River	118
4.5	Continued Monitoring	118
LITERATURE CITED		120
APPENDIX A		
Aerial Photography Digitization Results		129
APPENDIX B		
Transect Representations		139
APPENDIX C		
Kendall's Tau Rank Order Correlation for Physical and Biological Attributes		149
APPENDIX D		
Particle Distribution Curves		150

LIST OF TABLES

Table 1-1: Previous studies summary: Changes to percent cottonwood abundance along the southern tributaries of the Oldman River.....	16
Table 2-1: Gauging station attributes for the Waterton River and adjacent Belly River...	33
Table 2-2: Aerial photography acquisition details.....	35
Table 3-1: Gauging station attributes for the Waterton River and adjacent Belly River...	72
Table 3-2: Hydrological criteria for cottonwood recruitment analyses along upstream and downstream reaches.....	74
Table 3-3: Median tree, shrub, and sapling characteristics by reach with upper and lower quartiles in brackets.....	96
Table 3-4: Kendall's Tau correlations between physical and establishment characteristics.....	99
Table A-1: Coordinates and summary descriptions of changes between aerial photography digitizing segments for the Waterton River.....	134
Table C-1: Kendall's Tau correlations between physical and growth characteristics	149

LIST OF FIGURES

Figure 1-1: The major southwestern streams and reservoirs in the Oldman River Basin ..	9
Figure 1-2: A generalized hydrograph of many streams in southern Alberta.....	11
Figure 1-3: George Dawson’s map showing wooded and prairie tracts in the region and vicinity of the Bow and Belly Rivers.....	15
Figure 1-4: The Recruitment Box Model (RBM)	19
Figure 2-1: The Waterton River watershed along with the Belly River and major tributaries	29
Figure 2-2: Climatic and hydrologic data for the Waterton River along with cottonwood area dynamics.....	37
Figure 2-3: Average discharge through the Waterton – Belly canal during the growth season	39
Figure 2-4: Mean monthly discharges for the Waterton River	40
Figure 2-5: The mean number of days during the growth season below the minimum flow criterion and base flow	42
Figure 2-6: The two-component flood frequency analysis for the Waterton River displaying that substantial floods persist during post-dam implementation	44
Figure 2-7: The maximum mean daily discharge and forested area erosion for the Waterton River	44
Figure 2-8: Changes in forest density classification by segment between photographed years	48
Figure 2-9: Forested area removed by channel erosion between photographed years	49
Figure 2-10: Sequential aerial photography of the downstream Waterton River displaying typical and substantial channel erosion, patch recruitment of abandoned channels, fringe recruitment of point and lateral gravel bars, and forest maturation	50
Figure 2-11: Comparison of cottonwood trees along a constricted canyon on the downstream Waterton River	60
Figure 3-1: Field research sites and gauging stations along the upper Waterton River and adjacent Belly River.....	68
Figure 3-2: Field research sites and gauging stations along the lower Waterton River and adjacent Belly River.....	69
Figure 3-3: Schematic of a typical belt transect sampling method	78
Figure 3-4: Predicted likelihood of cottonwood recruitment upstream and downstream of the Waterton Dam	84
Figure 3-5: The Waterton River stage hydrographs for major flood years over the past half century	85
Figure 3-6: Stage hydrographs for the Waterton River for moderate flood years following the implementation of Environmental Flows.....	86
Figure 3-7: Typical field site photographs for the upstream and downstream reaches along the Waterton River	88
Figure 3-8: A typical transect along the downstream reach of the Waterton River	89
Figure 3-9: Cottonwood diameter versus age linear regression along the Waterton River.....	92
Figure 3-10: The sampled 3-year age structure of riparian cottonwoods along with accompanying averaged ramping recruitment score for the Waterton River	93

Figure 3-11: The 5-year averaged Basal Area Increments calculated from tree rings taken from cottonwoods and flow characteristics along the Waterton River	94
Figure 3-12: Elevation above the stage at base flow for cottonwoods along the Waterton River.....	97
Figure 3-13: Diameter of particle distribution curve percentiles for the downstream reach of the Waterton River.....	100
Figure 3-14: River slope correspondence between cottonwood elevation establishment above baseflow and the site median particle size	100
Figure 3-15: Site substrate heterogeneity correspondence with cottonwood density and sapling heights	101
Figure 3-16: Site cottonwood density correspondence with sapling height and tree diameter.....	102
Figure 4-1: The absence of cottonwood understory along the Waterton River downstream from the Waterton Dam	116
Figure 4-2: George Dawson’s physical geology map displaying the layers that the southern Oldman River Basin rivers flow across	117
Figure A-1: Original six category density classification for the Waterton River	129
Figure A-2: Condensed density classification of forested area along the Waterton River	130
Figure A-3: Forested area removed by human floodplain development between photographed years	131
Figure A-4: Woodland clearing along the Waterton River for crop agriculture purposes at the confluence with the Belly River	132
Figure A-5: Industrial feedlot and dairy ranching development along the upstream reach of the Waterton River	133
Figure B-1: Density of cottonwoods by distance from river and transect elevation above baseflow on the Waterton River	139
Figure B-2: Height of cottonwoods by distance from river and transect elevation above baseflow on the Waterton River	144
Figure D-1: Particle distribution curves for field sites located along the upstream and downstream reaches of the Waterton River	150

LIST OF ABBREVIATIONS

SSRB	South Saskatchewan River Basin
ORB	Oldman River Basin
SMRID	St. Mary River Irrigation District
RBM	Recruitment Box Model
APRS	Air Photo Record System
RMSE	Root Mean Square Error
RI	Radial Increment
BAI	Basal Area Index
Q	Streamflow discharge
T	Flood recurrence interval
M	Mortality coefficient

CHAPTER ONE: Overview of Cottonwoods and of the Waterton River

1.1 Importance of Cottonwoods in Southern Alberta

Cottonwoods (riparian poplars) are members of the *Populus* genus that establish in the floodplains of many river valleys. Like most riparian vegetation, cottonwoods have evolved to exploit the natural conditions in a floodplain. Cottonwoods are considered a pioneer species because they colonize the newly created gravel bars caused by floods. The prolific dispersal of their seeds and relatively quick root establishment anchors substrates allowing for primary succession to take place (Brayshaw, 1965; Braatne et al., 1996; Whited et al., 2007). Some species of cottonwood can also reproduce asexually, allowing for a quick regrowth following from beaver browse, cattle trample, and other disturbances (Samuelson and Rood, 2004; Rood et al., 1994; Rood et al., 2007).

When located in the Great Plains of North America, cottonwoods provide an important habitat for an otherwise treeless landscape. Cottonwoods are usually the only plant species that grow to considerable heights within the prairies. A forest with a diversity of tree ages provides the ranged vertical structure that is very important for the biodiversity of arthropods, arboreal birds, and other wildlife (Swift et al., 1984; Knopf et al., 1988; Finch and Ruggiero, 1993). By establishing along rivers for considerable distances the forests create wildlife corridors, commonly known as gallery forests. By supporting a high level of biodiversity amongst a relatively sparse ecosystem, cottonwoods can be considered a keystone species for this region (Naiman et al., 1993).

When located in a semi-arid climate with little rainfall cottonwoods are phreatophytic plants, meaning that their health is dependent on reliable groundwater

levels provided by an adjacent stream. They may exhibit signs of stress including expedited senescence, branch sacrifice, crown dieback, and mortality during periods of drought (Braatne et al., 1996; Rood and Mahoney, 2000; Rood et al., 2011). A healthy cottonwood forest indicates sufficient natural flow, while an unhealthy forest may indicate an excessive low flow history (Rood et al., 1995; Braatne et al., 2007). In addition to indicating historical flows, riparian vegetation is also indicative of a stream's water quality. Healthy riparian forests have been known to provide the ecological service of being a natural buffer by preventing pollutants and sediments from reaching the streams (Sweeney et al., 2004). Reducing instream pollutants not only benefits freshwater organisms but may also reduce the pressure on downstream water treatment facilities (Lee et al., 2003). Thus, cottonwoods can be used as an indicator species for the flow patterns and water quality of the adjacent stream.

Often, meeting the needs of cottonwoods can subsequently meet the needs of many biological systems. Therefore, cottonwoods can be considered an umbrella species; the care and maintenance of these riparian forests benefit many species and a successful forest is evidence to a biologically fit ecosystem. Unfortunately, cottonwood populations have been affected by many anthropogenic activities, including river impoundments utilized for irrigation (Rood and Mahoney, 1990; Braatne et al., 1996).

1.2 Cottonwoods Species in Southern Alberta and Life Strategy Requirements

With a focal point around Lethbridge, Alberta, a unique swarm of four *Populus* species hybridize in a zone that overlaps the outer fringes of pure stand ranges. Within the section *Tacamahaca*, balsam poplar (*P. balsamifera* L.) grow in more northern reaches

across Canada while the nearly indistinguishable black cottonwood (*P. trichocarpa* Torr. and Gray ex Hook) occur from the Pacific Coast into the foothills of Alberta. Also in the section *Tacamahaca*, the narrowleaf cottonwood (*P. angustifolia* James) range extends from the southcentral U.S.A. and fringe just past the 49th parallel. The only riparian poplar in southern Alberta within the section *Aigeiros* is the plains cottonwood (*P. deltoides* Bartr. ex Marsh.) that grow across the Great Plains of North America (Brayshaw, 1965; Floate, 2004; Cooke and Rood, 2007). Although all riparian poplar forests are ecologically significant, hybridized zones are especially important because of their enhanced genetic diversity that may increase arboreal species richness (Martinsen and Whitham, 1994). Also, specific genotypes may exhibit fast growth that would be ideal for environmental restoration and industrial uses (Floate, 2004; Schweitzer et al., 2002). Because of the increased importance of hybrid swarms, the health of cottonwoods along the rivers of southern Alberta is of special interest to conservationists.

For the purposes of this study, the definition of a ‘healthy’ riparian cottonwood forest is one that recurrently establishes seedling cohorts and sustains expected stem densities well into reproductive maturity. Only when a cottonwood forest exhibits a climax community, where cohorts of all age classes are present and continually replenished, can it successfully perform maximum ecological services. Although the life history strategies can specialize between the two sections and four species, cottonwoods generally require similar hydrologic and fluvial geomorphologic conditions to successfully reproduce and live healthy lifespans (Braatne et al., 1996; Rood et al., 2003a).

For sexual reproduction, cottonwoods are dioecious plants and female trees have evolved to release their seeds at approximately the same time as the peak flows in spring. Flows of substantial magnitude are required to create seedbeds by scouring vegetation and riverbanks and also depositing sediments into gravel bars (Scott et al., 1997). Cottonwood seeds then fall onto these moist gravel bars and a gradual decline of river stage (river level) after spring peak allows the seedling roots to establish and avoid drought mortality (Mahoney and Rood, 1998). Seeds are only viable for a short period (approximately 1 – 2 weeks) due to a limited endosperm. Thus, seeds need to encounter a suitable microsite for establishment during a specific timeframe that coincides with the spring flooding events. After establishment, root and shoot growth is rapid as the seedling becomes a more resilient sapling (Brayshaw, 1965; Braatne et al., 1996).

Especially in the section *Tacamahaca*, cottonwoods can reproduce asexually (Gom and Rood, 1999). Clones are created by branch, shoot and root suckering, and therefore clonal propagules develop utilizing a greater nutrient source than the endosperm of a seed (Rood et al., 1994). This allows clones to mature more vigorously. Expedited regrowth after disturbances limits invasive or facultative species from competing with cottonwoods. Therefore, clonal activity is important after disturbances such as floods, animal browse, fires, and wind storms by accelerating the recovery process (Rood et al., 1994; Braatne et al., 1996; Rood et al., 2007).

Cottonwoods roots are dependent on the capillary fringe as a water source. This fringe is a semi-saturated zone that is immediately above the completely saturated water table supplied by the stream. The height of the fringe is dependent on the substrate texture but generally extends 30 to 50 cm above the stream stage (Mahoney and Rood, 1992;

Rood et al., 1998). This moist yet aerobic location allows phreatophytic roots to thrive (Rood et al., 2011). Because rivers in semi-arid climates are ‘losing’ streams as opposed to ‘gaining’ streams, a river’s stage is approximately equivalent to adjacent groundwater levels (Rood et al., 1995; Rood et al., 2012; Amlin and Rood, 2003; Harner and Stanford, 2003). When the magnitude of flow in a river is manipulated, the stage is subsequently affected along with the adjacent groundwater tables and capillary fringe that support vegetation in riparian zones (Rood et al., 1995; Rood et al., 2012). When plants have a deficient water supply they will react by closing their stomata (gas and vapor ducts). This allows them to retain water but limits nutrient uptake resulting in the stress of the tree (Pearce et al., 2006; Rood et al., 2003a). Prolonged drought stress may also lead to root xylem embolism that may perpetuate issues with water uptake (Tyree, 1994; Sparks and Black, 1999). When dams are established to provide water for irrigation, water may deplete to a point where cottonwoods may not be able to access their water source.

1.3 Southern Alberta’s Agriculture - The Irrigation Capital of Canada

Southern Alberta contains many river structures that are crucial to the success of Alberta’s economy and livelihood. These river impoundments have a long and important history being located within a semi-arid region with minimal rain and high evaporation but also very nutrient rich soils. Starting in late 1890s, settlers diverted water from rivers to promise crop production and prosperity in Alberta. Now Albertans depend on these impoundments to provide irrigation that allows farmers grow more than 40 different types of crops for both local and exported consumption (Klassen and Gilpin, 1999).

Alberta has more irrigated land area than the rest of Canada combined. This culminated in 2012 to 70% of all land irrigated nationally, and 84% (420,940 ha) of that is located in southern Alberta alone. In Alberta, 88% of farmers depend on non-surface or groundwater sources and obtain them from off-farm irrigation canals (IJC, 2004; Statistics Canada, 2013). Southern Alberta contains one of the largest irrigation districts in all of Canada; the St. Mary River Irrigation District (SMRID; SMRID, 2012).

Economically, the importance of agriculture to Alberta cannot be overstated. Agriculture contributed 1.8% of the Albertan gross domestic product (GDP) in 2011, equating to approximately \$5,158,800,000 in revenue. About 20% of Alberta's agricultural GDP is linked to irrigation, with an additional 10% contribution when considering irrigation water use in food processing facilities (Alberta Government, 2012; AARD, 2014). Thus, Alberta has been aptly named the 'Irrigation Capital of Canada' (AARD, 2014).

In 2007, a moratorium was enacted on new applications for water licences in parts of southern Alberta because many streams were becoming over allocated resulting in water shortages (Regulation 171/2007). Thereafter, new water licenses are no longer available but may be transferred between parties (AMEC, 2009). This water shortage is compounded by a detectable decline in available annual and summer flows for the vast majority of streams originating from the Rocky Mountains (Rood et al., 2005a; Rood et al., 2008). With the high economic importance of irrigation in Alberta and the essential ecological services provided by cottonwood forests the scarce water must be shared to provide enough irrigable water while continuing to sustain ecosystems. Studying the

efficiency of how water is being distributed ensures that more will be available where it is needed the most.

1.4 The Southern Tributaries River Impoundments

The headwaters to the South Saskatchewan River Basin (SSRB) are some of the most regulated rivers in Alberta, including those in the Oldman River Basin (ORB). The Waterton, Belly, and St. Mary Rivers are commonly referred to as ‘the southern tributaries’ that flow into the Oldman River (Figure 1-1). Interestingly, the southern tributaries of the ORB are in close proximity to each other, originate from relatively similar and pristine montane regions of the Waterton-Glacier International Park, and all flow parallel to each other in a northeastern direction (Figure 1-1). Therefore, these 3 rivers allow for the unique opportunity to compare and evaluate differences in river management focusing on the cottonwood populations along these rivers. While the Belly River only has a weir, the St. Mary and Waterton rivers are dammed and contain storage reservoirs.

Two common infrastructures used to impound rivers in the ORB are weirs and dams. A weir (low head dam) is a submerged berm designed to elevate a backwater for directing water offstream usually into a canal system. The backwater pool created is small and does not store a substantial amount of water. Weirs of this design do not substantially attenuate the magnitude of spring flooding, but may divert a significant proportion of summer flows when the discharge is minimal (Rood et al., 1995). In contrast, a dam (such as an embankment, arch, or gravity dam), fitted with discharge tunnels and overflow spillway gates, impound a substantial section of a stream and creates a reservoir of stored

water. Reservoirs utilized for irrigation can pass water through a diversion canal system, or the dam can spill water in the natural channel to guarantee flow to a weir structure further downstream. A dam of sufficient storage volume can attenuate floods, but often fill to capacity and spill excess waters during spring flooding (Rood et al., 1995). The discharge tunnels and flood gates in dams allow for dynamic water release at an operator's discretion dictating the amount of water released downstream. Reservoirs of sufficient hydraulic head can also provide hydroelectric generation and most reservoirs provide recreational attractions.

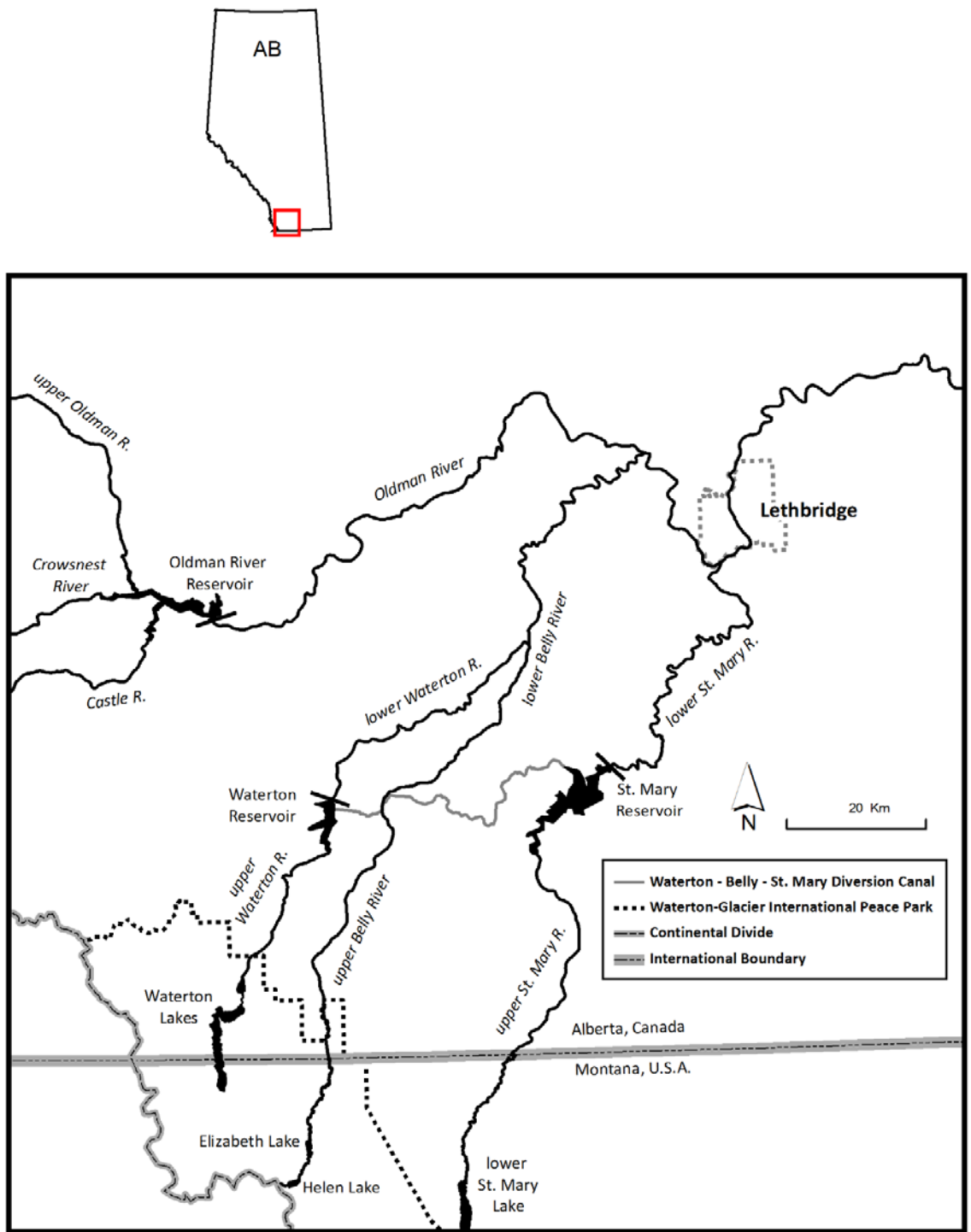


Figure 1-1: The major southwestern streams and reservoirs in the Oldman River Basin.

1.5 Flow Regime Requirements for Cottonwood Health

A flow regime is the interannual flow characteristics that can be described by analysing a hydrometric time series. In 1997, Poff and others described in their pivotal paper that a river's natural flow characteristics including magnitude, frequency, duration, timing, and rate of change will influence the integrity of a river system's ecosystem and geomorphology. Deviations from natural flow regimes can cause alterations in riparian health and composition, and thus river managers should strive to imitate the natural flow regime along lower river reaches (Stanford et al., 1996; Goodwin et al., 1997; Lytle and Poff, 2004).

Many major rivers in southern Alberta originate from mountainous regions. These rivers, including the ones in the ORB, have similar natural flow regime characteristics (Figure 1-2). Generally, the cycle commences with an abrupt spring runoff of considerable magnitude frequently occurring in late May to early June. The 'rising limb' of the hydrograph includes the portion of spring runoff until the greatest peak flow is achieved. Following this, the 'falling limb' of the hydrograph displays gradual receding characteristics after peak flow to the low flow (baseflow) around October when water is supplied solely by adjacent groundwater. Dams can drastically change the characteristics of the flow regime. Figure 1-2 depicts two potential alterations that impoundments frequently cause on downstream reaches. The first iteration (A) illustrates a reservoir that is managed for maximizing irrigation potential or hydroelectric generation. The peak of the flow is only slightly truncated and is followed by an abrupt decline to baseflow early in the falling limb. This low flow is maintained until water is released from the reservoir in preparation for winterization to reduce the risk of ice caused damages. The second

iteration (B) depicts a flow regime from a dam that is managed for flood attenuation. While the peak flow is truncated, the falling limb does not exhibit an abrupt decline. Instead, the peak flow duration is extended minimizing the negative effects of high magnitude flood waters downstream. While both iterations affect the ecology downstream from the dam, an abrupt decline and extended low flow throughout the summer is usually fatal for cottonwoods (Mahoney and Rood, 1991).

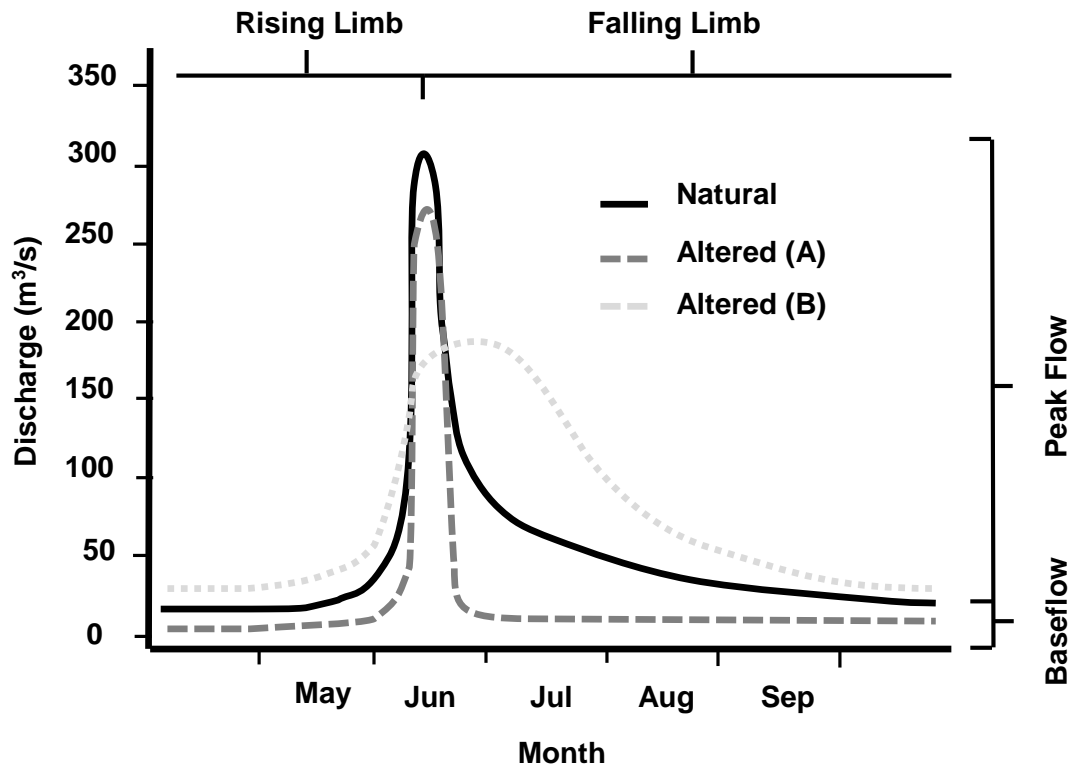


Figure 1-2: A generalized hydrograph of many streams in southern Alberta (from Rood and Mahoney, 1990).

1.6 Cottonwood Forests along the Southern Tributaries

The degradation of cottonwood forests downstream from river impoundments has been widely documented in North America (Rood and Mahoney, 1990; Braatne et al., 1996; Rood et al., 2003b, 2005b). In southern Alberta, the study of these effects took place as the development on the Oldman River began in the late 1980s when the Oldman River Dam was being planned (Figure 1-1). This impoundment gained national attention with controversies surrounding environmental regulations legislation but was eventually completed in 1994 (Glenn, 1999). Following this attention, the public gained interest in the effects of reservoirs on the southern Albertan watersheds and multiple studies began to critique current and historic river management to determine the impacts caused by the impoundments (Rood and Henize-Milne, 1989; Rood and Mahoney, 1991; Reid et al., 1992; Rood et al., 1995).

The southern tributaries principally support balsam poplars and narrowleaf cottonwoods and their hybrids. The upper reaches of the Waterton and Belly Rivers support black cottonwoods. Along the St. Mary River, hybrids with the plains cottonwoods occur near the confluence with the Oldman River (Floate, 2004). One of the earliest records of the vegetation along the southern tributaries comes from maps, pictures, and reports created from George M. Dawson's expeditions in the mid-1880's (Figure 1-3; Dawson and McConnell, 1884). The maps show the Waterton River with a densely populated forested river, while the Belly and the St. Mary Rivers were displayed as river valleys with small isolated groves. Since this initial survey, the cottonwood population has changed substantially. The Waterton River has retained its cottonwood population, but the Belly River's entire river valley has grown into a dense population. In

contrast, the St. Mary River has very few groves remaining (Rood and Heinze-Milne, 1989; Rood et al., 1995; Rood and Mahoney, 2000; Rood et al., 2016). Comparing the river management of these three rivers may provide insight to why and how river impoundment management impacts cottonwood health.

The most extensively regulated river of the southern tributaries is the St. Mary River. Water withdrawal began in the upstream reaches in 1898 with the Kimball weir implemented for water use in Alberta. In 1951, the Kimball weir was decommissioned, and the larger St. Mary Dam and Reservoir was established. The Belly River does not have a dam and reservoir but instead has one major weir (and a couple minor weirs) that was established in 1935 to divert water into a canal that flows to the St. Mary Reservoir (Gom and Mahoney, 2002). Because the Belly River only has weirs, it is regarded as relatively free-flowing and minimally impacted through river management (Rood and Heinze-Milne, 1989; Rood et al., 1995). The Waterton River is intermediately impacted. The Waterton River possesses a dam with a mid-sized reservoir that was established in 1964. Water from the Waterton River is diverted into a canal system that spills into the Belly River just upstream from the Belly – St. Mary diversion weir. Consequently, both the Waterton and Belly River's waters are partially diverted into the St. Mary Reservoir and supply water to the SMRID.

Rood and Heinze-Milne (1989) were the first to document a degradation of cottonwood forests downstream from dams along the southern tributaries using 1961 and 1981 aerial photographs. A drastic -47.8% and -22.9% decrease in linear cottonwood abundance along the lower St. Mary and Waterton Rivers (respectively) indicated acute cottonwood mortality (Table 1-1). This analysis was accompanied by a minimal change

in lineal abundance along associated upper reaches and along the relatively free-flowing Belly River. Three years later, the consultants Reid et al. (1992) performed the first 2D areal analysis for the southern tributaries along with another lineal abundance analysis. Total forested area between 1951 and 1990, the lower St. Mary River exhibited a 40% decrease, while the lower Belly and Waterton Rivers increased by 21.2% and 2.6%, respectively, while upper reaches changed minimally. Also, lineal cottonwood abundance results similar and progressive to the initial 1989 paper indicated a continued decline. Following from this study, Rood et al. (1995) published an extended analysis utilizing the 1992 report with results coinciding with a continued trend of a 68% decrease in lineal forest population along the St. Mary River. Increasing trends persisted on the Belly River, while the Waterton River population appeared to have stabilized without substantial changes.

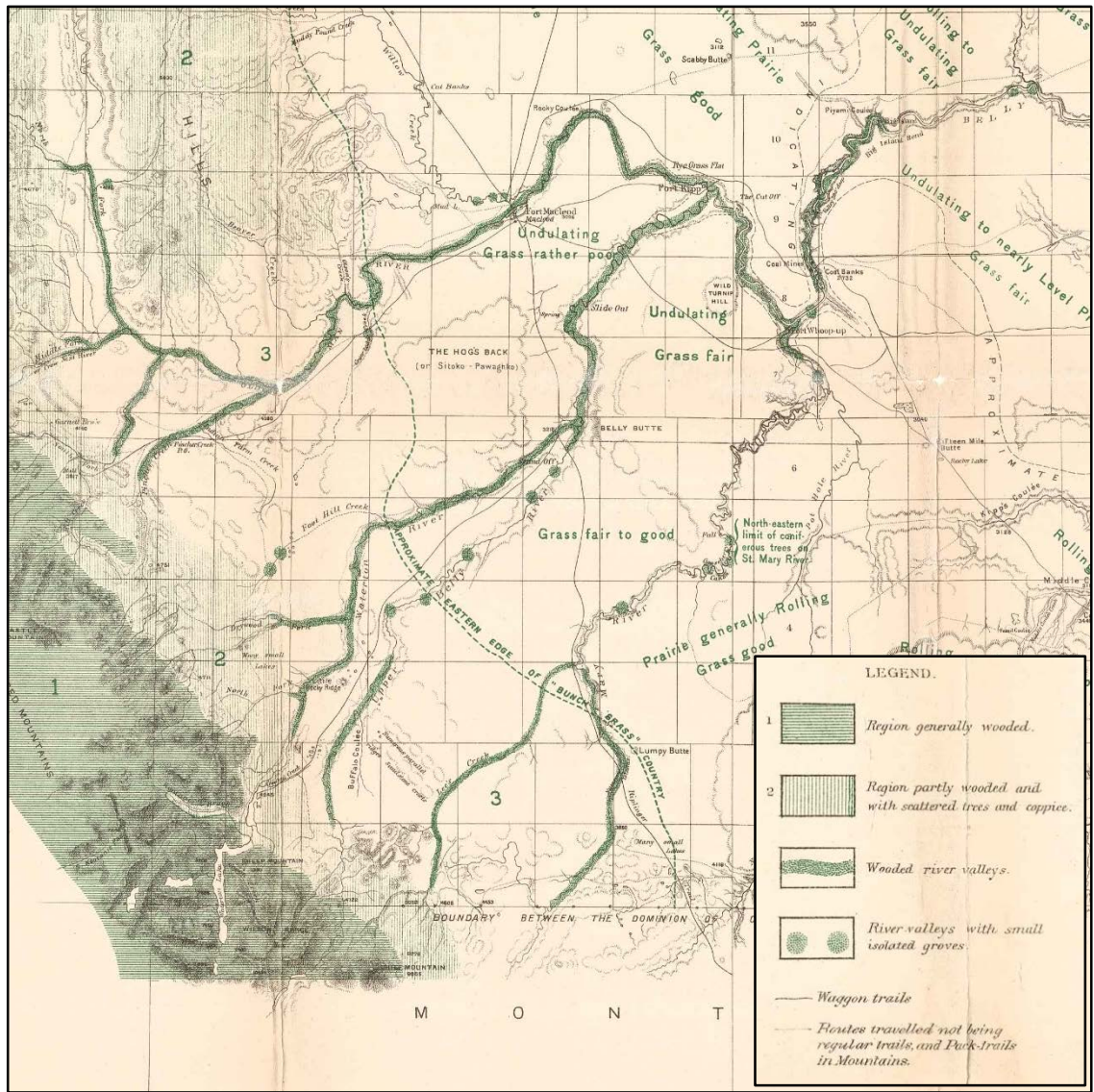


Figure 1-3: George Dawson's map showing wooded and prairie tracts in the region and vicinity of the Bow and Belly Rivers. This map was created in 1881 for the purposes of displaying the natural resources along the 49th parallel (Dawson and McConnell, 1884).

Table 1-1: Previous studies summary: Changes to percent cottonwood abundance along the southern tributaries of the Oldman River. Standard error for lineal distance and area measurements is approximately $< \pm 5\%$ and $\pm 20\%$, respectively. Bolded values were indicated as highly significant changes (from Clipperton et al., 2003).

Authors	Technique	Years	upstream reaches			downstream reaches		
			Belly	Waterton	St. Mary	Belly	Waterton	St. Mary
Rood & Heinze-Milne, 1989	Lineal distance	1961-1981	-4.6	-6.1	-4.7	-0.1	-22.9	-47.8
Reid et al., 1992	Lineal distance	1951-1985	-7.4	-5.8	-7.2	+0.4	-9.0	-73.7
	Lineal distance	1961-1981	-4.5	-8.0	-7.1	-0.9	-20.4	-45.4
	2D area	1951-1990	-13.1	+4.7	-4.8	+21.2	+2.6	-40.0
Rood et al., 1995	2D area	1951-1985	-9.1	+1.9	-0.5	+52.2	+3.5	-61
	Lineal distance	1951-1985	-9.0	-68

1.7 Environmental Flow Regime

Water management strategies have been utilized since mid-1970s to provide water requirements of downstream ecology. Beginning with a focus on the instream flow requirements for sport fish, there have been many studies aimed at supporting downstream riparian ecology including cottonwood forests (Tennant, 1976). Many of these strategies have recognized the importance of flooding and avoidance of minimal flows (Junk et al., 1989; Clipperton et al., 2003; Braatne et al., 2007).

Efforts to minimize cottonwood mortality began in 1991 with the implementation of instream flows with the Water Allocation Regulation addition to the '*Water Resources Act*' in the ORB with the Alberta Government addressing issues of reduced stream flow by legislating the Water Act in 1991 (section 7(2), Alb.Reg. 307/91). This act legislated a minimum flow criterion to be set for each of the southern tributaries. In the case of the regulated southern tributaries, this generally more than doubled the minimum flow allowances (Rood et al., 1995; Rood et al., 1998).

Laboratory experiments were carried out to understand a cottonwood's preferential water table dynamics in the falling limb of the hydrograph. Using rhizopods (plant growth tubes with a controllable water level supply), the response of water table decline on cottonwood growth was characterised (Mahoney and Rood, 1991). Whereas no decline in water table levels supported the greatest growth, rates greater than 4 cm/day produced decreased growth and survival ability. Subsequent studies looked at the influence of substrate size, differing *Populus* and other riparian species responses, and

clonal reactions (Mahoney and Rood, 1992; Kranjcec et al., 1998; Amlin and Rood, 2002).

The conclusions from these experiments formulated what is known as the Recruitment Box Model (RBM; Figure 1-4). This integrative model outlines the hydrologic conditions of when to implement ‘ramping flows’, a gradual stage decline designed to support cottonwood seedling establishment (Mahoney and Rood, 1998). The ‘box’ within this model is delimited by physical and biological constraints. Cottonwoods that establish at too low of an elevation are susceptible to ice and flood scour in subsequent years, while ones established at too high of an elevation may succumb to drought mortality. This recruitment elevation creates a band along gravel bars that may support cottonwood establishment. Biological constraints include the timing of initial seed release and the duration of seed viability that complete the ‘box’ by outlining the preferential timing for ramping flows to commence. For the Waterton River, seed release has been documented to occur mid-June until mid-July (Reid et al., 1992). The rate of stage decline that allows for acceptable levels of seedling mortality has been considered to be between 2.5 - 5 cm/day initiating when flow levels descend through the ‘box’ (Mahoney and Rood, 1993; Mahoney and Rood, 1998). This gradual decline of the falling limb allows the roots of newly established seedlings to remain in contact with the receding groundwater. This prevents the seedlings from desiccating and allows them to mature and harden into more formidable saplings.

Ramping flows were adopted within the ORB in 1993 and the successful implementation was first documented along the Oldman River by Rood et al. (1998). After the flood of the century along the Oldman River and the intentional gradual decline

of river stage, numerous cottonwood seedlings were established and many were documented to survive sequential years. Further, the ramping flows along with the implementation of the increasing minimum flow allowances were shown to be a successful management strategy along the final segment of the severely impacted lower St. Mary River (Rood and Mahoney, 2000).

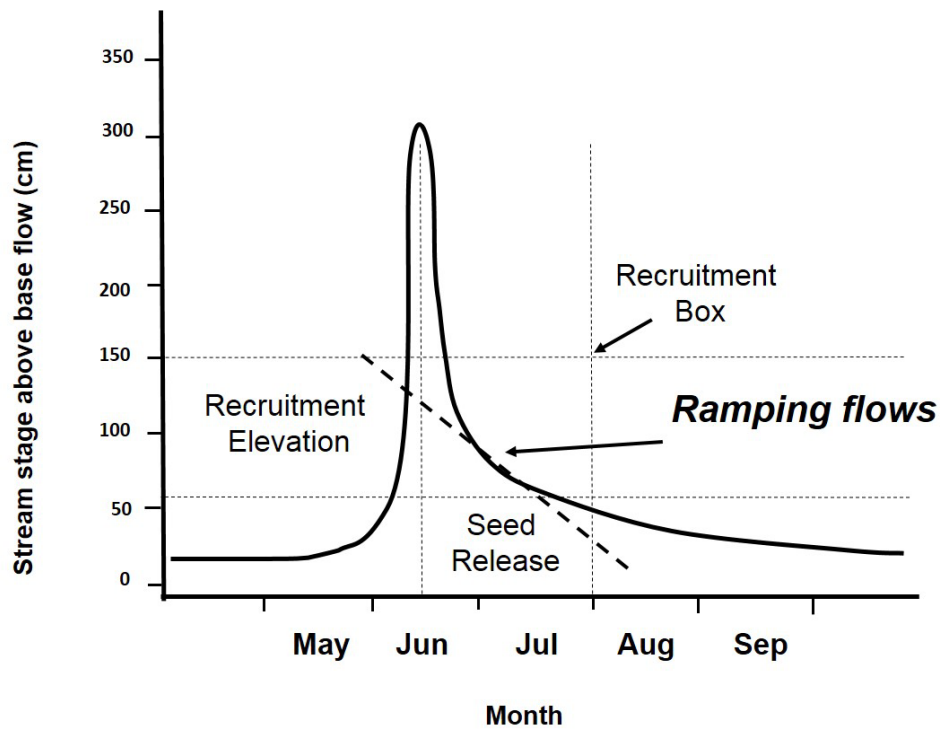


Figure 1-4: The Recruitment Box Model (RBM). This integrative model outlines the preferential elevation and time to implement ‘ramping flows’, which is a gradual stage decline rate, about 2.5 – 5 cm/day, designed to maintain water contact with seedling roots as they mature.

1.8 Focus on the Waterton River

The object of this thesis is to determine if the changes in river management since 1991 (minimum flow criterion) and 1993 (ramping flows) have benefited the health of downstream cottonwoods along the Waterton River. The river has now been dammed for half a century and new management strategies have been in utilized for two decades. Therefore, a substantial amount of time has elapsed allowing for a critical assessment of the management practices used in cottonwood stewardship.

The second and third chapters are presented as main research chapters. The second chapter encompasses a comprehensive aerial photograph analysis that tracks the forest population nearly every decade beginning in 1950. The results of the population dynamics are then related to the historical hydrology to determine how the dam management may have influenced the observed forest conditions. The third chapter details field research taken in the summer of 2014, where a cottonwood inventory along transects established both upstream and downstream reaches are compared to determine if the dam management strategies have influenced sapling health and growth.

The final chapter of this thesis provides general conclusions and suggestions to the research chapters. This research will increase our understanding of the management strategies employed in the Oldman River Basin that are designed to meet the needs of the riparian ecology while still supplying the demands of irrigation. The conclusions may be applied to other rivers that have experienced similar artificial stresses with confidence that they too may experience sustained ecological health as managers continue to strive for the least detrimental dam operations.

CHAPTER TWO: River Regulation and Riparian Woodlands: Cottonwood

Conservation with an Environmental Flow Regime along the Waterton River, Alberta

2.1 Summary

Following river regulation, riparian cottonwood forests have declined downstream from some dams in semi-arid regions of western North America. Prior aerial photographs and field observations in the 1980s suggested that the black and narrowleaf cottonwoods (*Populus trichocarpa* and *P. angustifolia*) along the Waterton River, Alberta were declining due to drought stress following the 1964 river damming. This raised concern for the riverine ecosystems and in 1991 the legislated minimum instream flow was more than doubled. Subsequently, to encourage cottonwood recruitment, flow ramping was also implemented, whereby flows are gradually reduced after the spring peak. These two changes provided the Environmental Flow regime that has generally been delivered to the downstream reach for two decades. In this study, the consequences of the Environmental Flows were investigated and the relationship between the river flow regime and the condition of riparian woodlands. Aerial photographs were analysed in five series from 1951 to 2009 and compared four flow management intervals: (1) the free-flowing Pre-Dam condition up to 1963; (2) the initial Dammed interval from 1964 to the mid-1970s; (3) a prolonged Drought interval that was corresponded with a negative phase of the Pacific Decadal Oscillation in the late 1970s through the 1980s; and (4) the Environmental Flow regime after 1991. These analyses revealed the decline of mature, closed canopy woodlands during the interval from 1961 to 1985 and this involved loss through bank erosion associated with major floods in 1964 and 1975. Further decline during the subsequent Drought interval, which was exacerbated by water withdrawal for

irrigation. Following the implementation of the Environmental Flows the woodland areas were relatively consistent, even though a major flood occurred in 1995 and drought conditions occurred in 2000 and 2001. These results demonstrate the responses of riparian cottonwoods to the river flow patterns, and the benefit from the Environmental Flow regime that apparently enabled woodland survival and replenishment while also allowing water withdrawal for irrigation agriculture.

2.2 Introduction

Cottonwoods, river valley poplars, provide an important environmental contribution to the landscape in western North America, and around the Northern Hemisphere. They are ecological pioneer species that colonize newly disturbed sites and line river valleys creating rich and biodiverse woodland corridors (gallery forests) in otherwise treeless prairie and shrub steppe ecoregions (Brayshaw, 1965; Scott et al., 1996, Rood et al., 2003a). Growing to sizeable heights, cottonwoods create an important habitat for birds, mammals, and invertebrate biodiversity (Swift et al., 1984; Knopf et al., 1988; Whitham et al., 1999). In addition to sustaining wildlife, cottonwood forests intercept surface and groundwater contaminants and consequently contribute to river water quality, provide litter and shade that benefit the aquatic food web and fish, provide parental genotypes for fast growing hybrid poplars, and provide valued aesthetic and recreation areas for human use (Peterjohn and Correll, 1984; Heilman et al., 1972; Jackson et al., 2001). Cottonwoods can be considered keystone species as they provide the foundation for the riparian woodlands and for the associated environmental attributes and services (Braatne et al., 1996; Ward et al., 1999). Consequently, the conservation and restoration of these riparian forests is of great importance.

In the Great Plains of western North America, riparian woodlands have sometimes declined or even collapsed following river regulation (Rood and Mahoney, 1990; Braatne et al., 1996). The naturally occurring cottonwoods within this semi-arid region are phreatophytic, with relatively deep roots to access the alluvial groundwater, since these dry ecoregions experience limited rainfall (Rood et al., 2011). The streams within these watersheds are often 'losing streams' as the floodplain groundwater is recharged from the adjacent river and the alluvial water table level is approximately equal to the stage (level) of the adjacent stream (Rood et al., 1995; Harner and Stanford, 2003). Cottonwoods acquire their water supply from the semi-saturated capillary fringe above this water table and insufficient water supply has been linked to stomata closure, growth cessation, xylem cavitation, and branch and crown dieback (Tyree, 1994; Sparks and Black, 1999). Thus, when river flows are low and the water table declines, insufficient water is available and the health of riparian cottonwoods suffers (Mahoney and Rood, 1992; Amlin and Rood, 2002).

The Waterton River is one of three southern tributaries that flow within the Oldman River Basin (ORB) along with the Belly River and the St. Mary River (Figure 1-1 in Chapter 1). These rivers originate in the Rocky Mountains of the Waterton-Glacier International Park and flow northeast, parallel to each other, through the montane and foothill ecoregions to the prairies, where cottonwoods provide the only native riparian trees. The Waterton and St. Mary Rivers were dammed in 1964 and 1951, respectively, and the Belly River has a weir, or low head dam, established in 1935 and is less extensively regulated. A canal system has been constructed from the Waterton Reservoir eastward to the Belly River upstream from the diversion weir. Water is then routed from

the Belly River weir into the St. Mary Reservoir where the stored water is then distributed throughout the St. Mary River irrigation districts that constitute the largest irrigation complex in Canada (SMRID, 2012). Due to this progressive water diversion and withdrawal, the cottonwoods along all three southern tributaries of the Oldman River have been affected by low flow intervals (Rood and Heinze-Milne, 1989; Rood et al., 1995; Rood and Mahoney, 2000).

The first reporting of the riparian forests in southern Alberta is displayed with Dawson and McConnell's (1884) natural resource map showing that the entire length of the Waterton River contained abundant riparian forests, whereas sparse forests occurred along the St. Mary and Belly rivers (Figure 1-3). Rood and Heinze-Milne, (1989) analysed aerial photographs from 1961 and 1981 and reported decline in cottonwood lineal abundance downstream of the St. Mary Dam (-48%), and apparently more moderate decline downstream from the Waterton Dam (-23%). Declines were not apparent along the free-flowing river reaches upstream of those two dams, or along the less regulated Belly River. To further quantify cottonwood populations, Rood et al. (1995) delineated the areal extents of cottonwoods along the St. Mary, Waterton, and Belly Rivers and reported a progressive decline in cottonwood abundance along the St. Mary River between 1951 and 1985 (-61%). This was in contrast to slight change in the cottonwood population along the downstream Waterton River (+3.5%) and a substantial increase in area along the downstream Belly River (+52%). This allowed for some comparison of different river flow regulation and the impacts on cottonwood forests. Analyses of the regulated flows also suggested challenges for the riparian cottonwoods,

encouraging future riparian monitoring as well as possible changes to instream flow regulation (Rood et al., 1995).

For the latter part of the twentieth century, dam managers operated the southern Alberta reservoirs to maximize water supplies for irrigation and this altered components of the river flow regime that are required for riparian woodland health. Previous studies indicated that river damming and water diversion altered two flow components that probably contributed to the cottonwood mortality: (1) insufficient late summer instream flows that did not satisfy the water requirements of new or established cottonwoods and (2) abrupt stage declines following the spring peak that cause newly recruited seedlings to lose root contact with the receding groundwater (Rood et al., 1995; Mahoney and Rood, 1998). In association with implementation of the Oldman River Dam in the early 1990s, water managers altered operational regimes for the established Waterton and St. Mary dams. These were intended to conserve or restore the riparian woodlands while continuing to supply the irrigation water from the storage reservoirs.

The first of these changes began in 1991 with the implementation of instream flows with the Water Allocation Regulation addition to the '*Water Resources Act*' legislation (section 7(2), Alb. Reg. 307/91). This increased the mandatory minimum instream flows released downstream of the Waterton and St. Mary Dams and the Belly weir. This provided more than a doubling increase from the prior low flow minimum and was intended to improve downstream water abundance and quality, and thus benefit the aquatic and riparian ecosystems.

After 1993, 'flow ramping' was implemented and this involved the regulated gradual recession of river stage (level) after natural floods. This was intended to enable survival of newly established cottonwood seedlings. This strategy applied the Recruitment Box Model that defines flow patterns to replenish cottonwood cohorts to replace the natural age related mortality within the population (Mahoney and Rood, 1998). This model outlines both the timing that ramping should commence, concurrent with cottonwood seed release, and the elevational band through which ramping should occur. This enables seedling colonization high enough to avoid subsequent ice or flow scour, and low enough to avoid drought induced mortality.

Although this flow management strategy has proven successful in recruiting cottonwood seedlings along the Oldman River (Rood et al., 1998) and the final segment of the St. Mary River (Rood and Mahoney, 2000), the extent and duration of regulation differs across the rivers in the ORB. Flow ramping was implemented along the Oldman River nearly immediately after its dam was completed in contrast to the St. Mary River which experienced almost a century of flow alteration before ramping was implemented. The Waterton River represents an intermediate case, with about three decades of regulation before improved dam management was implemented. The combination of maintaining minimum flows and ramping flood flows provides an Environmental Flow regime to the rivers which is currently delivered throughout the ORB. With varying degrees of regulation, comparison across these rivers allows for observation to determine if the Environmental Flow regimes have benefited the riparian ecosystems.

This study extends from research in the 1980s and 1990s when the forests along the Waterton River were directly observed with field trips, river floats, and low level

flights that were intended to complement analyses of aerial photographs and the hydrological records (Rood and Heizne-Milne, 1989; Rood et al., 1995). The present study was intended to determine the conditions and changes of the gallery forest along the Waterton River through intervals with differing patterns of river flows. It has now been half a century since the Waterton River was dammed, and about two decades after the initial analysis of the riparian cottonwoods. The primary expectation of this study was that the changes in dam management to implement the increased minimum flows and deliver flow ramping after spring peaks would benefit the cottonwood population along the Waterton River, similar to the benefits observed along the Oldman River and final reach of the St. Mary River (Rood et al., 1998; Rood and Mahoney, 2000). The findings from this study should contribute to identifying crucial flow regime characteristics and validate management strategies for cottonwood conservation.

2.3 Methods

2.3.1 Study Area

The Waterton River is an alluvial stream with channel bed and banks dominated by gravels and cobble. The river water originates from the snow melt and rain within the Lewis Range of the central Rocky Mountains straddling the Canada – United States border (Figure 2-1). From the headwaters, the river flows through a sequence of large lakes within the Waterton Lakes National Park before flowing 100 km to the confluence with the Belly River. The free-flowing river from the Waterton Lakes outflow to the Waterton Reservoir provides the ‘upstream reach’ that extends 32 km and flows northeast through a transition from foothills to the fescue prairie (Samuelson and Rood, 2004;

Samuelson and Rood, 2011). Most of the upstream reach is in a narrow valley where riparian woodlands are confined to narrow bands along the river. This upstream reach only has a few meander lobes with forested floodplains until approximately 5.5 km before the confluence with the Waterton Reservoir. There the valley broadens and the floodplain supports more abundant cottonwoods. The river flows into the Waterton Reservoir which is approximately 8 km long and impounds both the Waterton River and Drywood Creek (Figure 2-1). Drywood Creek contributes about 22% of the mean annual discharge below the reservoir and more substantially to floods, contributing about 30% of the 1995 peak downstream of the Waterton Dam. The 'downstream reach' flows for 60 km from the Waterton Dam to the confluence with the Belly River near Standoff. The downstream reach generally displays broad forested floodplains except for two short and narrow canyons, 4.5 and 7.5 km downstream from the dam.

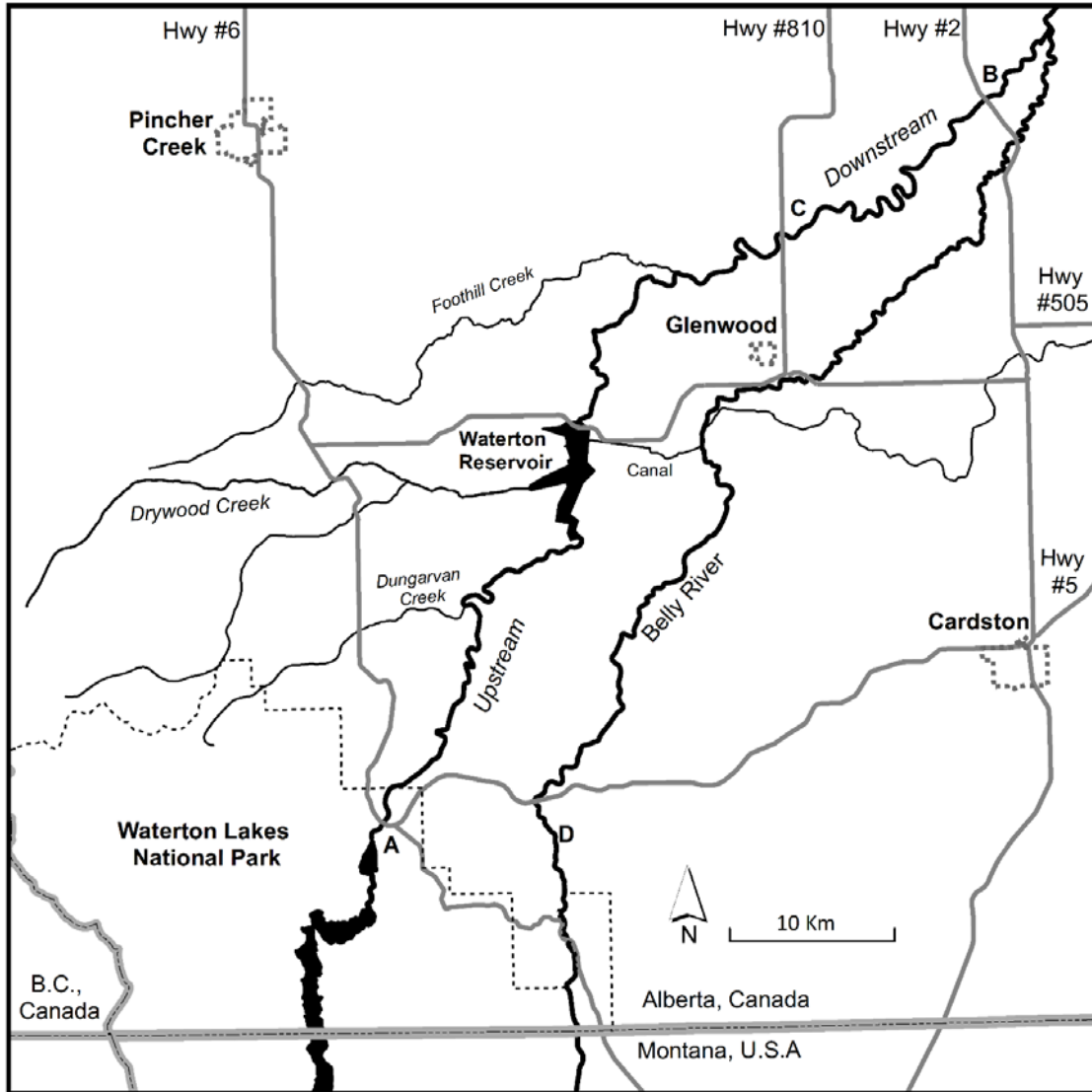


Figure 2-1: The Waterton River watershed along with the Belly River and major tributaries. Gauging station locations are as follows: (A) Waterton River near Waterton Park, (B) Waterton River near Standoff, (C) Waterton River near Glenwood, and (D) Belly River near Mountain View.

2.3.2 Historic Hydrology

The Waterton River's mean daily discharge data were accessed from the Water Survey of Canada's HYDAT archived hydrometric records (Table 2-1). Data from the ice-free months of March to October, were analysed as mean daily, mean monthly, maximum mean daily, and mean growth season discharge (May to October). Four dam management intervals were identified as: '*Pre-Dam*' (before 1963), *Dammed* (1964 to 1976), dammed and *Drought* (1977 to 1990) and *Environmental Flows* (1991 to 2012).

A 104-year hydrometric time series was developed utilizing four gauging stations (Table 2-1). The station near Waterton Park (05AD003) is located immediately downstream from the final of the Waterton lakes. It provides the earliest discharge dataset for the Waterton River, commencing seasonally in 1908 (no winter values) and this expanded to provide continuous records from 1912, with a data gap from about 1931 to 1947. To interpolate for this data gap, a regression was undertaken with this gauge and adjacent free-flowing Belly River near Mountain View (05AD005). Linear regressions yielded high correspondences for mean daily discharge ($r^2 = 0.920$), maximum daily discharge ($r^2 = 0.871$), mean monthly discharge ($r^2 = 0.965$) and mean growth season discharge from May to October ($r^2 = 0.921$).

Downstream from the Waterton Reservoir, two hydrometric records were combined to provide an extended time series. The station near Standoff (05AD008) began recording seasonal data in 1916, lapsed between 1931 and 1934, and continued recording until 1966. To replace the Standoff station, a new station was established in 1966 near Glenwood (05AD028) that provides a current and continuous flow recording. The

Standoff and Glenwood stations are located near the downstream side of the Hwy #2 and #810 bridges, respectively. The Standoff and Glenwood gauging stations have a slight difference in drainage area and no inflowing tributaries between the stations. The brief period of overlap between these two stations in 1966 provided a high degree of correspondence ($y = 1.221x - 1.448$; $r^2 = 0.978$), and therefore the river discharges of these two stations were directly combined. To fill the short data gap in the early 1930s and to extend the time series to the 1908 upstream reach record, regressions were undertaken between the pre dammed Standoff station and the extended upstream reach time series. Close correspondences between mean daily discharge ($r^2=0.896$), maximum daily discharge ($r^2=0.656$), mean monthly discharge ($r^2 = 0.956$) and mean growth season discharge ($r^2=0.861$) were used for data infilling. Continuous daily discharge data were also considered for the Waterton – Belly canal gauge (05AD027) that commenced in 1968 and represent withdrawal from the Waterton Reservoir.

To investigate climatic effects on the Waterton River, mean precipitation (April to Sept.) from the Waterton Park Gate, Alberta (Climate ID 3056214) and from Lethbridge, Alberta weather station (Climate ID 3033890) were assessed using Environment Canada's historical climate data reports (1908 – 1960) and Alberta Agriculture and Forestry's AgroClimatic Information Service Data Viewer (1961 – 2013). Also, the upstream reach mean growth season streamflow was compared with the Pacific Decadal Oscillation (PDO) index with inversion that provides similar change directions. The PDO index data were acquired from the University of Washington (<http://jisao.washington.edu/pdo/PDO.latest>) and averaged by year.

The 1991 *Water Allocation Regulation* legislated a minimum instream flow criterion of 2.27 m³/s for the Waterton River at the mouth. To investigate compliance, the number of days with discharge below 2.27 m³/s was tabulated for the period of May to October for both the upstream and downstream reaches. Since there is no instream minimum flow criterion set for the free-flowing upstream reach, base flows were determined as the typical low flow for ice-free periods for the upstream (4.56 m³/s) and downstream (6.78 m³/s) reaches and the occurrences of flows below these were analyzed.

Climate and hydrological analyses were processed using SPSS 21 (IBM Corp., Somers, NY, USA, 2010). Pearson product correlations (r) and coefficients of determination (r^2) were used to determine the correspondence between 5-year moving averages of the time series for: 1) mean precipitation (April – Sept.) at Lethbridge; 2) the PDO index, and 3) the mean growth season (May – Oct.) streamflow for the free-flowing upstream reach.

Flood frequency recurrences for the annual maximum mean daily discharge (Q_{max}) were determined using the Weibull Distribution formula:

$$T = (n + 1) / m$$

where T is the return interval in years, n is the total number of years considered, and m is the order of flow events beginning with the largest event as 1. These were plotted with a logarithmic (base 10) scale and displayed a two component function (Rood et al., 1995), with moderate flow peaks of up to 20-year recurrence displaying a linear response and then an abrupt upturn to provide a steeper linear pattern for the extreme floods.

Table 2-1: Gauging station attributes for the Waterton River and adjacent Belly River. All data was recorded continuously throughout the year except for where indicated.

Station Name/ ID#	Drainage Area (km ²)	Years Available
Waterton River near Waterton Park (05AD003)	612	1908 - 1911*, 1912 - 1930, 1948 - 2012
Waterton River near Standoff (05AD008)	1730	1916 - 1930*, 1935 - 1947*, 1948 - 1966
Waterton River near Glenwood (05AD028)	1631	1966 - 2012
Belly River near Mountain View (05AD026)	319	1911 - 2012
Waterton - Belly Diversion Canal (05AD027)	n/a	1968 - 2012

* Indicates a variable seasonal data record

2.3.3 Analyses of Riparian Woodlands

The riparian forest along the Waterton River contains two *Populus* section *Tacamahaca* species with the black cottonwood, *P. trichocarpa* Torr. & Gray ex Hook, and the narrowleaf cottonwood, *P. angustifolia* James, and hybrid intermediates (Berg et al., 2007; Floate, 2004). Stereoscopic pairs of aerial photography of the Waterton River for 1951, 1961, 1985, 1999, and 2009 were acquired from the Alberta Air Photo Distribution of Alberta Environment and Parks (Edmonton, AB) and analysed to compare changes in woodland populations in sequential years (Table 2-2). This provided a sampling of two photograph series in the Pre-Dam interval, one in the Dammed/pre-Drought interval, one shortly after the Drought, and the final series after 18 years of Environmental Flow operations.

All images were corrected for scale distortions by georectification using orthorectified photographs that were imported in ArcMap 10 (ESRI, 2010) for forest digitization. A minimum of ten control points were spread relatively evenly around the scene and this produced an overall root mean square error of less than 5 m after quadratic transformations (flat terrain and uncorrected 9-inch aerial photography; Bolstad and Smith, 1992). Images were then cropped with a footprint of 15% to reduce interpretation of inherent photographic distortion errors and were then mosaicked together for each series.

The entire Waterton River was divided into approximately four km long segments varying slightly in length to account for geomorphic, vegetation, and human development features. In total, seven segments were established upstream while fourteen segments were established downstream. The segments along the upstream reach extended from the Waterton Lakes National Park border until just before the Waterton Reservoir (Range Road 282A Bridge). The downstream reach segments began slightly downstream from the Waterton Dam spillway and ended at the confluence with the Belly River. Apparent cottonwood forests were digitized in ArcMap usually at a scale of 1:5,000 while aerial photographs were viewed stereoscopically with up to 3x magnification. Density classifications were attributed to the woodland polygons and areas were compared across segments and between reaches. Originally, a 6 category classification was utilized, but this was condensed to produce 3 categories (Appendix A-1 and A-2). The analyses of aerial photographs yielded substantial portions of cottonwood forests being removed through river channel movements and erosion as well as with artificial floodplain clearing and developments, which was also tabulated. The entire forests along the Waterton River

were digitized for density analyses rather than a sampling system that would be followed by inferential statistics for the population. Following digitization, each classification was weighted by multiplying the apparent cottonwood area as follows: sparse canopies by 2, open canopies by 3, and closed canopies by 4. This provided a simplified forest area index, from which changes in cottonwood forest between the photographed years could then be calculated.

Table 2-2: Aerial photography acquisition details. The majority of photos in the first two series were taken in 1951 and 1961, respectively and will be used to label their entire series. Laser copier prints (LP) were primarily used, but occasionally contact prints (CP) were used when available. These were greyscale photographs except for true colour in 2009.

Year	Scale	Copy
1950, '51, '52	1:40,000	LP/CP
1961, '62	1:31,680	LP
1985	1:30,000	LP/CP
1999	1:30,000	LP/CP
2009	1:30,000	LP

2.4 Results

2.4.1 Free-flowing Upstream Reach

The growth season discharge along the upstream reach of the Waterton River has been variable with substantial intervals below the averaged Pre-Dam flow (Figure 2-2). A 15-year drought occurred throughout the 1930s and another began in the late 1970s that currently persists despite some short periods near the beginning of the new century achieving the approximate average. The precipitation time series for the Waterton Park Gate station was only available from 1961, and therefore precipitation trends utilized data from the nearby Lethbridge station that contained a more complete data set. The upstream reach growth season discharge was substantially variable when considering the precipitation observed at Lethbridge, but a significant trend was suggested ($n = 102$, $r^2 = 0.082$, $p = 0.004$; Figure 2-2). The mean precipitation in Lethbridge did not correspond with the changes in the PDO ($n = 102$, $r^2 = 0.007$, $p = 0.418$). The dynamics in upstream reach discharge significantly corresponded to the PDO phases ($n = 101$, $r^2 = 0.522$, $p < 0.001$).

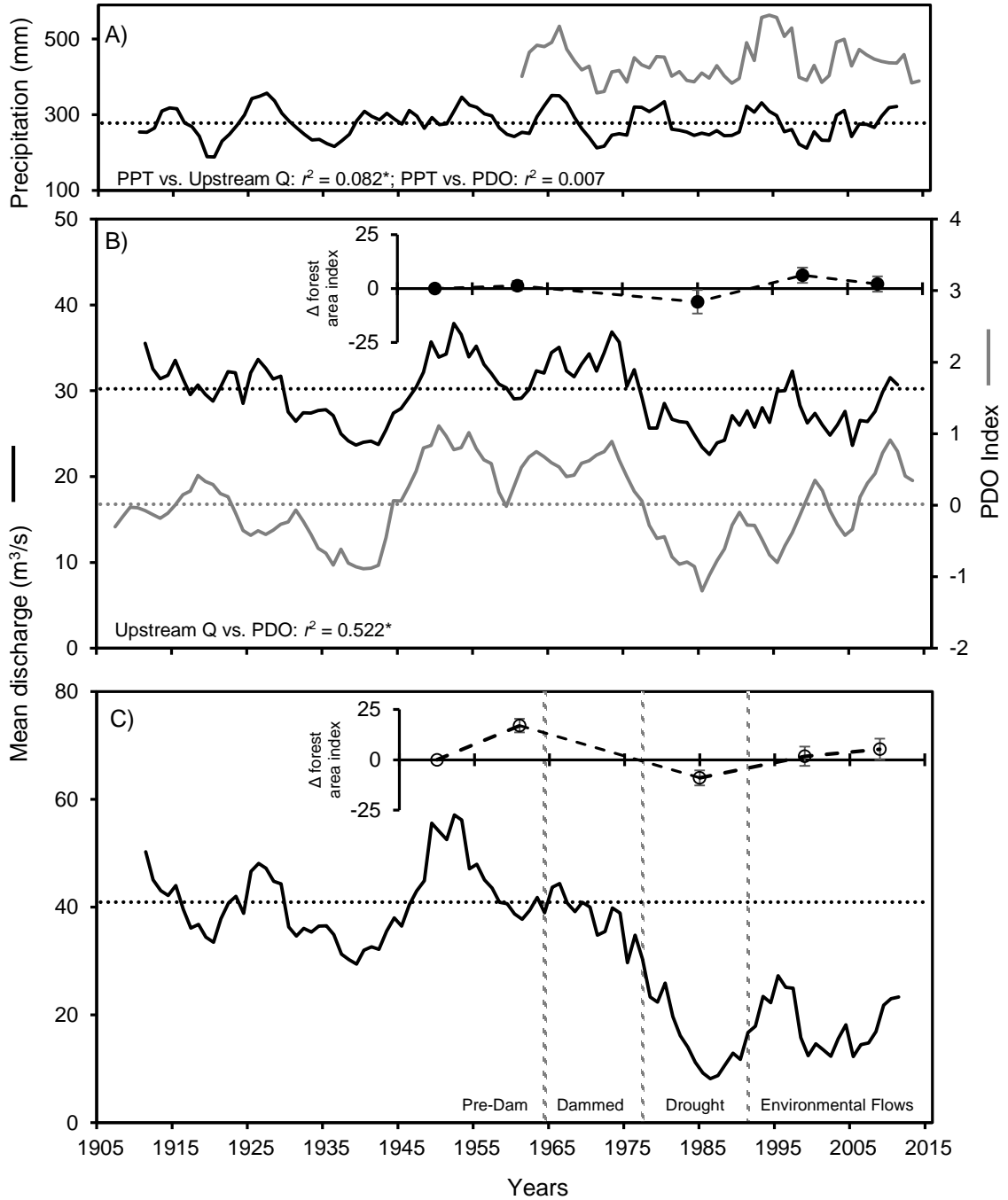


Figure 2-2: Climatic and hydrologic data for the Waterton River along with cottonwood area dynamics. Data are presented as 5-year moving averages. Horizontal dotted line represents pre-1963 averages. Discharge data are mean annual growth season (May to Oct.). A): Total precipitation (PPT; April to Sept.) for Lethbridge, and Waterton Park Gate, Alberta, are black and grey lines, respectively. B): The relationship of the upstream Waterton River and the PDO. C): The downstream Waterton River with the 4 dam management intervals (vertical dashed lines). Statistically significance (*) at 0.01. Inset figures show change in forest area index between each aerial photograph year for upstream and downstream reaches.

2.4.2 Regulated Downstream Reach

As the upstream reach is the principle supplier of discharge for the downstream reach, the downstream hydrometric time series up to 1963 resembles the natural dynamics of the upstream reach (Figure 2-2). Once the dam was implemented in 1964, obvious decoupling of the upstream and downstream relationship occurred as the drought periods within the dammed intervals were exacerbated due to water withdrawal for irrigation along the downstream reach. Compared to the Pre-Dam interval, mean growth season discharge along the upstream Waterton River only slightly declined during the Drought and Environmental Flow intervals. In contrast, the downstream reach experienced an increase in water withdrawal during the onset of the droughts and high demand for irrigation agriculture (Figure 2-3). The average growth season discharge of the downstream Waterton River had decreased by -64% during the Drought interval as compared to Pre-Dam conditions. When Environmental Flows were implemented, flows increased by +18% from the Drought interval, but still remained -58% below Pre-Dam conditions. The marginal improvement of the Environmental Flows mean discharge is reflected in the steady withdrawal rates of the diversion canal (Figure 2-3). The needs of irrigation do not appear to have been affected by the implementation of increased minimum flows and ramping flows. Annual canal discharge has remained at similar seasonal and maximum discharges to pre-Environmental Flow periods (Figure 2-3).

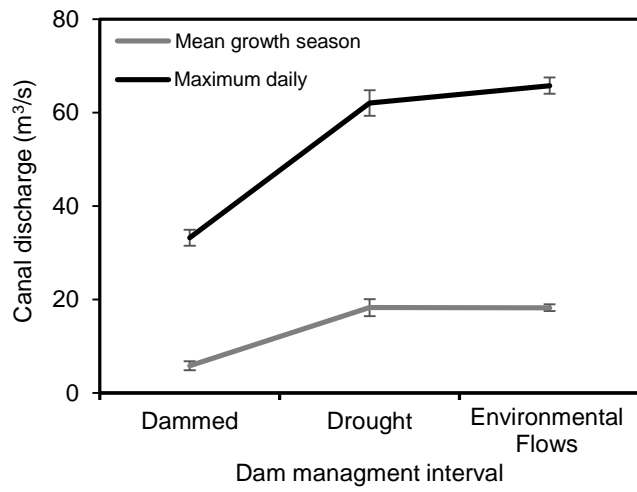


Figure 2-3: Average discharge through the Waterton – Belly canal during the growth season (May to October). Bars represent \pm standard error.

2.4.3 Monthly Flow Patterns

Flows along the Waterton River before the Drought interval were relatively consistent for both upstream and downstream reaches except for an increase in mean flows for June (Figure 2-4). With the onset of the Drought interval, mean monthly flows declined in all months along both reaches of the Waterton River. These differences were amplified along the downstream reach in coordination with increased irrigation demand, especially in the late summer months. After Environmental Flows were implemented, with the exception of mean May discharge, flows substantially increased along the Waterton River.

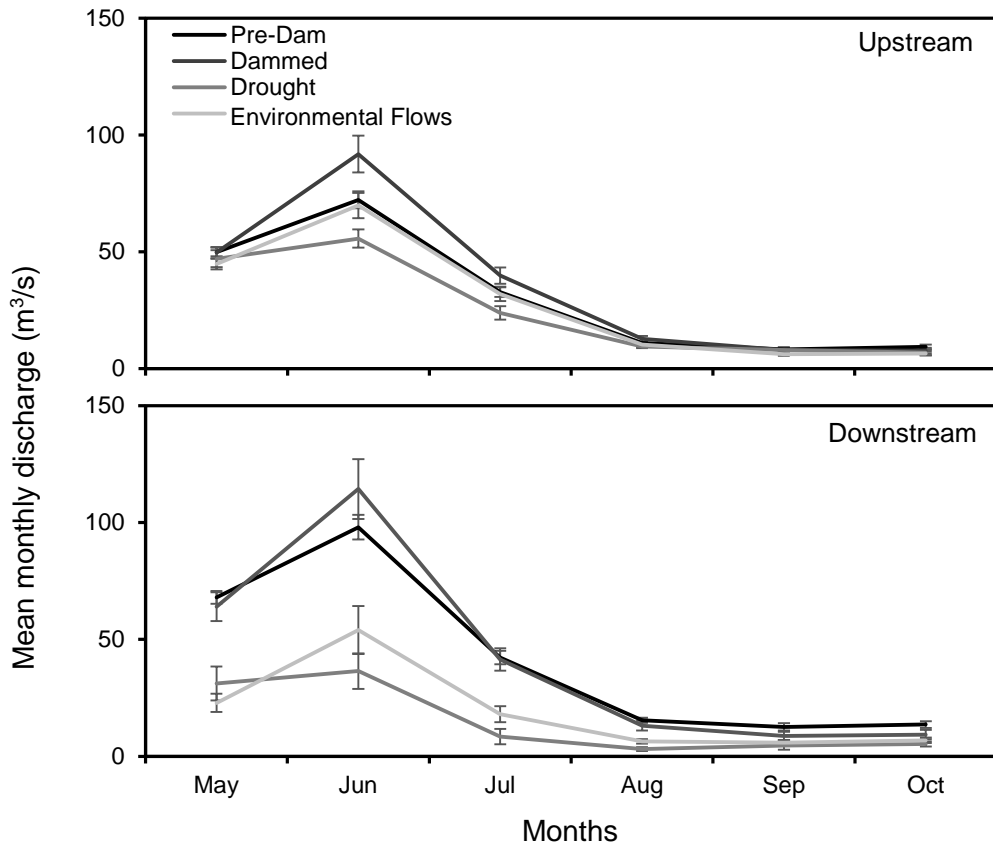


Figure 2-4: Mean monthly (growth season) discharges for the Waterton River. Bars represent \pm standard error.

2.4.4 Minimum Flows

The number of days below the minimum flow criterion and the number of days below base flow were marginal before the 1977 drought (Figure 2-5). During the Drought interval, the downstream reach experienced an average of more than half of the growth season below both the low flow limits while no substantial exceedance was experienced upstream. After Environmental Flows were implemented, the excessive low flows along the downstream reach returned to Pre-Dam conditions although flows were probably maintained just above the minimum criterion as there were still a substantial number of days below base flow (Figure 2-5). It is possible that even in years that experienced substantial high flows, the remaining summer months may be held at excessively low flow as water is stored and diverted following the peak flow event.

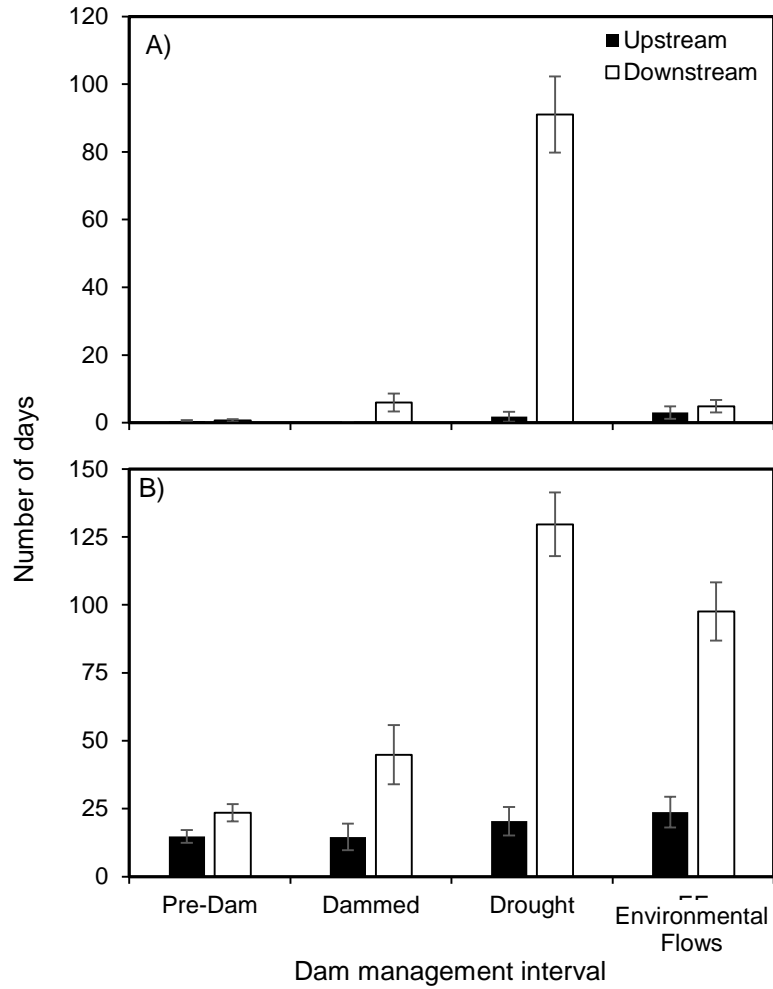


Figure 2-5: The mean number of days during the growth season (May to October) below the (A) minimum flow criterion ($2.27 \text{ m}^3/\text{s}$) and (B) base flow (4.56 and $6.78 \text{ m}^3/\text{s}$ for upstream and downstream reach, respectively). Bars represent \pm standard error.

2.4.5 Maximum Flows

The Weibull Distribution clearly displays a two-component function for return internals on both reaches (Figure 2-6). General flooding events are predictable and occur often and at high magnitudes while large substantial floods occur with very high magnitudes and occur more often than what would be predicted using the trend produced from the more common general flooding events. Major floods (>20 year recurrence) occurred in 1964, 1975, and 1995 for both upstream and downstream reaches (Figure 2-7). The magnitude of the major flood flows were substantially larger along the downstream reach than the upstream with the exception of the flood in 1964 when magnitudes were larger upstream. The flood of 1975 and 1995 achieved the third and second largest floods on record, but only the 1995 flood occurred when Environmental Flows had been implemented.

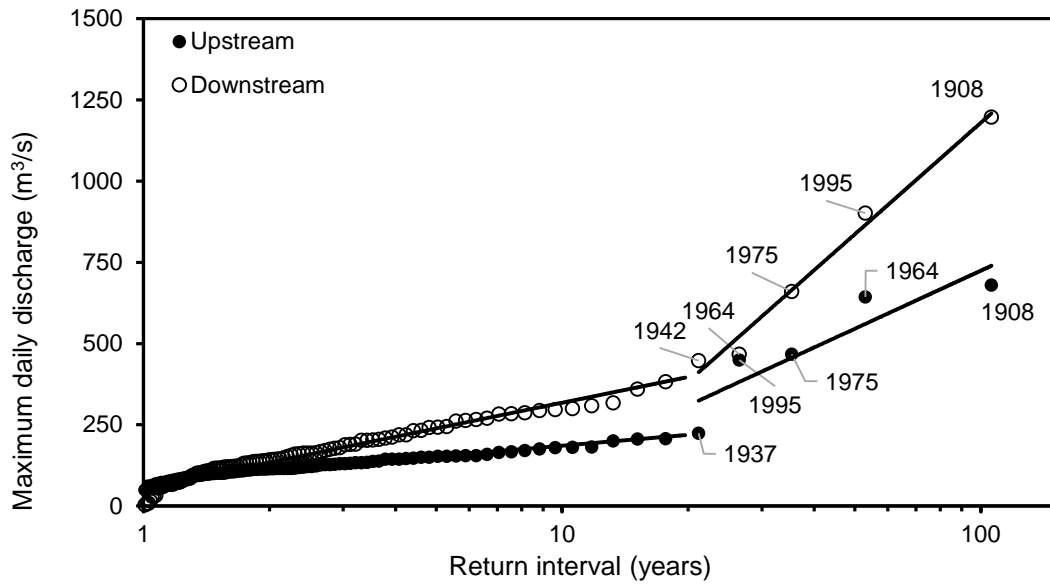


Figure 2-6: The two-component flood frequency analysis for the Waterton River displaying that substantial floods persist during post-dam implementation. Hydrometric data is fit to a Weibull distribution.

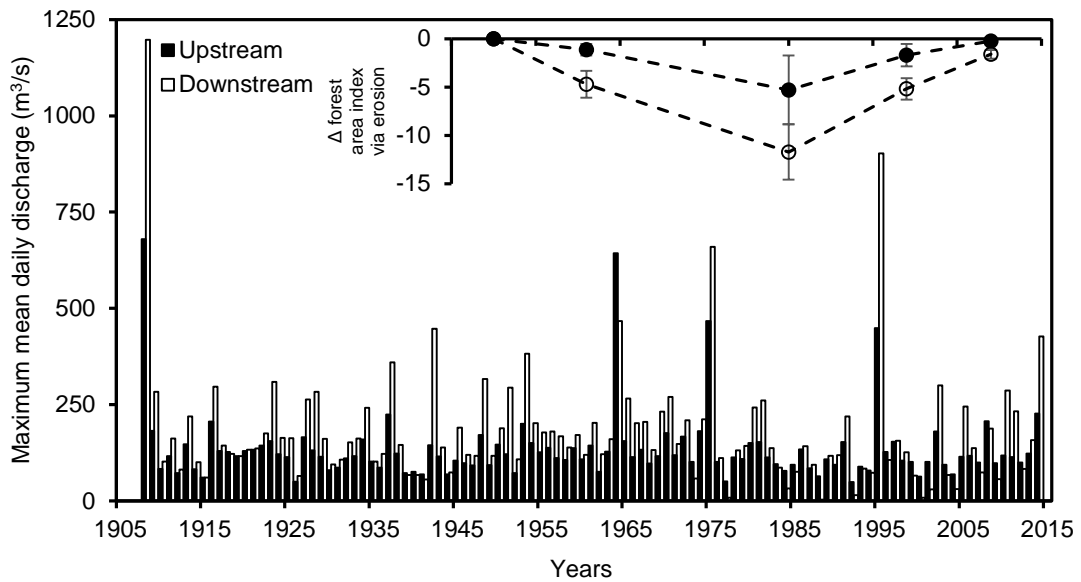


Figure 2-7: The maximum mean daily discharge and forested area erosion for the Waterton River. Inset figure shows change in forest area index via channel erosion between each aerial photograph year for upstream and downstream reaches.

2.4.6 Forest Dynamics

The downstream Waterton River contains much more total cottonwood woodland area (479 ha) than the upstream (114 ha) reach (Appendix Figure A-1 and A-2). The cottonwood forest area index appears to have remained relatively unchanged over the last 60 years despite river impoundment, changes in management flow regimes, extensive drought periods, and the occurrences of multiple high magnitude floods (Figure 2-2; Appendix Table A-1). No significant changes in total forest area occurred along the Waterton River between 1951 and 2009, although specific segments could change considerably between years (Figure 2-8). Channel erosion removed substantial areas of forest following multiple large magnitude floods (Figure 2-7). Specific segments appear to have been more susceptible to channel erosion than others but generally occurred more along the downstream reach (Figure 2-9).

Prior to dam implementation, cottonwoods along the Waterton River were characterized mainly by open and sparse canopies maturing and woodlands becoming more closed, especially along the downstream reach (Figure 2-8). The upstream reach displayed only slight amounts of channel erosion while the downstream reach displayed more general river migration and some abrupt avulsion probably following from the 1953 flood (Figure 2-9). Very little human developments occurred within this time interval (Appendix A3).

Changes between the 1961 and 1985 aerial photographs were substantial as the river was now dammed and two major floods (1964 and 1975) had occurred. Substantial amounts of closed canopy areas were absent along the upstream (-32%) and downstream

(-17%) reaches (Figure 2-8). Changes are largely attributed to episodic and progressive channel movement erosion that resulted in large swaths of forests to be removed in many segments (Figure 2-9). This produced multiple abandoned channels and newly created barren gravel bars. Compared to the upstream reach that only lost -12 ha to channel erosion, the downstream reach lost -46 ha. However, this represents about 10% of the total forested area for both reaches because the upstream reach has proportionally fewer trees than the downstream reach. Within this time period, some drought related mortality is evident within the narrow and constrained floodplains. Human developments were also prominent within this time interval. The final segment before the reservoir of the upstream reach has been developed with an industrial feedlot and farm that resulted in a total of 12 ha of forest removed. Likewise, the downstream reach experienced the most human development between 1961 and 1985 within the final segment before the confluence with the Belly River where 9 ha of woodland was cleared for crop agriculture purposes (Appendix A-4, Appendix A-5).

Only 8 years had passed since the minimum flows were increased along the Waterton River and when the 1999 photographs were taken. Therefore, the 1999 photographs probably displayed some residual conditions following from the pre-Environmental Flows interval. Generally, the 1985 to 1999 period was characterised by forest maturation, but some continued erosion still occurred as a high magnitude flood in 1995 had occurred. Cottonwood recruitment within the abandoned channels and along the barren gravel bars occurred in a few segments. Woodland maturation was evident as more closed canopy woodlands replaced the sparser forests, especially within the first segment of the upstream reach (Figure 2-8). Channel erosion was less severe along the upstream

reach than the downstream reach. Gradual channel migration commonly caused forest removal along with episodic avulsions but was less frequent than during the prior photographic interval (Figure 2-9). Very little floodplain development occurred in this time interval and many segments experienced no substantial changes to the woodland areas.

Few changes occurred between 1999 to 2009, as no substantial floods or major human developments occurred. Forest maturation was evident in some segments that recruited cottonwoods in abandoned channels and along gravel bars (Figure 2-10). Channel erosion and human developments were minor in this time interval for both upstream and downstream reaches (Figure 2-7, and Appendix A-3). With marginal changes occurring in this time interval, this period is characterised by maturation of the forest and stabilization of the stream banks.

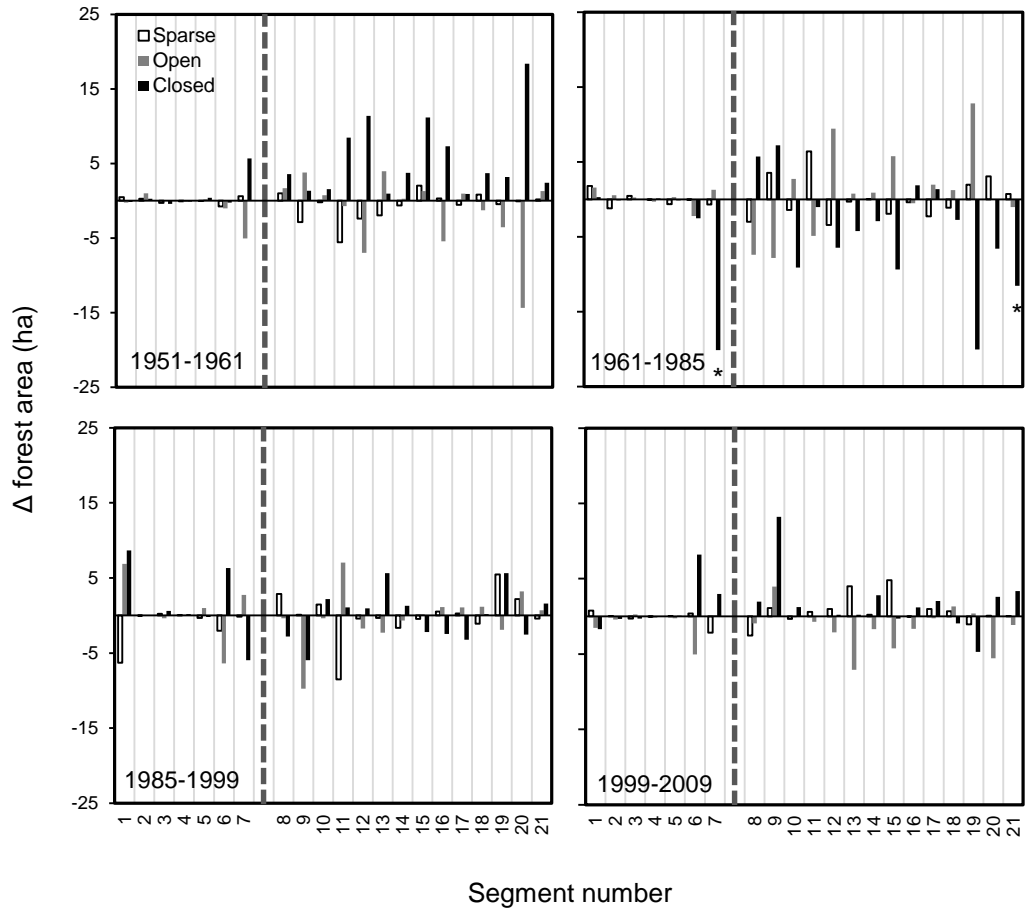


Figure 2-8: Changes in forest density classification by segment between photographed years. Dashed vertical line represents the Waterton Reservoir and separates upstream from downstream reaches. Substantial forest area removed via human developments are denoted with a (*).

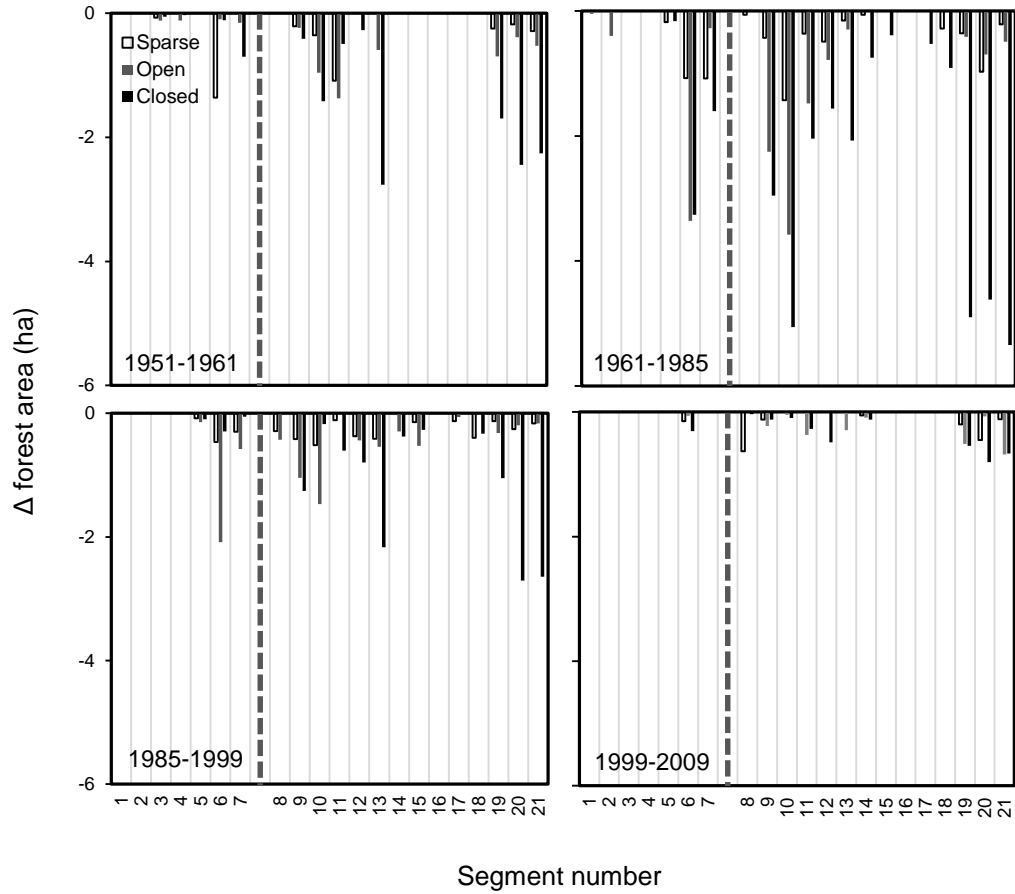

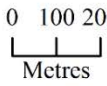


Figure 2-9: Forested area removed by channel erosion between photographed years. Dashed vertical line represents the Waterton Reservoir and separates upstream from downstream reaches.



Figure 2-10: Sequential aerial photography of the downstream Waterton River displaying typical and substantial channel erosion, patch recruitment of abandoned channels, fringe recruitment of point and lateral gravel bars, and forest maturation. Foothill Creek is visible to the north.

 N

 0 100 200
Metres

2.5 Discussion

This study indicates that, overall, the cottonwood population along the Waterton River have avoided drought induced mortality and established replacement cohorts due to the Environmental Flow regime that was initiated in the 1990s. The beneficial dam management strategy included increasing the flow minimum and gradually ramping flow recession after the spring peaks (Figure 2-2). Better instream management was thus implemented before the artificial, chronic drought stresses due to water withdrawal became lethal to this population.

Ecologically, floods can act very similarly to fires in fire suppressed locations; they are a driver of community succession. The destruction of old habitats provides the foundation to develop new habitats through a cut and fill alluviation (Scott et al., 1997; Whited et al., 2007; Rood et al., 2007). Floods in this region are abrupt and episodic erosion has been a recognized issue along the Waterton River causing damaged property (Beckstead, 1981). After these episodic avulsions occur throughout the floodplain, seedling safe sites, locations at an elevation that avoids drought or scour, permit the survival of patch recruited seedlings and produce an even aged forest within the disturbance site (Polzin and Rood, 2006). These abrupt channel shifts are accompanied by fringe recruitment along the point and lateral gravel bars of meander lobes where gradual channel migration and deposition produces the barren seedling sites required for cottonwood establishment (Figure 2-10). Regardless of where new cottonwoods establish along the Waterton River, the seedlings would not be able to survive in this semi-arid region without proper flow ramping rates since the available floodplain groundwater is directly linked to streamflow levels (Mahoney and Rood, 1998). Ramping flows has

limited the mortality of seedlings as evidenced by new cohorts have established along the downstream Waterton River.

The Pacific Decadal Oscillation (PDO) affects the weather conditions that supplies the snowpack along the Rocky Mountain range which is the primary contributor to streamflow in southern Alberta (Rood et al., 2005a; Rood et al., 2008; Figure 2-2). Precipitation is affected by the wet systems originating from the Gulf of Mexico and may explain the low correspondence with the PDO and the lesser contribution to streamflow. There was less synchronization with river discharge and the PDO near the beginning and end of the century as some lags were apparent and may explain some of the variability. The Waterton Reservoir was established during a cool phase of the PDO that brought abundant snow that persisted for about 13 years before a transition to the drier warm phase began. The naturally wet years of the Dammed interval are apparent when considering the relatively high mean June discharges (Figure 2-4). Also, this wet period was reinforced by the two major floods of 1964 and 1975 occurring within this cool phase. Abundant regional water availability created little demand for irrigation water until 1977 and in the mid-1990s Environmental Flows were implemented, therefore the Waterton River was only seriously impacted for about 14 years. This short interval of severe dam management apparently caused only temporary woodland dieback along the Waterton River.

2.5.1 Floods

Major floods occur at about decade intervals along the Waterton River (Figure 2-6). During these events, typically in late May or early June, warm and moist air from the

Gulf of Mexico flows northward and becomes trapped by polar cold fronts moving southward. These two weather systems collide, prompting substantial precipitation along the east slope of the east-west Continental Divide and often near the north-south Hudson's Bay Divide. When this system stalls over this area for a number of days there is a substantial flood event.

Prior to 1993, after a major flood, dam operations caused abruptly reduced flows along the downstream reach. A consequence of this was the abrupt decline of the alluvial water table along the downstream reach, effectively disengaging water contact with the roots of new cottonwood seedlings and causing desiccation and mortality (Rood et al., 1995, Mahoney and Rood, 1998; Rood and Mahoney, 2000). During flood years, water is usually plentiful in the region and there is a low demand for irrigation water. This allows for managers to utilize the normally diverted water to perform flow ramping. After the implementation of Environmental Flows, in the flood years, flow ramping mimicked the natural recession rate required for successful cottonwood seedling recruitment.

Cottonwood regeneration correlates with peak flow events (Junk et al., 1989; Stromberg and Patten, 1996; Scott et al., 1997). Large magnitude floods are particularly important for the recruitment of cottonwoods along streams that are regulated for irrigation. Floods not only promote the requirements for seedling recruitment but can also cause gradual erosion and episodic avulsions that scour a substantial amount of forests (Bradley and Smith, 1986; Dykaar and Wigington, 2000). This channel movement and erosion is characteristic of alluvial rivers where the river is not constrained and relatively free to move throughout the floodplains. With the broad and open floodplains of the Waterton River, substantial channel movement and erosion along with sediment

transportation and deposition is expected in this system. Therefore, the Waterton River contained many barren nursery sites that are suitable for cottonwood recruitment.

During the 1964 flood, there was a greater maximum daily discharge along the upstream reach than observed downstream (Figure 2-7). This is because the reservoir had just been completed and was probably relatively empty and therefore able to capture substantial water. This differed from the 1975 and 1995 floods where the discharge was much larger along the downstream reach. Particularly, the 1995 flood would predictably produce numerous recruited cottonwood seedlings due to the high magnitude of the flood and the flow ramping strategy employed by the managers of the Waterton River dam.

There may be a decline in the magnitude of floods originating from the Rocky Mountains in association of climate change over the past century (Cunderlik and Quarda, 2009; Rood et al., 2016). Although patterns for major floods are unclear due to the limited occurrences and historic records, it is likely that the lower magnitude floods are declining. In the study by Tiedemann and Rood, (2015), they found that damming the Boise River in Idaho caused there to be less flood disturbances downstream and therefore decreased the sexual reproduction in cottonwoods. If flood moderation occurs, then there probably will be an armouring of the banks and subsequently less scour and deposition that promote cottonwood recruitment (Rood et al. 1999).

2.5.2 Low Flows

The implementation of the minimum flow criterion greatly reduced the number of excessively low flow days and returned their occurrence to near pre-Drought/ Pre-Dam intervals (Figure 2-5). The downstream Waterton River still frequently experiences

discharge below base flow during the growth season that is not reflected in the upstream reach. These results suggest that dam operators have effectively reduced excessively low minimum flows and may be avoiding acute drought stress, but also suggests that operators have aimed for a low minimum flow between 2.27 and 6.78 m³/s and long term stresses may still be imposed. In Rood et al. (1995) it was suggested that the instream flow minimum implemented in 1991 was probably still well below the minimal requirements for cottonwood health. If the minimum flow set for the Waterton River is still below the requirements, it is not obviously impacting the forests yet because the total forested area has remained relatively consistent. Apparently, the minimum criterion is set at a sufficient level because the forests have evidently not been substantially affected within the range of this study. Shaw (1994) recommends that the instream flow objective for the Waterton River should be 6 m³/s to maintain a sufficient water quality below the Waterton Reservoir. The 6 m³/s corresponds to 90% of the exceedance of natural flow in July and August for the Waterton River. Although this amount was deemed unrealistic for socio-economic objectives, it may be recommended to increase the set minimum flow criterion to better match the historic base flow levels and promote riparian health and instream flow quality.

2.5.3 Monthly Means

When comparing the mean monthly discharge between the varying river management periods, it is clear that water deficits are experienced during all months of the growth season (Figure 2-4). The effects from this may cause cottonwoods to be established at too low of an elevation on river banks and therefore susceptible to be scoured away by ice in the early spring or by subsequent flooding. With reduced flows in

the later summer months, established and mature trees are likely to become increasingly stressed due to water shortages below historical levels.

Prior to the Drought interval the monthly discharges for both the upstream and downstream reaches appear similar to the Pre-Dam conditions (Figure 2-4). A cause for the Dammed interval having slightly larger monthly discharges than the Pre-Dam interval is in part due to the PDO being in a cool phase beginning in the 1940s and irrigation withdrawal being relatively low. There was no obvious deviation of the downstream Waterton River monthly discharge from upstream patterns until the droughts combined with irrigation needs substantially decreased the downstream Waterton River discharge. The continued decreased mean May discharges experienced along both reaches during the Environmental Flows period may be explained by an earlier spring runoff caused by the Drought interval bringing warm weather and melting the mountain snow packs earlier in the year.

2.5.4 Adjacent Stream Comparison

The Waterton River and the nearby St. Mary River have been regulated similarly in that they had previously experienced artificially low flows in the late summer months and abrupt stage declines following from flood events (Rood and Heinze-Milne, 1989; Rood et al., 1995). Between the years 1951 and 1985, there was a -68% decline of the St. Mary River cottonwood abundance (Rood et al., 1995). In contrast, the Waterton River had experienced less severe drought stress and mortality than that along the St. Mary River. There are multiple reasons to explain the differences between these two river systems.

Firstly, the St. Mary River has been regulated for a much longer time than the Waterton River. The St. Mary River's regulation begins in 1898 when the Kimball weir was implemented to provide irrigation in Canada, and in 1917 water from the St. Mary River was diverted upstream of the international border to the Milk River to provide irrigation water in northern Montana. Next, to replace the Kimball weir, the St. Mary Reservoir was established in 1951 to enable trapping of the high spring flow and irrigation was progressively expanded. Therefore, the demand for diverted water has been more substantial and for a much longer time than along the Waterton River, incurring a chronic artificial drought regime along the St. Mary River especially in June and July. This may have influenced the recovery period that the St. Mary River needs to rebound from dam management.

Next, as suggested by Rood and Mahoney (2000) and Rood et al. (2016), the lack of parental trees to provide a seed source inhibits cottonwood restoration along the St. Mary River. The St. Mary River has not been able to restore its cottonwood populations because the mature forests being almost entirely removed during a century of dam management practices that affected cottonwood health. When a river floodplain has been severely impacted such as the St. Mary River, direct seeding of cottonwoods may be necessary to produce a cohort of cottonwoods and initiate vegetation succession (Rood et al., 2016). A lack of seed source was not an issue along the Waterton River. Even with some woodland dieback and substantial channel erosion, the downstream reach has broad floodplains inhabited by many cottonwood trees that supply seeds.

Lastly, although the Waterton and St. Mary Rivers originate from adjacent geographic locations and flow parallel to each other, the river valleys are of different

forms. The floodplain surface area limits the hypothetical maximum area that may establish forests (Willms et al., 2006). Whereas the Waterton River has a relatively broad floodplain averaging approximately 425 m, the St. Mary River is comparatively constrained with a floodplain width averaging about 155 m. Also, the changes in stage would probably be more drastic along the constrained valley causing more abrupt declines after a flood reducing the potential of ramping flows. Compared to the St. Mary River, the Waterton River was slightly impacted and has apparently thrived even within constricted segments of the downstream reach. Images of the 2nd canyon (Buhrman and Young, 1982), were captured by George Dawson in 1881 and display pre-European settlement conditions along the downstream reach. These images were retaken in 2015 to compare the changes over the 134-year time interval. However, it should be recognized that influences such as buffalo grazing and fires set by the First Nations residents may have affected the condition of these cottonwoods (Figure 2-11). In this photo comparison, cottonwood woodlands have not collapsed despite marginal surface area to allow establishment and abrupt changes in river stage. By this confined segment being capable to sustain a healthy cottonwood woodland, it is evident that the Waterton River was only impacted for a short period of time and there were abundant seed sources to propagate subsequent cohorts.

The Waterton River flows through broad floodplains that inherently provide abundant surface area for cottonwood establishment and can therefore, support more sexually mature trees capable of providing a plethora of seeds. Because the cottonwood populations do not seem to be severely impacted, it is apparent that the Waterton River exemplifies the 'Rubber Band Model' as described within the conceptual model from

Sarr, (2002). The Waterton River was only marginally impacted by a severe river management interval and the woodlands are able to 'snap back' to a condition near to pre disturbance. This is in contrast to the St. Mary River that exemplifies the 'Humpty-Dumpty' model where the cottonwoods along the St. Mary River have surpassed a 'tipping point' where recover is extremely delayed and recovery will probably not achieve pre-disturbance conditions (Sarr, 2002; Suding et al., 2004). These examples suggest that expedited initiation of proper management flow regimes for other impacted rivers are the key to preventing riparian collapse.



Figure 2-11: Comparison of cottonwood trees along a constricted canyon on the downstream Waterton River. Photos on the left were taken in 1881 (G. Dawson, 1881; Glenbow Museum Archives, 2015). Photos on the right were taken in 2015 (S. Foster, 2015). Top photographs look upstream to the south-southeast. Bottom photographs look downstream to the northeast. Location at lat: 49.38° long: -113.66°.

2.6 Conclusion

Overall, the Waterton River's riparian ecosystem has a promising future with the Environmental Flow regime. The total forested area has not substantially changed from the Pre-Dam condition suggesting that the Environmental Flows minimum flow criterion has reduced the drought stress imposed during the Dammed and Drought intervals and avoided woodland mortality. However, cottonwoods along the downstream reaches are still experiencing many low flow days caused by a high demand for irrigation water and chronic drought stresses may still be present.

High magnitude floods are common along the Waterton River, and these floods have caused substantial erosion that removed large portions of cottonwood forest. However, the disturbances caused by floods were revegetated with forests that were sustained to sexual maturity. The ramping of flows during the Environmental Flows interval has promoted seedling establishment allowing for younger cohorts to replace those lost. This indicates that the flow regime along the downstream reach was sufficient for cottonwood health.

This case study of the Waterton River contributes to the growing knowledge of instream flow management. These results indicate that dam managers can sustain riparian ecosystems downstream from a heavily allocated reservoir with an Environmental Flow regime strategy. Although it is impractical for complete recovery of natural flow regimes along regulated rivers, the pragmatic approach by identifying the components of the hydrograph necessary for ecological functional objectives may allow river managers to sustain riparian communities.

CHAPTER THREE: Implementation of an Environmental Flow Regime Promotes Cottonwood Colonization and Growth along the Waterton River, Alberta

3.1 Summary

River damming and water withdrawal have led to the collapse of riparian (streamside) cottonwood forests along some rivers, including the St. Mary River in southern Alberta. The nearby Waterton River drains the adjacent Rocky Mountains and was dammed in 1964 to enable water storage and offstream diversion for irrigation. Following the woodland mortality along the St. Mary River and in association with implementation of the Oldman River Dam, Environmental Flows were implemented along the Waterton River, with an increase of the minimum flow from 0.93 to 2.27 m³/s (mean discharge 21.9 m³/s) and flow ramping, gradual recession, after the spring peak.

In this study, the riparian (streamside) responses along the Waterton River were assessed and compared forest condition along the free-flowing upstream reach versus the regulated reach downstream of the Waterton Dam. River flow and stage patterns during four management intervals were investigated: (1) the pre-dam period from 1908 to 1963; (2) the initial post-dam period from 1964 to 1976; (3) a drought interval from 1977 to 1993; and (4) the Environmental Flow regime in 1993. The hydrological assessment was compared with riparian vegetation, with analyses of sapling, shrub, and tree sized black (*Populus trichocarpa*) and narrowleaf (*P. angustifolia*) cottonwoods in belt transects at sites along the river. Cottonwood tree ring counts of increment cores or cross sections determined ages and annual growth. Physical characteristics of surface sediment textures and floodplain measurements were also assessed.

The Waterton River has had progressive colonization by riparian poplar through the post-dam interval. Analyses of particular years somewhat supported the cottonwood recruitment box model which had predicted benefit from the flow ramping along with the increase in minimum flow. There was apparently a downward shift in the sapling distribution, indicating that cottonwood colonization was occurring at lower positions along the downstream reach after damming. There was correspondence between cottonwood growth and river discharge, with growth increasing with the Environmental Flow regime, confirming physiological benefit. This study demonstrated the value of the Environmental Flow regime to riparian cottonwoods but due to the continuing water withdrawal there may be bands of younger cottonwoods at lower elevations downstream from the Waterton Dam.

3.2 Introduction

Cottonwoods are riparian poplars (*Populus* species) that grow along rivers throughout North America (Rood et al., 2003a). The associated riparian woodlands support a rich abundance of animal biodiversity with extensive invertebrates and vertebrate wildlife, especially birds (Swift et al., 1984; Knopf et al., 1988; Finch and Ruggiero, 1993). The gallery forests provide important wildlife corridors allowing movement along the river valleys and into the adjoining uplands (Naiman et al., 1993), which are treeless prairie grasslands and shrub steppe in much of southern Alberta.

The success of the riparian cottonwoods largely depends on sufficient water (Braatne et al., 1996). In the semi-arid climate of southern Alberta, the cottonwoods are generally phreatophytic and they obtain their water from the floodplain aquifer (Rood et

al., 2011). In this dry region, the level of alluvial water table is approximately horizontal from the adjacent river stage and rises and falls with the river level (Amlin and Rood, 2003; Harner and Stanford, 2003). Dams are constructed on the prairie rivers to provide irrigation water. The associated reservoirs trap the spring and summer flows and the stored water is diverted during the irrigation season. This reduces downstream river flows and corresponding water availability for riparian vegetation (Rood et al., 1995; 2012). As a consequence, cottonwood populations have dramatically declined downstream from some irrigation dams within the North American prairies (Rood and Heinze-Milne, 1989; Rood and Mahoney, 1990).

The Waterton River in southern Alberta was dammed in 1964 to provide water to a network of irrigation districts that comprise the largest irrigation system in Canada (SMRID, 2012). That dam was operated to store the spring snow melt and runoff and water is diverted from the Waterton Reservoir throughout the irrigation season, which also corresponds with the natural cottonwood growth interval (Braatne et al., 1996). The St. Mary Dam was constructed on the nearby St. Mary River in the 1950s and it is likely that two changes in the flow regime were especially stressful for riparian cottonwoods downstream of that dam, abrupt declines in river stage (level) after spring peaks and extended periods of low flows through the mid- to late- summer (Rood et al., 1995; Mahoney and Rood, 1998). These factors probably contributed to the reduced cottonwood seedling recruitment and the growth and overall health of the associated riparian woodlands. The reduced flow can also cause physiological stress to the trees by inducing xylem cavitation and subsequent branch sacrifice, crown dieback, and trunk mortality (Rood et al., 1995; Stromberg and Patten, 1996). With the reduction in cottonwood

seedling recruitment, over a long interval there are fewer cottonwoods reaching sexual maturity to compensate for the natural aging and mortality of the population (Howe and Knopf, 1991). This results in a woodland population dominated by mature vegetation and absent younger cohorts.

In the 1980s another nearby dam was proposed on the Oldman River (Figure 1-1 in Chapter 1). The Oldman River Dam Project was controversial due to increasing public interest and awareness of the environmental impacts from dams, including the collapse of riparian cottonwoods along the lower St. Mary River (Glenn, 1999). This interest promoted opposition from a number of environmental groups who challenged the legality of the project and this judicial consideration advanced to the level of the Canadian Supreme Court (Glenn, 1999). Despite this challenge, the Oldman Dam was completed by the Government of Alberta in the early 1990s and as part of the environmental mitigation program for the project, the Government of Alberta sought to avoid a collapse of the Oldman River valley cottonwoods as had occurred downstream of the St. Mary Dam. This prompted more deliberate planning for the dam operations within the Oldman River Basin with a common objective of enabling irrigation agriculture while sustaining the aquatic and riparian ecosystems.

The minimum allowable flows were more than doubled for the southern tributaries to the Oldman River and this involved an increase from 0.93 to 2.27 m³/s for the Waterton River, downstream of the Waterton Dam (*Water Act Alb.Reg. 307/91*). This would ensure that the flows did not drop below about 10% of the average flow of that river (pre-dam annual mean: 21.9 m³/s). In addition, there was concern for the abrupt flow decline downstream from the regional dams and ‘flow ramping’, gradual flow

recession implementation especially after the spring peak, and this practice commenced following the major floods of 1995 (Rood et al., 1998; Kalischuk et al., 2001). This combination of increased minimum flows and flow ramping provided the 'Environmental Flow' regime that commenced in the early 1990s, and was intended to sustain and even restore the riparian cottonwood forests.

To investigate the environmental impacts from the river dams and flow regulation in southern Alberta, and particularly the consequences from the Environmental Flow regime, the river flow patterns were analysed and aerial photographs of the riparian woodlands downstream from the Waterton Dam were assessed (Chapter 2; Rood and Heinze-Milne, 1989; Rood et al., 1995). For this chapter, the field conditions were investigated, with comparisons of surface sediments and especially riparian cottonwoods at study sites along the Waterton River both upstream and downstream from the Waterton Dam. The reach upstream from the Waterton Dam is free-flowing and is used for a reference comparison. At the onset of the study it was expected that: (1) cottonwood recruitment would be relatable to the river flow patterns during the different management intervals, (2) there would be improvements in cottonwood recruitment following the implementation of the Environmental Flow regime, and (3) the Environmental Flow regime would also benefit established cottonwood trees, as evidenced by increased growth.

3.3 Methods

3.3.1 The Waterton River

The Waterton River watershed covers 1730 km² of southern Alberta with the headwaters originating within the relatively pristine Rocky Mountain region of the Waterton - Glacier International Park. The gravel and cobble channel bed and banks are especially influenced by spring snowmelt and the river passes through a steep sequence of ecoregions, commencing with alpine, subalpine, and montane zones, draining into the very large Waterton Lakes. The river then flows through foothills and northeastward to the prairies grasslands. For this study, the 'upstream reach' commences at the Waterton Lakes National Park boundary and flows for 32 km to the Waterton Reservoir. The 'downstream reach' flows for 60 km from the Waterton Dam outflow to the confluence with the Belly River (Figures 3-1 and 3-2). Drywood Creek is a major tributary that also flows into the Waterton Reservoir. Drywood Creek supplies approximately one quarter of the discharge into the reservoir. However, its contributions are greater in major flood years.

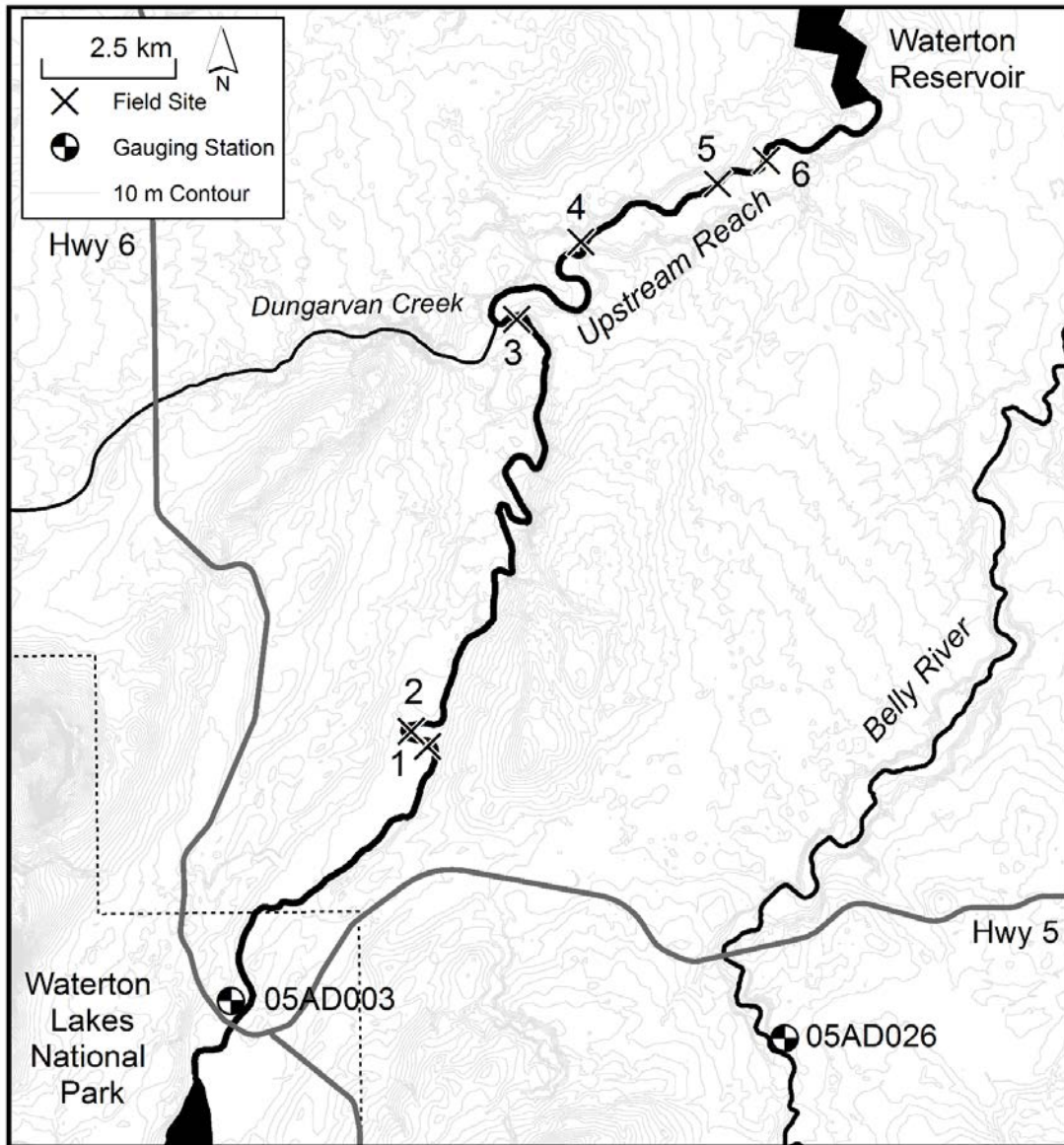


Figure 3-1: Field research sites (1 to 6) and gauging stations along the upper Waterton River and adjacent Belly River.

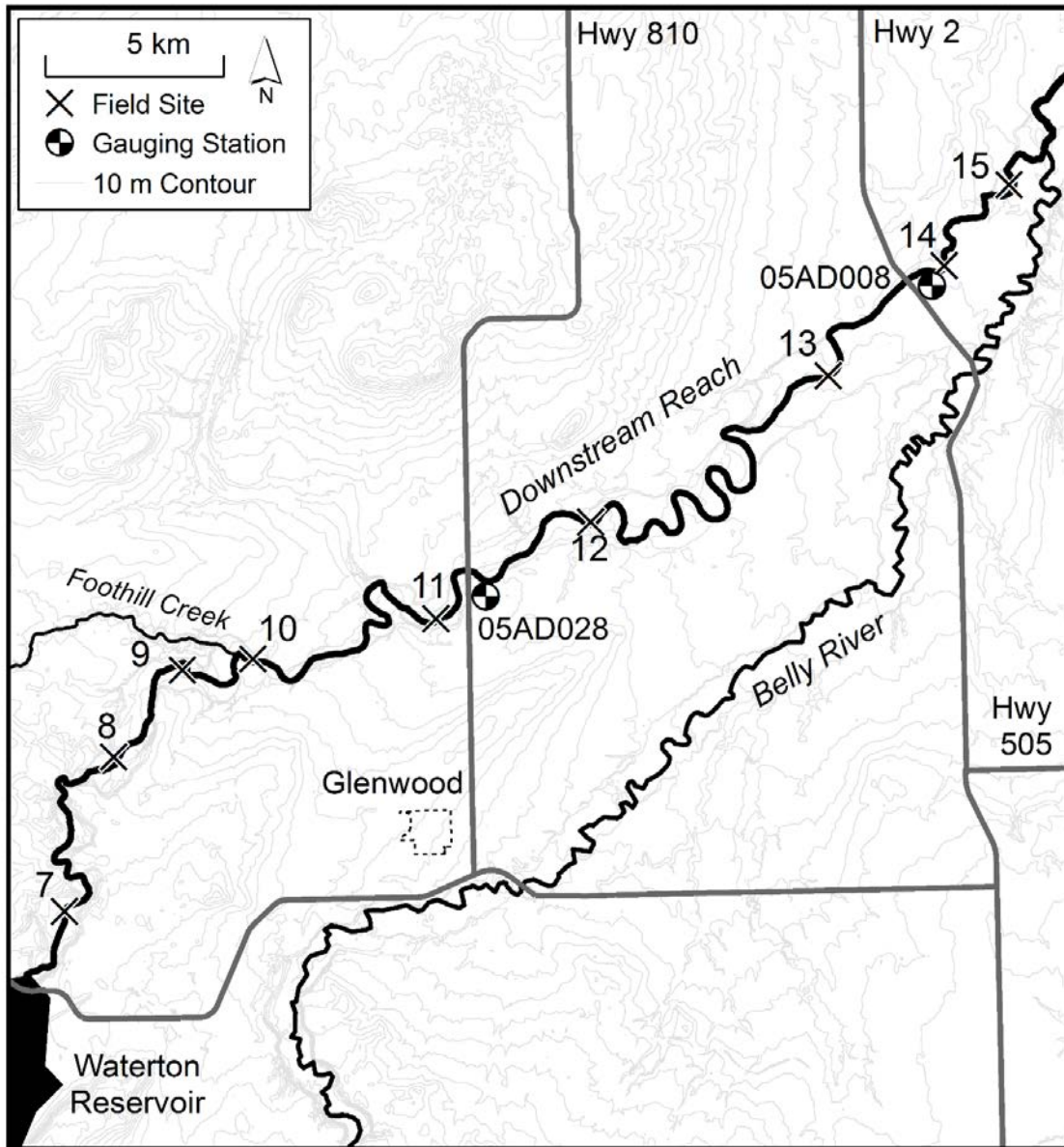


Figure 3-2: Field research sites (7 to 15) and gauging stations along the lower Waterton River and adjacent Belly River.

3.3.2 The Historic Hydrometric Record

The Waterton River's discharge data were acquired up to 2012 using the Water Survey of Canada's HYDAT archived hydrometric records. Unverified, preliminary data for 2013 and 2014 were supplied by Alberta Environment (Table 3-1). The ice-free months from March through October were selected to analyse the river dynamics that influence the life history strategies of cottonwoods (Braatne et al., 1996). Mean daily, maximum mean daily, and mean growth season (May – October) discharge were selected for each gauging station. Four dam management intervals were identified as *Pre-Dam* (before 1963), *Dammed* (1964 to 1976), *dammed* and *Drought* (1977 to 1990), and *Environmental Flows* (1991 to 2014). For analyses of stage patterns, gauging station ratings curves were applied but it is acknowledged that the river stage versus discharge relationship is influenced by site specific geometry and would somewhat differ along the study reaches (Shafroth et al., 1998; Willms et al., 2006).

For the upstream and downstream reaches, 104-year hydrometric time series were constructed utilizing three gauging stations along the Waterton River and one station from the adjacent Belly River (Table 3-1). The earliest record was from the upstream reach near Waterton Park (05AD003), with initial seasonal records (no winter values) from 1908, and this record was expanded to provide continuous data in 1912. There is a data gap in this record from 1931 to 1947 and these values were estimated with interpolation from linear regressions of discharges from a gauging station for the adjacent Belly River near Mountain View (05AD005). High correspondences were observed for mean daily discharge ($r^2 = 0.920$), maximum daily discharge ($r^2 = 0.871$) and mean annual growth season discharge ($r^2 = 0.921$).

Along the downstream reach, the hydrometric station near Standoff (05AD008) began recording seasonally in 1916 until 1966, with a brief data gap between 1931 and 1934. To replace the Standoff station, the station near Glenwood (05AD028) began recording continuously in 1966 and a high degree of correspondence ($y = 1.221x - 1.448$; $r^2 = 0.978$) occurred for daily discharges during the overlapping time period in 1966 for the two stations. These two stations have similar drainage areas and no tributaries inflow between these two locations. Consequently, the stations were considered as directly comparable and the records were combined. To interpolate the missing data in the 1930s and extrapolate back to 1908, linear regressions were undertaken between discharges at the pre-dam Standoff station and the previously extended upstream discharge time series. Close correspondences between mean daily discharge ($r^2=0.896$), maximum mean daily discharge ($r^2=0.656$) and mean growth season discharge ($r^2 = 0.861$) were utilized to complete the downstream time series.

River base flow is generally considered as the natural input of water supplied by the adjacent groundwater (Leopold, 1994). Base flow is important for mature cottonwoods to meet their water requirements, especially in the hot, late summer. For the purpose of this study, the definition of base flow is relative to the survivorship of cottonwoods and is calculated as the typical low flow (pre-dammed) experienced during ice-free periods. Using a Weibull probability distribution, a flood recurrence of >5 years was used to identify over bankfull discharge and a >20 year recurrence interval to identify large floods (Smith, 1979). To account for changes in base flow for each visited field site, the difference between the stage at arrival on site and stage measured at the gauging station was calculated with a transit time of 1 m/s to account for the lag in timing.

Table 3-1: Gauging station attributes for the Waterton River and adjacent Belly River. All data was recorded continuously throughout the year except for where indicated.

Station Name/ ID#	Drainage Area (km ²)	Years Available
Waterton River near Waterton Park (05AD003)	612	1908 - 1911*, 1912 - 1930, 1948 - 2014
Waterton River near Standoff (05AD008)	1730	1916 - 1930*, 1935 - 1947*, 1948 - 1966
Waterton River near Glenwood (05AD028)	1631	1966 - 2014
Belly River near Mountain View (05AD026)	319	1911 - 2012

* Indicates a variable seasonal data record

3.3.3 Cottonwood Recruitment Criteria

To assess the favourability of cottonwood recruitment along the downstream reach, flow characteristics were compared before and after dam establishment and after Environmental Flows were implemented. Results are also compared to the free-flowing upstream reach to control for regional hydrological variability. River discharges were back-converted to stage using rating curves provided from the Water Survey of Canada (2013, table no. 17 for both gauges). An analysis of six specific hydrograph components was undertaken in a manner similar to that performed by Braatne et al. (2007). These components were rated for every year and both reaches within the hydrometric time series (Table 3-2). Stage hydrographs were plotted as 3-day moving averages for the major floods (>20-year recurrence) and other notable establishment years. Recruitment boxes, the delineation of cottonwood seed release and recruitment elevation that avoids scour or drought, were plotted along with a favorable 5 cm/day stage decline rate (Mahoney and Rood, 1998). The upper limit of the upstream reach recruitment box was reduced by 50 cm to more accurately represent the lower magnitude floods experienced along this reach.

Table 3-2: Hydrological criteria for cottonwood recruitment analyses along upstream (up) and downstream (down) reaches. These criteria were used to determine the hypothetical potential of recruitment years along the Waterton River (Table 3-3). Recruitment analyses adapted after Braatne et al., 2007.

Hydrograph Component	Rating	Criteria	Weight
1. Magnitude of <i>Disturbance</i> flow	+++	>20 yr	1
Return period utilizes a Weibull distribution	++	>10 yr	0.66
Recruitment must occur within 2 years of a flood	+	>5 yr	0.33
20 yr = 224 and 447 m ³ /s (up, down)	-	<5 yr	0
10 yr = 180 and 297 m ³ /s (up, down)			
5 yr = 153 and 243 m ³ /s (up, down)			
2. <i>Establishment Peak</i> stage	+++	>2 m	1
Base stage subtracted from peak stage	++	1.3 - 2 m	0.66
	+	0.6 - 1.3 m	0.33
	-	<0.6 m	0
3. <i>Timing</i> of spring peak	+	May 24 - May 31	0.5
Peak needs to precede or occur during seed release	++	June 1 - June 15	1
Timing corresponds to Julian day	+	June 16 - June 30	0.5
	-	July 1 - July 15	0
4. Daily stage <i>Recession</i> rate	++	M < 20	1
Moving 3-day average classified as favorable (<5 cm/d),	+	M = 20 - 30	0.5
stressful (5 to 10 cm/d), or lethal (>10 cm/d).	-	M > 35	0
Calculations commence at peak flow or June 10 and completes on August 15 or the day when 7 consecutive mean Aug stage occur.			
Mortality coefficient = M			
M = (% lethal days X 3 + % stressful days) / 3			
5. Late summer (August) discharge - <i>Drought</i>	+++	> minimum	1
Values derived from typical minimum or lower quartile Aug. discharge	++	< min., > quartile	0.66
August Min. = 7.2 and 10.0 m ³ /s (up, down)	+	< quartile, > criterion	0.33
August 25th quartile = 5.1 and 6.4 m ³ /s (up, down)	-	< criterion	0
Minimum flow criterion - 2.27 m ³ /s			
6. Magnitude of post-recruitment <i>Scour</i>	++	<85%	1
Scouring flow occurred 2 years following a recruitment event	+	85 - 115%	0.5
Scouring flow is compared to spring peak flow	-	>115%	0

3.3.4 Field Study Sites

Field sites were selected prior to visitation based on valley morphology (non-constrained valley with gradually sloping gravel bars), land owner permission, and apparent presence of cottonwood forests. Throughout June to August of 2013, field sites were accessed by hiking or rafting into the locations. Sites with limited cattle and beaver damage were preferred but these factors are common in this area and difficult to eliminate completely (Samuelson and Rood, 2004; Samuelson and Rood, 2011). Fifteen sites were accessed, with six sites located on the upstream reach and nine sites downstream from the reservoir to the confluence of the Belly River (Figures 3-1 and 3-2). Two transects per site were established with a tape measure perpendicular to the river channel commencing at the edge of the river and ending at the apparent mature poplar stand. Transect elevation profiles were surveyed to the nearest 0.5 cm using a transit-level and staff gauge with measurements at 4 m intervals on gradual slopes, and with 1 m intervals on steep slopes. River gradient was calculated as the percent slope along a 60 m length parallel to the river channel, with assessment using a transit-level and staff gauge.

Two *Populus* section *Tacamahaca* species, the black cottonwood, *P. trichocarpa* Torr. and Gray ex Hook, and the narrowleaf cottonwood, *P. angustifolia* James occur along the Waterton River. No distinction was made between the species because of the extensive hybridization between species and the challenge of identification during the juvenile stage, when leaves are similarly narrow (Berg et al., 2007; Floate, 2004).

Three overlapping quadrat sizes were established to provide belt transects along each transect (Figure 3-3). Quadrat distance from the river was associated with elevations

via interpolation of the transect elevation profile. To address issues of decreasing tree density with forest self-thinning, quadrats of 1 x 1, 2 x 4, and 5 x 10 m were used to sample trees of <0.5 m in height (saplings), 0.5 to 2 m in height (shrub sized), and >2 m in height (trees), respectively. Within every quadrat, cottonwood heights and diameters were measured. Short cottonwoods were measured using a staff gauge. An inclinometer and tape measure were used to measure the height of tall trees. Diameters were measured using a diameter tape on trees 30 cm above the ground. Calipers were used to measure diameters of saplings at ground level. Stem densities, heights, and diameters were averaged by quadrat transect, site (two transects per site), and reach.

Approximately 15 trees per site were randomly chosen to create a diameter versus age estimation. Trees <10 cm in diameter were sacrificed to obtain a cross sectional disc at ground level. Larger trees were cored three times with a 5.15 mm increment borer as low as possible to facilitate handle rotation (~30 cm above ground) and the annual radial increments were averaged. To determine ages and annual basal areal increments (BAI), each sample was surfaced with a razorblade and growth ring radial increments were measured with a dissecting microscope (10-40x) using a Velmex stage, Acu-Rite encoder (precision of 0.002 mm, Velmex Inc., Bloomfield, New York) and MeasureJ2X software (VoorTech Consulting, Holderness, New Hampshire, Version 5.0). Concentric circles were used to estimate the age of tree cores with missed piths (Applequist, 1958). Composite skeleton plots were created to identify potential false or missing rings by matching high and low growth years and correcting apparent anomalies (Stokes and Smiley, 1968). Two additional years were added to the cored tree age to compensate for the 30 cm height of extraction but it is recognized that there would likely have been

variations in early height growth and duration to the level of the increment coring (Scott et al., 1997; Willms et al., 2006). Age and year of apparent establishment for the transect cottonwoods were estimated using the age versus diameter regression for the respective reaches. For interpretation, the observed age structure was plotted along with cumulative yearly scores derived from the recruitment criteria analysis in Figure 3-4.

Site distance from the Waterton Lakes National Park boundary was measured using the river centre line. Floodplain valley widths at each site were calculated by averaging by 5 measurements spaced along the valley between the first contour lines present on a 10 m DEM in ArcMap 10 (ESRI, 2010). A modified Wolman Pebble Count was performed to determine substrate texture for each site (Wolman, 1954). Four hundred pebbles were sampled in a grid matrix of 4 lines running parallel to the river and spaced 1 m apart. Each line had 100 stones sampled at varying distances dictated by the size of the largest clast present within the study area. The pebble to be measured was directly under the increment marker and was sized by being passed through a gravelometer. Pebbles were tallied in respective Wentworth scale bins and percentiles (D_x) were interpolated from a particle distribution curve. The sediment heterogeneity was determined using the half distribution range by subtracting the D_{25} from the D_{75} .

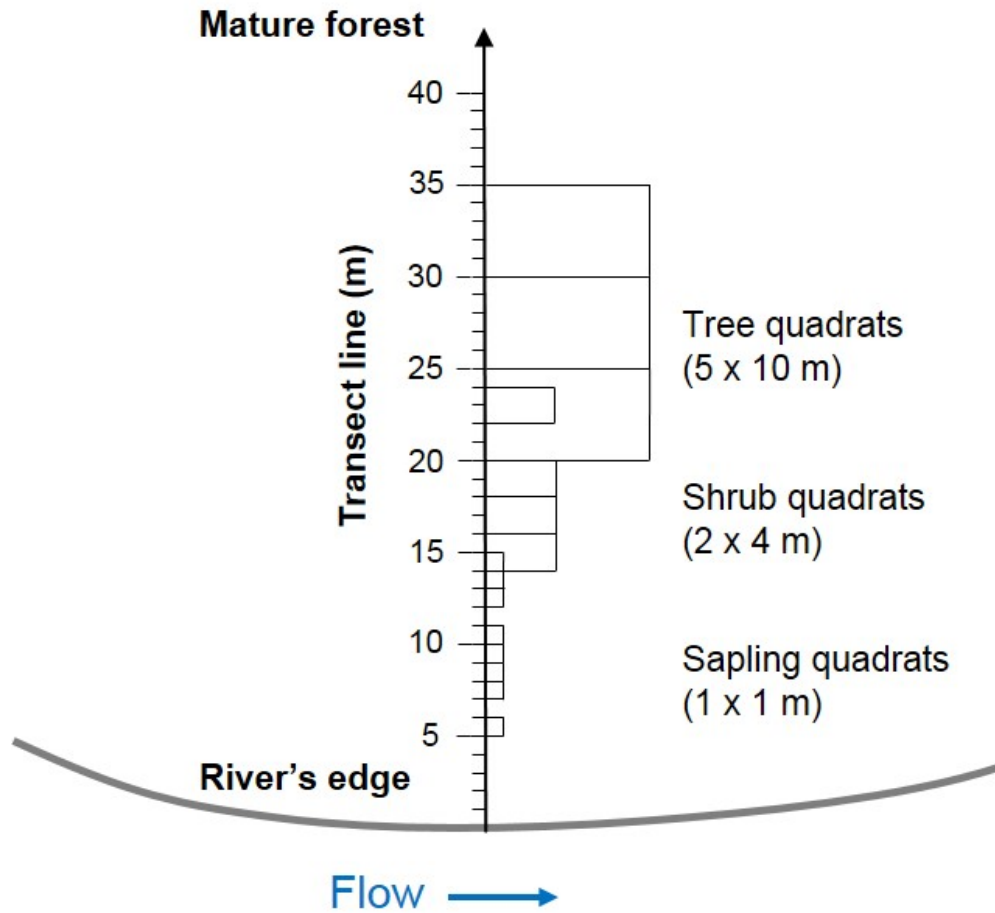


Figure 3-3: Schematic of a typical belt transect sampling method. Although the entire length of the transect contained continuous placement of all quadrat sizes, only when a cottonwood occurred in the respective height classification was a quadrat placed and the cottonwoods were measured. Note: each site contained two transects.

3.3.5 Statistical Overview

Linear regressions and the hydrometric recruitment analyses were undertaken utilizing Microsoft Excel 2013 (Microsoft, Redmond, WA, USA). Other statistics were undertaken utilizing SPSS 21.0 (IBM Corp., Somers, NY, USA). Shapiro-Wilks tests for normality and Levene's test for homogeneity were undertaken to assist in determining appropriate parametric and non-parametric tests. Mann-Whitney *U*-tests were used to detect differences in densities and elevations between upstream and downstream reaches. Kruskal-Wallis *H* tests were undertaken to detect elevation establishment differences between the 3 quadrat sizes followed by pair-wise Mann-Whitney *U* tests. Correlation matrices for remaining physical and biological site characteristics were undertaken using Kendall's Tau rank-order tests.

3.4 Results

3.4.1 Hydrology

The six-component cottonwood recruitment analyses assessed the favourability for cottonwood seedling establishment based on the river flow and stage characteristics (Table 3-2). The analyses included criteria that were generally based on those of Braatne et al. (2007) with revisions to reflect the river valley conditions along the Waterton River. Figure 3-4 displays the results from the recruitment criteria analyses. Annual scores for the upstream and downstream reaches were from 0 (unfavourable) to 1 (ideal) for each criterion and are plotted from 1930 to 2014 with dots and open circles for the upstream and downstream reach, respectively. These scores were often similar and are thus superimposed. For each reach and criterion, the average scores are presented as the

horizontal lines for the four flow management intervals: Pre-Dam, Dammed, Drought, and Environmental Flows. Means presented for the Dammed interval for 'Timing' were identical and have been offset by 0.05 for graphic clarity. This presentation thus displays the impacts of dam operations, with the natural variation reference provided by the free-flowing upstream reach.

The first criterion was *Disturbance* and this required major floods that were sufficient to provide substantial sediment erosion and deposition that creates the barren cottonwood colonization sites. Larger magnitude floods provide more geomorphic disturbance along the channel and floodplain, and increase the area suitable for seedling establishment. The Disturbance patterns were very similar for the upstream and downstream reaches (Figure 3-4), indicating that this component was not substantially altered by river regulation. There were four major floods over the study interval along with generally common moderate floods, and these occurred along both the upstream and downstream reaches (Figure 3-5). The benefits of these floods were carried over to the year following, as competing vegetation may encroach thereafter.

Following a Disturbance event, seedling establishment can follow and requires a sufficient *Establishment Peak*. This represents the stage or height that the river water reached immediately prior to and during seed release and defines the prospective wetted recruitment area that could support seed germination and initial seedling establishment. The Establishment Peaks appeared to be consistently more favourable along the downstream than the upstream reach and this pattern persisted through the interval of regulation (Figure 3-4). The sequence of very large Waterton Lakes moderates the flow pattern and thus diminishing the Establishment Peaks along the upstream reach. Also,

Drywood Creek flows into the Waterton Reservoir and provides very dynamic inflows. This increased the Establishment Peaks along the downstream reach before and after the implementation of the Waterton Dam, indicating that this criterion was not substantially altered by the river damming.

The Establishment Peak must occur prior to or during the limited interval of cottonwood seed release and this defines the criterion of *Timing*. The flow peaks along the Waterton River consistently occurred in late May or more commonly through June, and were thus just prior to and during the seed dispersal interval. This Timing was generally ideal and not altered by river regulation and thus, not a factor hindering cottonwood seedling recruitment along this river system.

After cottonwood establishment, the river stage *Recession* should be gradual in order to allow contact between the elongating seedling roots and the receding groundwater to be maintained. This avoids drought induced mortality. The Recession was consistently favourable along the upstream reach, throughout the study interval (Figure 3-4). In contrast, while Recession was similarly favourable along the downstream reach in the Pre-Dam interval, after damming, the Recession was frequently abrupt and thus unfavourable (Figure 3-4). The Recession was least favourable during the Drought interval and somewhat improved with the implementation of Environmental Flows, which included deliberate flow ramping. The flow ramping was particularly targeted in the higher flow years that would provide greater flexibility for flow regulation (Figure 3-6). While the Environmental Flow interval mean value was still somewhat unfavourable (Figure 3-4), the Recession patterns were quite favourable during 1995, 2002, 2008, 2010, 2011, and 2014 (Figure 3-6), when 'Functional Flows', deliberate flow patterns for

the benefit of riparian woodlands and fish, were implemented (Rood et al., 2016). Although the minor flood that occurred in 2005 achieved a disturbance score, the post-peak recession rate was too abrupt to achieve a favourable Recession score (Figure 3-4 and 3-6). The Recession criterion was thus substantially impacted by river damming and flow management and more favourable gradual ramping was a major component of the Environmental Flow regime (Figure 3-6).

Following the post-peak Recession, sufficient late summer (August) discharge sustains the new seedlings and thus avoids *Drought* induced mortality through that typically hot, dry and low flow interval. Late summer flows were consistently sufficient along the upstream reach and along the downstream reach prior to damming and during the initial Dammed interval while water was relatively abundant (Figure 3-4). In contrast, late summer flows were unfavourable during the Drought interval with many years not achieving any favourable score. With the implementation of Environmental Flows, favourability scores for the Drought criterion substantially recovered with the increase of the required minimum flow and all subsequent years achieved a favourable Drought score (Figure 3-4). This then provided the second recruitment criterion that was impacted by river regulation and improved with the Environmental Flow regime.

The five flow criteria combined to determine the opportunity for cottonwood seedling establishment and survival through the very vulnerable first year. Subsequently, any moderate or major floods within the next two years would *Scour* and physical remove the seedling providing another hydrological influence (Figure 3-4). The extent of Scour was quite variable and often unfavourable along both the upstream and downstream

reaches (Figure 3-4). There was little alteration with river regulation and the degree of favourability was fairly consistent across the different management intervals.

Thus, the recruitment analyses indicated that two of the six hydrological characteristics, Recession and Drought, were especially altered by the river regulation and these two characteristics were also the flow features that were partially restored with the Environmental Flow regime.

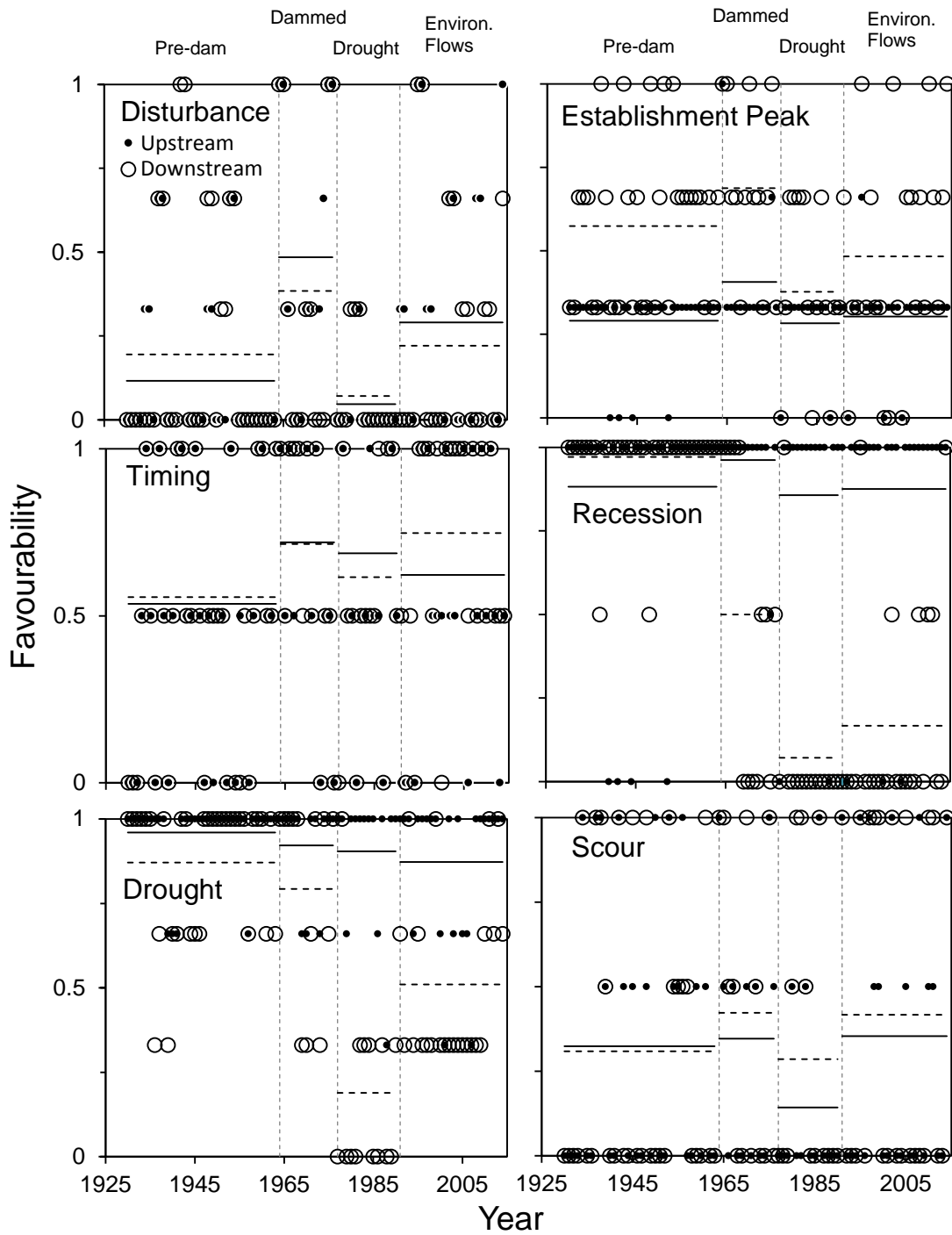


Figure 3-4: Predicted likelihood of cottonwood recruitment upstream and downstream of the Waterton Dam based on hydrological criteria in Table 3-2. Upstream (•) and downstream (◦) reaches may achieve the same score and those symbols were overlapped. Upstream (solid) and downstream (dashed) horizontal lines represent the mean value for each management interval. The criteria averages for the Dammed interval for ‘Timing’ are identical and have been offset by 0.05 for graphical display.

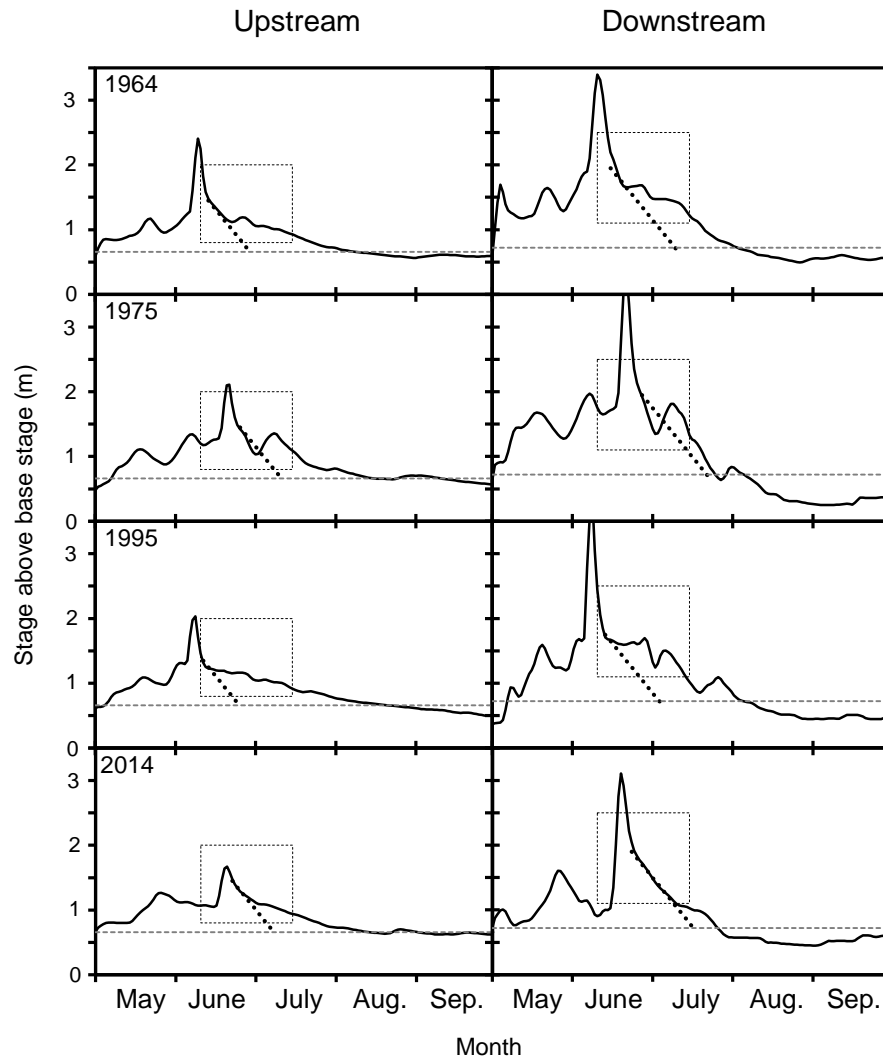


Figure 3-5: The Waterton River stage hydrographs for major flood years over the past half century. Upstream hydrographs are presented on the left with the downstream reach along the right. The dash boxes represent the survivable recruitment zone in elevation and time and dash line represents the average pre-dam August stage.

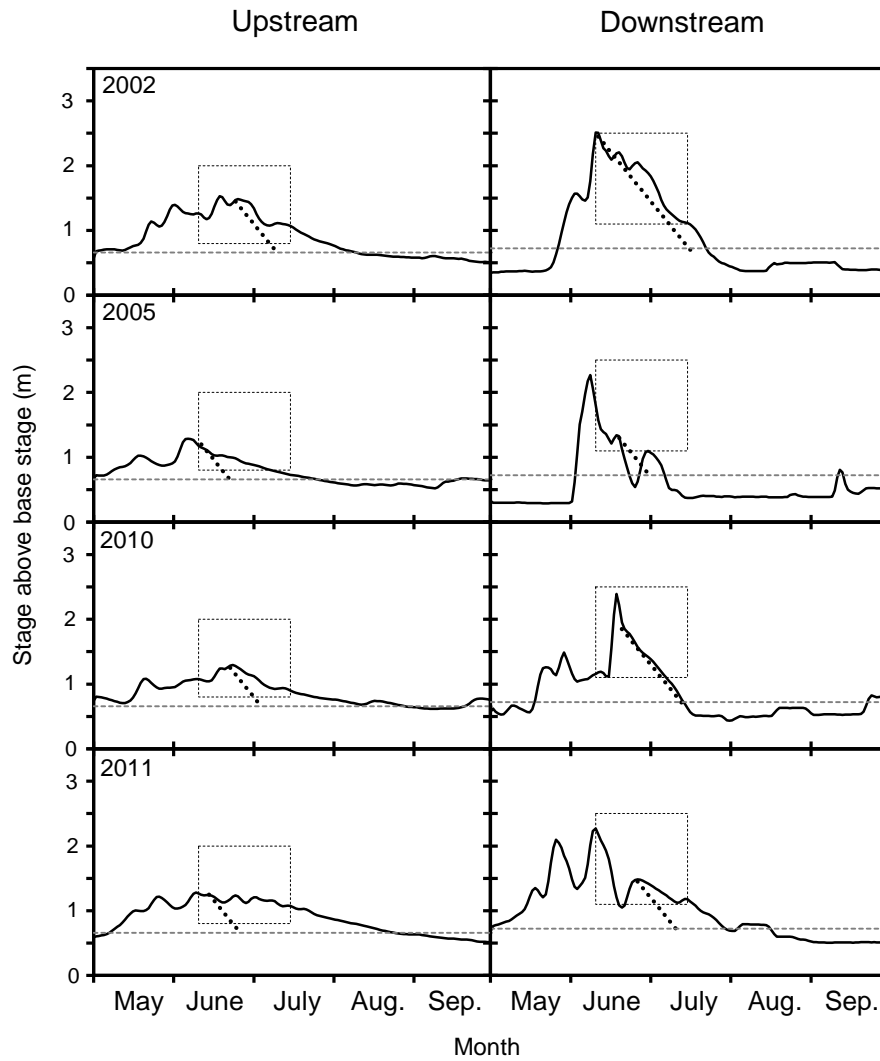


Figure 3-6: Stage hydrographs for the Waterton River for moderate flood years following the implementation of Environmental Flows. Upstream hydrographs are presented on the left with the downstream reach along the right. The dashed boxes represent the survivable recruitment zone in elevation and time and the dashed line represents the average pre-dam August stage.

3.4.2 Field Study Sites

The riparian conditions along the downstream field sites generally resembled those along the upstream reach with a mature forest along with abundant younger cottonwoods (Figure 3-7). For both reaches, there were narrow bands of mature cottonwoods and then, extending in bands closer to the river, juvenile trees and smaller, shrub and sapling sized cottonwoods. The average transect lengths varied between upstream (65 m) and downstream (108 m) reaches ranging from 36 to 96 m and 52 to 164 m, respectively. This reflected the wider valley zone along the downstream reach. A typical transect along the downstream reach is displayed in Figure 3-8 and additional data are presented in Appendix B. The upstream reach had 71 sapling, 117 shrub, and 69 tree sized quadrats. Along the downstream reach, Site 7 was unusual with sand deposition over the cobble and vegetation and consequently quadrats from that site were excluded from further analyses. This resulted in 81 sapling, 204 shrub, and 128 tree sized quadrats for the downstream reach. In total, 78 and 132 cottonwoods were sampled for the age versus diameter regression for the upstream and downstream reaches. Ten upstream and thirteen downstream trees were old enough to display mature growth and were thus suitable for the BAI analyses (Willms et al., 2006; Berg et al., 2007).



Figure 3-7: Typical field site photographs for the upstream (top) and downstream (bottom) reaches along the Waterton River. Photographs were taken at site 4 (July 23, 2014) and 8 (July 20, 2014).

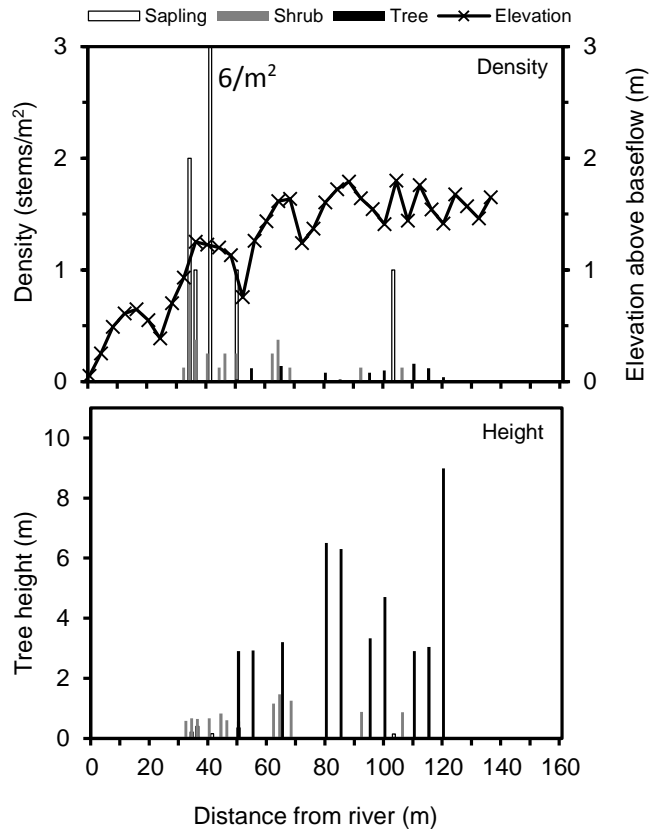


Figure 3-8: A typical transect along the downstream reach of the Waterton River, displaying cottonwood densities by size category and surface elevation (top) and cottonwood heights (bottom) with plots extending away from the river. Figures are a representation from site 15, transect 1.

3.4.3 Dendrochronology

Increment cores from mature trees and discs from smaller trees were obtained from 210 cottonwoods to determine the diameter versus age relationships (Figure 3-9). The plots displayed substantial scatter especially for the smaller and younger saplings and shrub sized cottonwoods. This probably reflects the inclusion of the two different cottonwood species and their intermediate hybrids, differing microsite conditions, and the inclusion of juveniles that had been established as seedlings or as the initially faster growing clonal root suckers. The two reaches provided quite similar distributions and the regressions were almost superimposed and proved correspondences of about 88% (Figure 3-9).

These regressions were used to estimate the ages of the other trees along the study transects but it should be recognized that determining the specific establishment year is very difficult due to the distributional scatter and due to site specific sediment accumulation that raised the substrate surface, and therefore the height of coring or cutting on the stem (Scott et al., 1997). Recognizing this complexity, the downstream reach displayed an apparent age structure that was very similar to that of the upstream reference reach (Figure 3-10). Both upstream and downstream reaches demonstrate relatively continuous cottonwood establishment over the past half century with increasing numbers of younger trees that reflect extensive recruitment within the past decade. In contrast to expectation, there was little correspondence between the apparent age structure and the prospective recruitment scores that were based on the six hydrological characteristics (Figure 3-10). The three-year groupings of cottonwood ages were assessed

and this provided some smoothing of the population distribution and dampened interannual patterns.

While the establishment years were less certain, the increment cores from mature trees should provide an indication of the growth patterns over the past few decades. Figure 3-11 displays the patterns for basal area increments (BAI) and these provide more comparable measures of interannual growth than radial increments that progressively decline with trunk enlargement (Willms et al., 2006; Berg et al., 2007). Along with the BAI, the yearly growth season discharge and the number of days below the minimum flow criterion ($2.27 \text{ m}^3/\text{s}$) are displayed to compare hydrological influences on tree growth. However, the downstream reach includes the inflow from Drywood Creek and other tributaries and would naturally be substantially higher than that along the upstream reach.

During the initial Dammed interval, the downstream BAI was somewhat lower than that observed for trees along the upstream reach (Figure 3-11). In this early post-dam interval, growth season discharge was relatively abundant along either reach (Figure 3-11). With the Drought interval through the 1980s, the growth of the downstream cottonwoods declined substantially while growth of the upstream trees was less affected. Mean growth season discharge declined, especially in the late 1980s, along the downstream reach as regional irrigation demand increased during the regional drought (Figure 2-3 in Chapter 2). Following the drought and with the reduction in mean growth season discharge, there were many low flow days, often even exceeding one half of the 183 days long growth season (Figure 3-11). When Environmental Flows were implemented, the minimum flow was substantially increased and this almost eliminated

the extreme low flow days despite regional drought in the early 2000s (Figure 3-11). During the Environmental Flows interval there remained substantial reduction in the mean growth season flows for the downstream reach, and this was only slightly improved relative to the Drought interval. However, the downstream reach BAI increased substantially with the initiation of Environmental Flows and BAI became coordinated with the growth pattern of the upstream reference control reach (Figure 3-11). This growth sequence indicates that extreme low flows rather than the overall growth season flows are limiting for the growth of riparian cottonwoods.

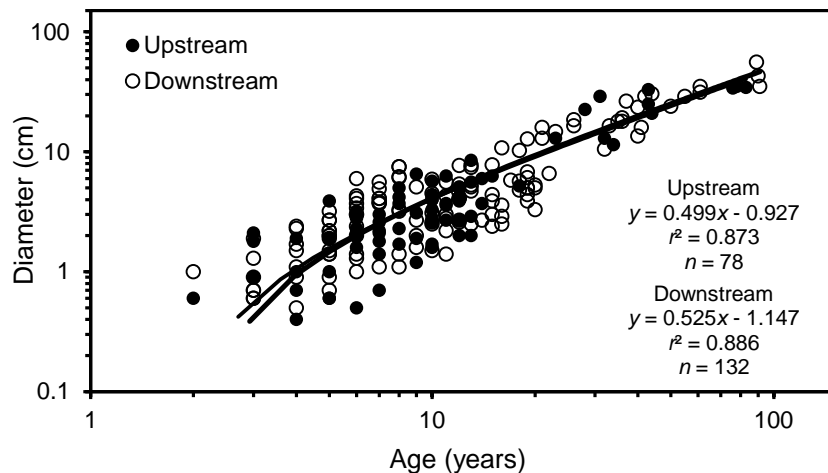


Figure 3-9: Cottonwood diameter versus age linear regression along the Waterton River. Young cottonwoods diameters and cross-section discs for aging were sampled at ground level while mature trees diameter and cores were taken 30 cm above the ground. Note the logarithmic axis to expand the distributions.

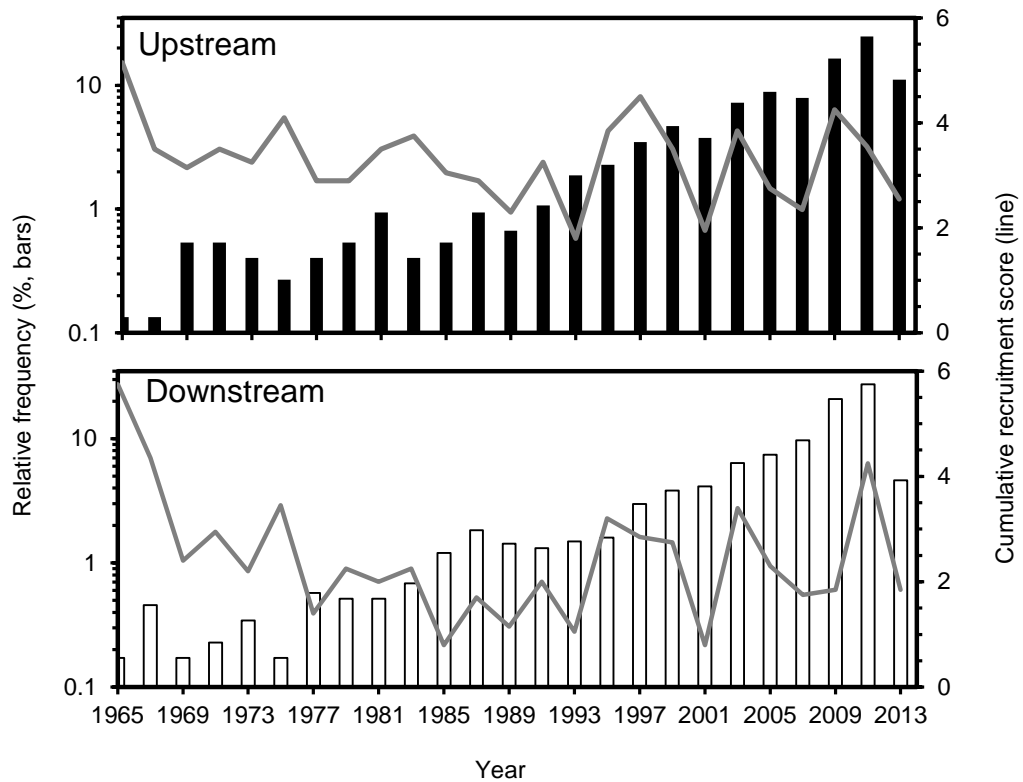


Figure 3-10: The sampled 3-year age structure of riparian cottonwoods along with cumulative ramping recruitment scores for the Waterton River. Note the logarithmic axis to expand the distributions. Labels denote the middle year of the 3-year interval.

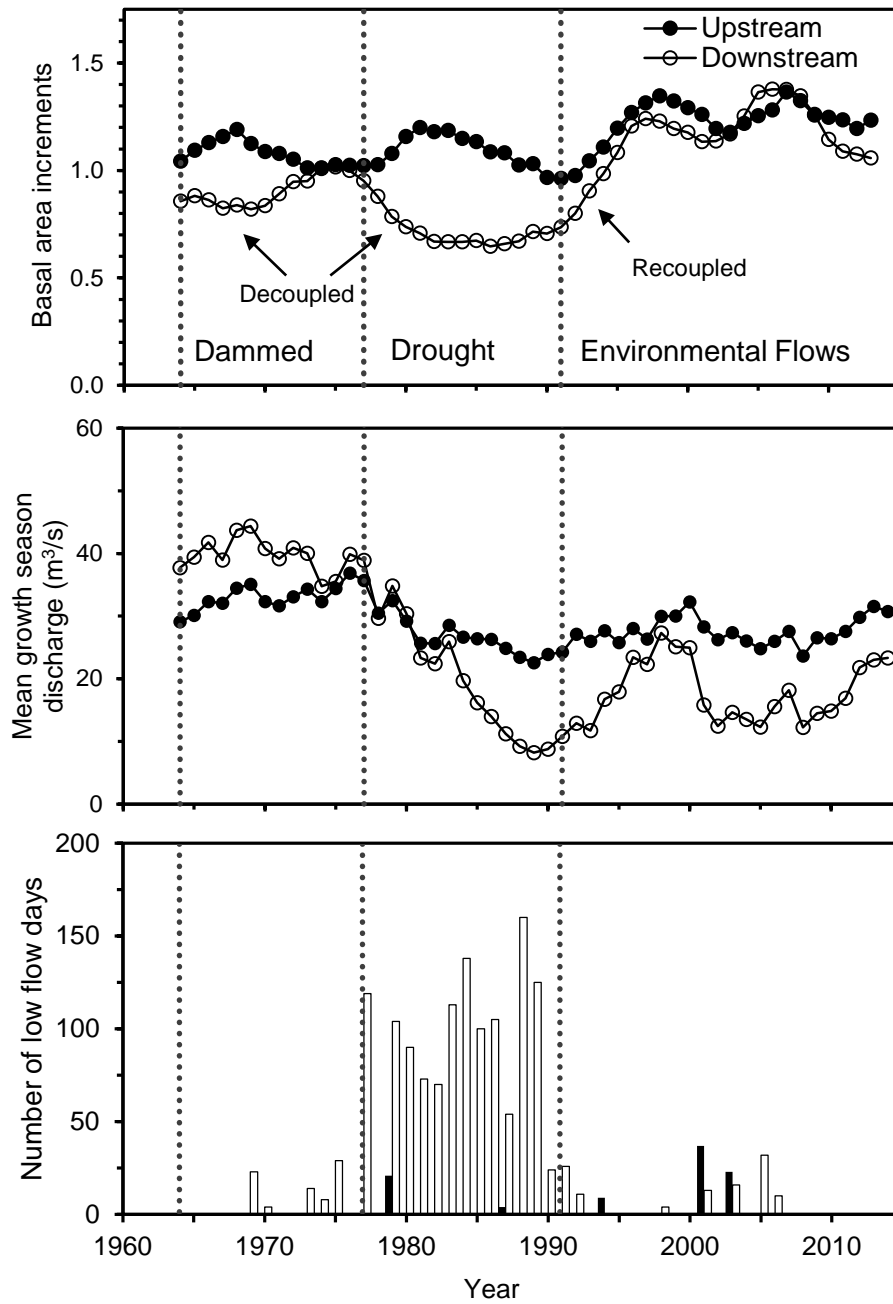


Figure 3-11: The 5-year averaged proportional Basal Area Increments (BAI) calculated from tree rings taken from cottonwoods and flow characteristics along the Waterton River. Associated 5-year moving average growth season discharge and the annual number of days below the minimum flow criterion ($2.27 \text{ m}^3/\text{s}$) are presented. Average standard error for upstream and downstream BAI are 0.196 and 0.137, respectively.

3.4.4 Density and Elevational Profile

The smaller saplings quadrats had similar cottonwood densities between the two reaches (Table 3-3). The saplings occurred at slightly lower elevational positions along the downstream reach. The older shrub sized cottonwoods (0.5 to 2 m) occurred in greater densities along the downstream reach, and these occurred higher in elevation than the downstream saplings and also at higher elevations than the shrub sized cottonwoods along the upstream reach (Table 3-3 and Figure 3-12). There was a trend ($p = 0.09$) toward greater tree densities along the downstream reach and these occurred at higher elevations than the trees along the upstream reach or the shrubs along the downstream reach (Figure 3-12). This shows some differences in the population structure along the two reaches. Narrower bands that contained saplings, shrub, and tree sized cottonwoods occur along the upstream reach, while there is more spatial differentiation along the downstream reach, with the progressively older and larger cottonwoods occurring at higher positions, further from the river (Figure 3-12).

Along the upstream reach, there were no significant differences in establishment elevation between the differing plant categories, but the downstream reach did display significant differentiation (Figure 3-12; Kruskal-Wallis H : Upstream $\chi^2 = 3.88$, $df = 2$, $p = 0.144$; Downstream $\chi^2 = 32.26$, $df = 2$, $p = <0.001$). This shows sapling establishment elevations were significantly lower than for the shrub and tree quadrats (Mann-Whitney: Sapling and Shrub $U = 5115$, $p < 0.001$; Sapling and Tree $U = 3009$, $p < 0.001$; Shrub and Tree $U = 11781$, $p = 0.134$).

Table 3-3: Median tree, shrub, and sapling characteristics by reach with upper and lower quartiles in brackets. Mann-Whitney U values and probabilities provide the statistical comparisons, with $t = p < 0.1$ and $* = p < 0.05$.

	Density	Elevation
Trees		
Upstream	3.0 (2.0, 5.0)	1.3 (1.0, 1.7)
Downstream	4.0 (2.0, 7.0)	1.6 (1.1, 1.8)
U	3782 (0.094 ^t)	3938 (0.211)
Shrubs		
Upstream	2.0 (1.0, 4.0)	1.2 (0.9, 1.6)
Downstream	3.0 (2.0, 6.0)	1.3 (1.1, 1.7)
U	8643 (< 0.001 [*])	9669 (0.005 [*])
Saplings		
Upstream	2.0 (1.0, 3.0)	1.2 (1.0, 1.6)
Downstream	2.0 (1.0, 3.0)	1.0 (0.8, 1.4)
U	2866 (0.972)	2041 (0.002 [*])

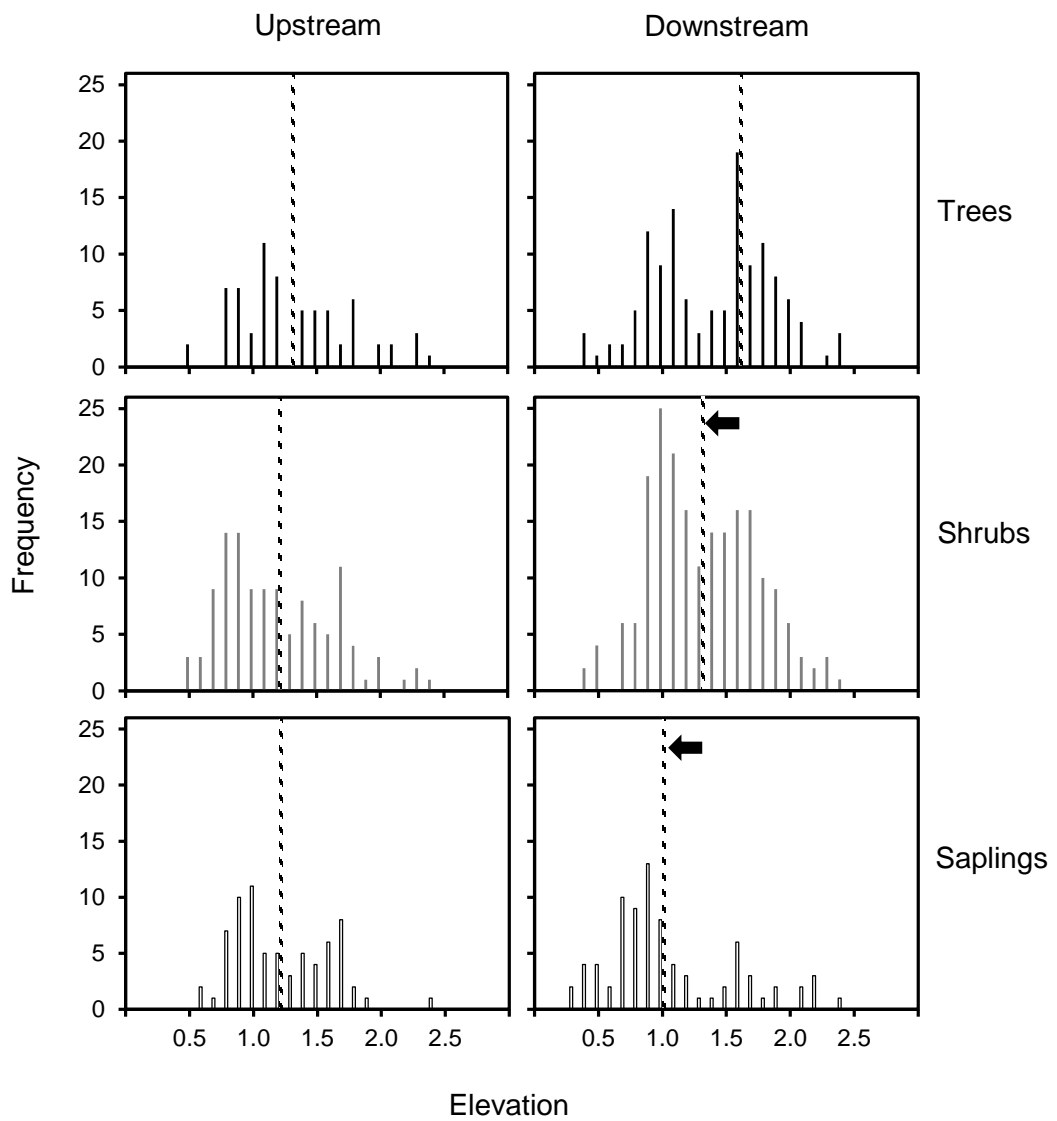


Figure 3-12: Elevation above the stage at base flow for cottonwoods along the Waterton River. Sample classification was based on cottonwood height with saplings <0.5 m, shrubs 0.5 to 2 m, and trees >2 m. Vertical lines represent median elevations for respective quadrats types. The arrows indicate the progressive decline in cottonwood elevation establishment.

3.4.5 Floodplain Physical Attributes

The downstream reach was investigated for to correspondences between the site physical characteristics of floodplain valley width and sediment texture and the cottonwood growth characteristics (Table 3-4). Cottonwood recruitment characteristics of density and elevation appeared to be influenced by the site's physical attributes, but these had little effect on the size of the cottonwoods (Appendix C). Consequently, only the site physical characteristics that correspond with recruitment characteristics are presented (Table 3-4). There also were some repeated, tightly correlated relationships between sediment texture and cottonwood density and elevation measurements (Table 3-4). Consequently, only typical representations of these associations are presented in figures to avoid redundancies.

Physical attributes, such as floodplain width and river slope, corresponded with specific components of the sediment particle distribution curve of a site and that texture was in turn related to cottonwood recruitment characteristics (Table 3-4; Figure 3-13; Appendix D). Generally, the proportion of finer sediment was correlated with increasing distance downstream, wider floodplains, and shallower river slope (Figures 3-13 and 3-14). A site that contained large clasts generally had a larger texture heterogeneity range, which decreased cottonwood densities and increased heights (Figures 3-13 and 3-15). Sites that contained finer clast sizes supported high densities of cottonwoods and generally established cottonwoods at higher elevations (Table 3-4). As sediments became coarser and heterogeneity increased, vertical extent of the capillary fringe would decrease (Mahoney and Rood, 1992). In association with these changes the cottonwood densities declined while the establishment elevation decreased. Figure 3-16 shows the effect of

thinning, which starts with abundant small plants and as they mature they become larger and therefore competition increases and the densities decrease.

Table 3-4: Kendall's Tau correlations between physical (site width, slope, and sediment) and establishment (density and elevation) characteristics. Statistical associations are in bold font: *= $p < 0.05$; t = $p < 0.1$. Sample sizes vary between physical ($n = 8$) and biological ($n = 16$) characteristics.

	Floodplain Width	River Slope	D ₁₆	D ₅₀	D ₈₄	Heterogeneity	Tree Density	Shrub Density	Sapling Density	Tree Elevation	Shrub Elevation	Sapling Elevation
Distance	0.429	-0.071	0.000	-0.357	-0.786*	-0.571^t	0.175	0.251	0.541*	0.267	0.168	0.178
Floodplain Width		-0.357	-0.429	-0.500^t	-0.357	-0.286	0.123	0.147	0.342^t	0.018	0.186	0.089
River Slope			0.500^t	0.571^t	0.143	0.071	-0.368^t	-0.234	-0.108	-0.462*	-0.577*	-0.658*
D ₁₆				0.357	0.071	-0.143	-0.088	0.095	0.108	-0.142	-0.279	-0.302
D ₅₀					0.429	0.500^t	-0.193	-0.320^t	-0.324^t	-0.373^t	-0.372^t	-0.373^t
D ₈₄						0.786*	-0.158	-0.320^t	-0.541*	-0.409*	-0.242	-0.196
Heterogeneity							-0.018	-0.320^t	-0.541*	-0.267	-0.112	-0.071
Tree Density								0.366^t	0.089	0.358^t	0.393*	0.341^t
Shrub Density									0.288	0.345^t	0.316	0.207
Sapling Density										0.027	0.122	0.090
Tree Elevation											0.677*	0.584*
Shrub Elevation												0.649*

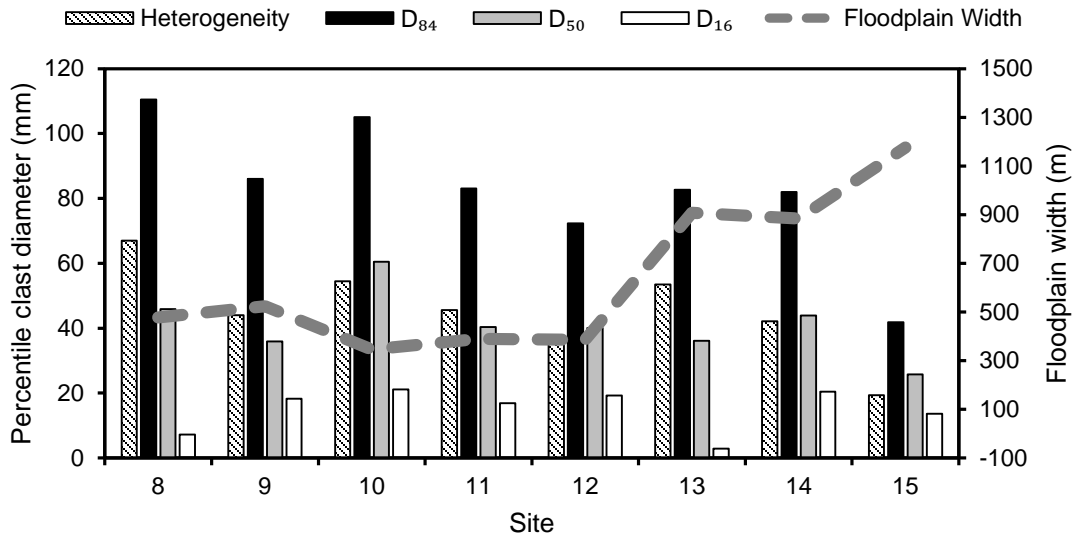


Figure 3-13: Diameter of particle distribution curve percentiles for the downstream reach of the Waterton River. The site heterogeneity is calculated as the $D_{75} - D_{25}$.

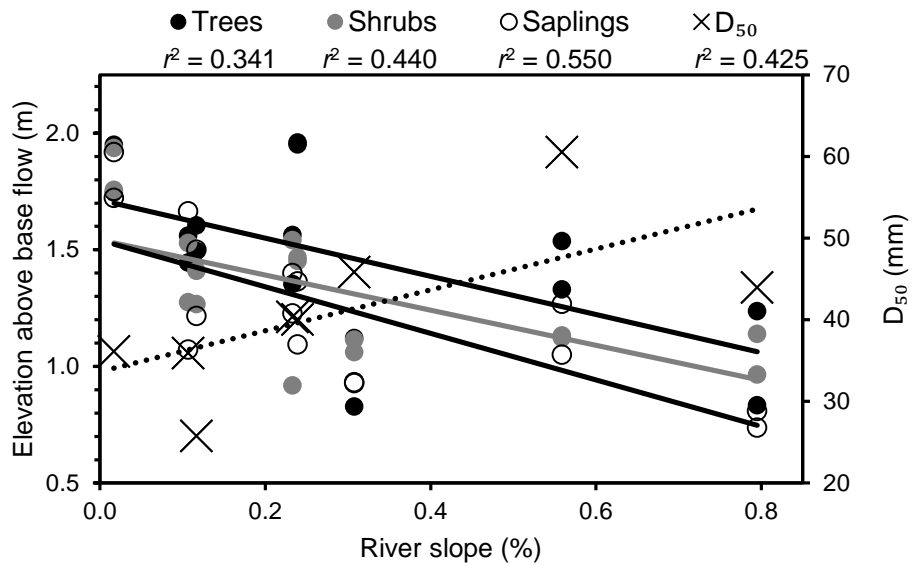


Figure 3-14: River slope correspondence between cottonwood elevation establishment above baseflow and the site median (D_{50}) particle size.

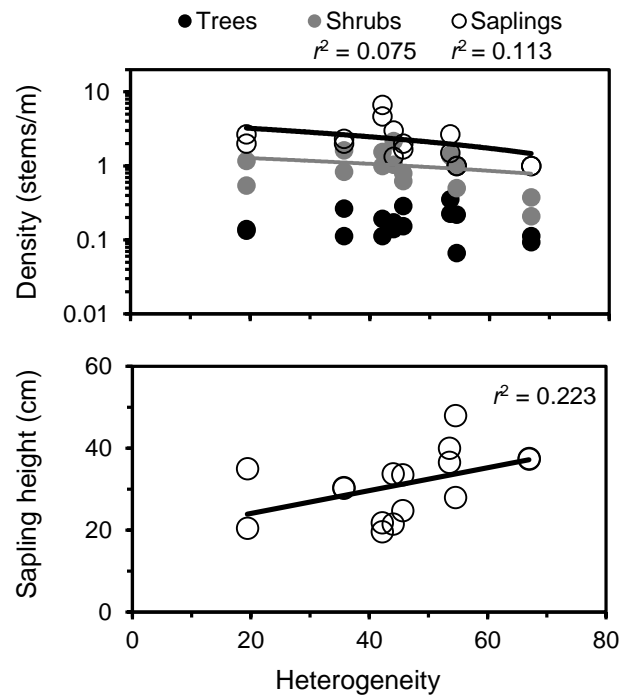


Figure 3-15: Site substrate heterogeneity correspondence with cottonwood density and sapling heights. Heterogeneity is calculated as the $D_{75} - D_{25}$.

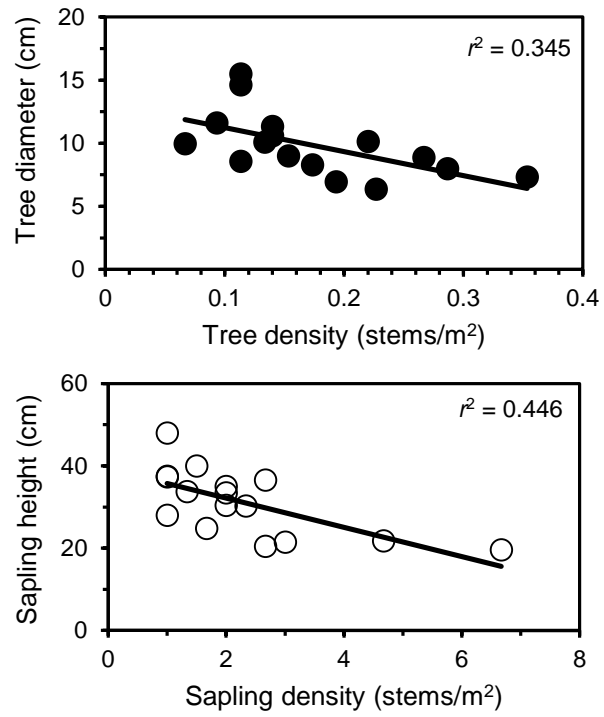


Figure 3-16: Site cottonwood density correspondence with sapling height and tree diameter.

3.5 Discussion

The implementation of Environmental Flows in the early 1990s appears to have been successful and have benefited the health of cottonwoods downstream from the Waterton Dam that was established in 1964. Cottonwood recruitment generally reflects the river flow patterns through the different management intervals. Substantial cottonwood recruitment persists along the Waterton River, especially within the last two decades when ramping flows were implemented (Figures 3-3 and 3-10).

It is well recognized that floods provide the underlying mechanism for cottonwood recruitment by providing the geomorphic disturbance necessary to produce extensive barren nursery sites through scour, transportation, and deposition of the alluvial sediments (Junk et al., 1989; Scott et al., 1997; Polzin and Rood, 2006). Flood years are particularly important for the downstream reach because water is usually abundant from the heavy rains that contributed to the flood and consequently there is less demand for irrigation and other uses, permitting more flexibility for meeting environmental needs. The Waterton Dam operators were able to provide an Environmental Flow regime to the downstream reach that returned favourable stage Recession rates following flood peaks that had been previously absent during the Drought interval throughout the 1980s (Figure 3-3).

Of the major floods, the flood of 1964 occurred in the first year of dam operation, and was substantially attenuated due to reservoir filling. Consequently, this major peak was proportionally lower along the downstream reach relative to the upstream peak than for the other major flood peaks (Figure 3-4). Other than this reduction of the 1964 flood

in the first year of reservoir filling, major floods have persisted along the downstream reach with little attenuation. For the smaller flood of 2014, the flood was somewhat reduced downstream, but still persisted with a substantial magnitude. This indicates that the reservoir capacity, combined with the pattern of regulation, does not substantially attenuate the major floods (Figure 3-4).

The cottonwood forest recruitment does not have an evident age gap missing from the population indicating recruitment has been consistent throughout the river management intervals (Figure 3-10). Also, the expected progressive punctuated age structure observed by Samuelson and Rood, (2004) along Drywood Creek, the major tributary of the Waterton River, was not observed along the Waterton River (Figure 3-10). Instead, a substantial amount of recruitment was younger than 10 years old and very few trees were observed to be older than 20 years old. This population structure is similar to that observed along a reach of the Rio Grande River in New Mexico described by Howe and Knopf, (1991) and the Elk River in British Columbia described by Polzin and Rood, (2006). This displays the 'r-life history' strategy of cottonwoods where many juveniles are established but a substantially fewer number, relative to the site carrying capacity, are expected to live into maturity (Braatne et al., 1996).

The population structure in Figure 3-10 has an added element of complexity as the cottonwoods along the Waterton River are from the *Tacamahaca* section (Rood et al., 1994). The *Tacamahaca* hybrid swarm is exceptionally adapted to the Rocky Mountain region that is characterized by coarse substrates and frequent high magnitude floods. Floods scour and erode the lower elevations and induce root suckering. Clones often follow from disturbance events, and may have blended a possible gap in the population

structure caused by the absence of ramping in the dammed pre-Environmental Flow interval, possibly following from the major flood from 1975.

A major benefit of Environmental Flows was the discontinued extreme low flow days with the implementation of the minimum flow criterion (Figure 3-11). Although growth season discharges remained relatively low with the extended droughts into the early 2000s, the increased minimum flow criterion nearly eliminated the extreme low flow days. By reducing this excessive artificial drought stress, downstream cottonwood tree ring growth appears comparable to that observed along the upstream reach. This suggests the woodlands long term health is largely dependent on the avoidance of low flow days and that the minimum flow criterion is sufficient for the success of the cottonwoods. The continued utilization of the minimum flow criterion will limit the artificial drought stress on cottonwoods.

Cottonwood saplings are establishing at similar densities between the upstream and downstream reaches (Table 3-3). This is in contrast to the shrub and tree sized cottonwoods that are establishing at significantly greater densities along the downstream reach. This may be caused by the downstream reach usually experiencing substantial cut and fill alluviation followed by patch recruitment (Chapter 2, Figure 2-10). The shrub and tree sized cottonwoods may have had the benefit of these recruitment processes during the major 1964, 1975, and 1995 floods. Besides the 2014 flood, there were no recent substantial floods and avulsions to generate a mass recruitment event that would have caused patch recruitment and increased sapling densities downstream (Chapter 2, Figure 2-7). However, following from the 2014 flood, greater downstream densities may be observed once new cottonwoods recruit from this disturbance.

Another consideration of the cause of lower downstream sapling densities may be in relation to the significantly lower elevation of sapling establishment along the downstream reach (Table 3-3 and Figure 3-12). Recruiting cottonwoods at lower elevations increases their susceptibility to scour (Braatne et al., 2007). With increased potential for scour, fewer saplings may be capable of recruiting along the downstream reach and therefore lower densities are observed.

Although increasing the minimum flow criterion has reduced the stress upon the cottonwood along the Waterton River, the minimum flow criterion ($2.27 \text{ m}^3/\text{s}$) is substantially lower than the Pre-Dam typical August minimum flow of $10 \text{ m}^3/\text{s}$. Reduced late summer flows appear to have had a major impact on cottonwoods within the observations of the study. New cottonwoods appear to be recruiting at lower elevations relative to the recruitment structure observed along the upstream reach (Figure 3-12). While the upstream reach was observed to have recurrent cottonwood recruitment at similar elevations throughout all quadrat sizes, the downstream reach had established cottonwoods at progressively lower elevation. With reduced summer flow, cottonwoods appear to be encroaching into the newly exposed portions of the gravel bars following from the reduced stage levels (Figure 3-12). However, the progressively lower elevation of establishment observed along the downstream reach may actually be expected throughout most river systems through processes of aggrading surfaces. It is possible that the upstream reach of the Waterton River experiencing overlaid recruitment may be an artifact of the presence of more confined floodplains.

However, the observation of lower cottonwood elevation establishment is supported by Wildings et al. (2014) who detected prolific narrowleaf cottonwood, *P.*

angustifolia, establishment downstream from many dams in Colorado, USA where flood peaks were attenuated and channel narrowing had occurred. Although all riparian cottonwoods are susceptible to droughts, narrowleaf cottonwoods, which occur along the Waterton River, are somewhat resistant to flood disturbances. This may explain the readiness of the narrowleaf cottonwoods to establish at lower elevations and survive despite the continuing frequent large floods (Figure 3-12). Also, Braatne et al. (2007) observed establishment of black cottonwood, *P. trichocarpa*, at lower elevations along the Yakima River in Washington, USA following major dam regulation. They concluded that lower establishment was still susceptible to scour. This may be because the black cottonwoods are not as flood tolerant as the narrowleaf cottonwoods (Amlin and Rood, 2002; Rood et al., 2010a). The pliable stems and narrow leaves may allow the narrowleaf cottonwoods along the Waterton River to better survive the scour or shearing from flood flows.

There are many geomorphologic characteristics that may impact the water availability of cottonwoods. Willms et al. (2006) found that wider floodplains supported cottonwoods that were smaller in size and attributed that finding to increased competition due to higher cottonwood densities and broader woodland bands. In this study, although floodplain widths did not substantially affect cottonwood size, floodplain geomorphology did influence sediment texture (Table 3-4). Cottonwoods have been observed to grow and thrive on a wide range of sediment textures (Rood and Mahoney, 2000). In particular, narrowleaf cottonwoods are well adapted to grow on coarse substrates (Rood et al., 1995, Rood et al., 1998). A site containing finer substrate particles will have an increased capillary fringe potential and bring water to higher elevations, generating greater water

availability (Mahoney and Rood, 1992). Site along the Waterton River that contained larger clasts sizes often had less sediment texture heterogeneity and this influenced cottonwood density and height, especially saplings (Figure 3-13 and 3-15). Among the sites that contained finer particle textures, cottonwoods generally had high densities probably due to the greater abundance of water (Table 3-4 and Figure 3-16). Cottonwoods on these sites tended to be shorter and thinner probably due to the increased vegetation competition. Likewise, when a site contained more coarse material, cottonwood density declined but they were generally larger in size (Figures 3-15, and 3-16). These characteristics probably benefit the cottonwood population along the Waterton River. The high density groves occurring along the finer textured sites, and therefore experiencing a greater capillary fringe, would be better suited to compete with other floodplain vegetation. Cottonwoods growing in narrower and steeper floodplains containing more coarse substrates tended to grow in lower densities but larger in size and thus may be capable of greater resistance against flood disturbances at lower elevations.

3.6 Conclusion

In conclusion, the Waterton River has been impacted by, and is adapting to, a new flow regime since the dam and reservoir establishment in 1964. The implemented flow management strategies and moderate reservoir capacities for flood attenuation have limited the negative effects and have even benefited cottonwood growth and establishment characteristics. The river was dammed for irrigation supply but the flow regime was not noticeably modified until the droughts commencing in the late 1970s. Environmental Flow management strategies were adopted in the early 1990s and subsequently the downstream reach was only severely impacted for approximately the

previous 15 years. The Waterton River clearly still contains a relatively healthy gallery forest with a range of age cohorts. The large floods, timing, stage, and scouring effects of floods have not been affected by the operation of the dam. The ramping rate following peak flows and late summer river flows have been impacted by the implementation of the Waterton Dam, but Environmental Flow strategies introduced in the 1990s have reduced these impacts.

The imposition after Environmental Flows had several effects on the downstream reach of the Waterton River. The basal area increments of downstream cottonwoods have increased and are comparable to those observed along the upstream reach. This is attributable to the implementation of the minimum flow criterion. Cottonwood saplings are establishing at lower elevations along the downstream reach than they had previously and also compared to the upstream reach. The current status of the Waterton River's gallery forest is positive despite being located downstream from a major dam and the success is attributed to a prompt initiation and continuation of Environmental Flows. The Waterton River currently provides a positive case study for the implementation of an Environmental Flow approach and encourages adopting a similar strategy along other regional rivers to utilize similar methods to support floodplain woodlands.

CHAPTER FOUR: Conclusion: Suggestions and Future Recommendations

4.1 Introduction

The Waterton River was dammed in 1964 to satisfy the growing demand for irrigation water within southern Alberta, a semi-arid region. With the national controversy surrounding the environmental impacts and the legality of the Oldman River Dam Project in the late 1980s, public attention was focused on the ecological impacts of damming rivers (Glenn, 1999). One prominent criticism was the potential effects on riparian cottonwood (*Populus* tree species) forests. Cottonwood forests are especially important in this region because they support a high level of wildlife and biodiversity as compared to the adjacent treeless plains (Swift et al., 1984; Knopf et al., 1988; Finch and Ruggiero, 1993, Naiman et al., 1993).

Special attention was placed on the St. Mary River because it is a major tributary to the Oldman River and has been regulated for irrigation since 1898 and dammed in 1951 (Rood and Heinze-Milne, 1989; Reid et al., 1992; Rood et al., 1995). Beginning in the late 1980s, the St. Mary River woodlands were compared to both the adjacent, more recently regulated, Waterton River and the free-flowing Belly River. Aerial photograph interpretation indicated that the woodlands along the St. Mary River had almost entirely collapsed, while those along the Waterton River were somewhat impacted, and those along the Belly River were thriving (Rood and Heinze-Milne, 1989; Rood et al., 1995). The woodland mortality was attributed to abrupt river stage declines that limited seedling establishment and insufficient late summer flows that stressed mature trees (Rood et al., 1995). Beginning in the early 1990s, dam operators within the Oldman River watershed

began to employ deliberate Environmental Flow strategies in an attempt to meet the critical hydrological needs of the riparian cottonwoods (Rood and Mahoney, 2000; Rood et al., 2016). First, for the Waterton River the minimum allowable flow was more than doubled, from 0.93 to 2.27 m³/s (*Water Act Alb.Reg. 307/91*). Second, gradual flow recession was implemented downstream of the Waterton Dam after the spring peaks, especially after major floods, in an effort to encourage woodland rejuvenation (Rood et al., 1998).

4.2 Thesis Chapters Summary

In this study, the health of the cottonwood forest along the Waterton River was evaluated after half a century of regulation and after about two decades of deliberately regulated Environmental Flows. For Chapter 2, aerial photographs were acquired for approximately decadal intervals between the 1950s to 2009 and digitized to delineate the areal extents of the Waterton River cottonwood forests (Figure 2-2). These comparisons revealed the persistence of the riparian woodlands over the study period. Apparently, few cottonwood groves were impacted by artificial drought stress, probably because the interval between damming and the implementation of Environmental Flows was relatively brief.

The capacity of the Waterton Reservoir is insufficient to completely attenuate major floods (Figure 2-7) and therefore substantial flows that cause scouring, channel movements, and avulsions have persisted along the downstream reach. Variability in forest area mainly corresponded with river channel migration and avulsions following major floods that eroded patches or bands of cottonwood forests (Figure 2-9). These

channel changes create suitable seedling establishment sites (Polzin and Rood, 2006). The total cottonwood forest area appeared to remain relatively consistent throughout the photographic series, suggesting that cottonwood forests were being replenished at rates similar to mortality rates (Figure 2-2). The floodplains along this river are large especially along the downstream reach and contain an abundance of mature cottonwoods. When river processes remove existing cottonwood trees, a sufficient number of mature trees remain to provide seeds for regeneration, thus allowing for a successful and prompt recovery of the overall forest.

In Chapter 3, a hydrological recruitment analysis was undertaken to evaluate favourable years for cottonwood seedling establishment. Results were then compared to the field observations. The established cottonwoods were quantified using transects at field study sites along the downstream reach and compared to the upstream reference or control reach. The components that were substantially affected by the dam operation were abrupt river stage recession rates and low summer flows, especially during the drought interval throughout the 1980s (Figure 3-3). When Environmental Flows were implemented in the early 1990s, there was some recovery of the late summer flows along the downstream reach and gradual stage recession rates were introduced following the substantial flood peaks. Consequently, the cottonwood population structure along the downstream reach currently resembles that of the upstream reach including younger cohorts (Figure 3-10).

The field observations indicated that the newly established saplings appear to be recruiting at progressively lower elevations along the downstream reach, while the upstream forests appear to establish at consistent elevations (Figure 3-12). Lower

elevation encroachment may be an expected consequence following the establishment of a dam and reservoir (Bradley and Smith, 1984; Braatne et al., 2007; Wilding et al., 2014). However, it is possible that the progressively lower establishment elevation observed along the downstream reach is normal, and that the recruitment along the upstream reach of the Waterton River might be an unusual consequence of the more confined floodplains.

A substantial decline in tree ring growth increments for mature trees along the downstream reach was evidence of additional drought stress after dam establishment (Figure 3-11). After the Environmental Flows were implemented, the downstream woodlands appear to have recovered from the drought stress since there was subsequently comparable tree ring wood production between the upstream and downstream reach. This provided a measurable benefit from the implementation of the Environmental Flow regime. Thus, if the current minimum flow criterion is adhered to, the woodlands along the Waterton River are predicted to remain healthy.

4.3 Methodology Suggestions

4.3.1 Aerial Photographs

Cottonwood populations along the downstream reach appear to benefit from river disturbances associated with floods (Chapter 2). The establishment of the Waterton Dam could impose changes to the frequency of disturbances by altering the downstream flow patterns. Flow stabilization can reduce river migration and subsequently limit suitable cottonwood seedling establishment sites and thereby influence forest structure (Bradley and Smith, 1984; Rood et al., 1999). Channel changes are difficult to measure along the Waterton River. A random placement of cross sections to measure channel width or a

thalweg migration rate is problematic because of river avulsions in sequential photographs. These avulsion occurrences are common and make random sampling of gradual migration nearly impossible. Sites that are manually chosen to provide measurements of channel migration may impose a bias because these sites are probably more resistant to river shifting forces.

Hard copies of aerial photography allow an interpreter to view the scene in stereo vision and observe the vertical growth of sapling maturation. The Alberta Air Photo Distribution centre has discontinued the reproduction of contact print hard copies but instead offer laser print copies, which do not have comparable resolution. Future studies will not substantially benefit from laser prints of historical aerial photography for stereo interpretation. Acquiring historical photos in digital copy instead of hard copy may provide better resolution since there is less scanning and printing which compound distortions.

4.3.2 Field Research Sites

In this study, field sites were chosen in an effort to minimize human influences such as livestock grazing or floodplain developments. Although not the case for over the entire river, some sections of forest did not have an understory containing juvenile cottonwoods due to cattle browsing and trampling (Figure 4-1). It is well documented that allowing cattle into riparian zones greatly reduces the potential of vegetation establishment (Fenner et al., 1985; Samuelson and Rood, 2004; Samuelson and Rood, 2011). These sites will be completely treeless when the existing mature trees eventually die, unless emergency management is introduced to allow the riparian zone to recover

from disturbances. It is recommended to support offstream livestock watering facilities and limit floodplain human activities to allow cottonwoods seedlings to establish in these areas and allow the riparian zones to recover.

A challenge when comparing the upstream versus downstream reaches of rivers within the Oldman River Basin is accounting for the differing underlying geology. As early as the 1880s, George Dawson distinguished the geologic transition zones that occur in the Oldman River Basin (Figure 4-2; Dawson and McConnell, 1884). The lower St. Mary River flows through the 'St. Mary' and 'Pierre' formations that is characterised by sandstone. The lower Waterton and Belly Rivers flow through the 'Willow Creek' formation that is characterised by mudstone. The erodibility differences between these sandstone and mudstone formations may influence floodplain widths and thus limit the areal extents that riparian forests may establish (Hicks et al., 1996; Willms et al., 2006).



Figure 4-1: The absence of cottonwood understory along the Waterton River downstream from the Waterton Dam. Notice in the foreground an ATV is being driven in the riparian zone and cattle have access to the river.

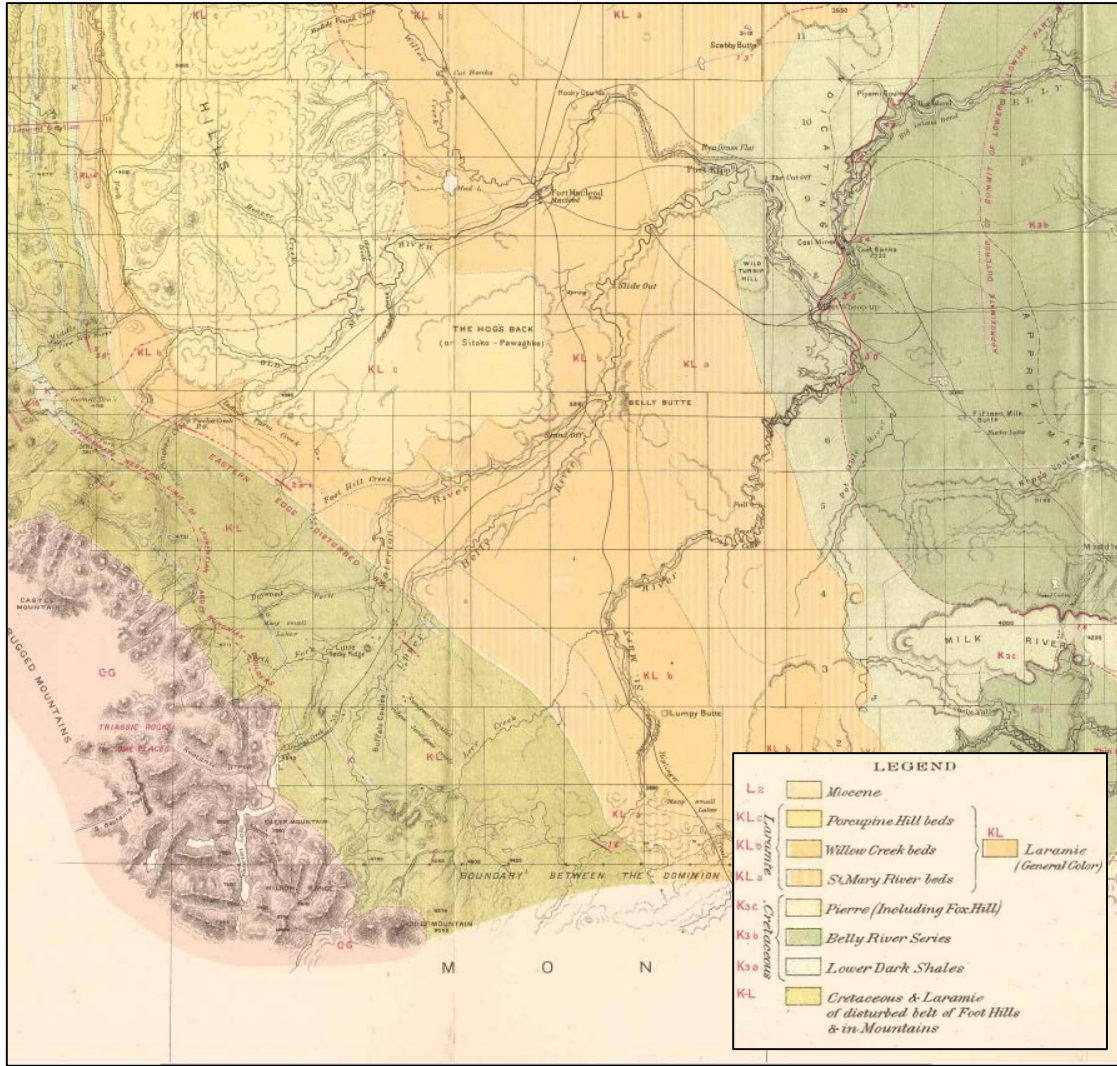


Figure 4-2: George Dawson's physical geology map displaying the layers that the southern Oldman River Basin rivers flow across.

4.4 The Belly River

The natural resources map drawn by Dawson and McConnell in 1884 shows the vegetation along rivers in southern Alberta (Figure 1-3). Observing the current condition of vegetation and comparing it to this historic document indicates that substantial change has occurred to the Belly River. This map displays sparse forest vegetation along the Belly River, but currently the Belly River has a great abundance of cottonwoods that fill the entire length of the river as confirmed by Rood et al. in 1995. In that study, the Belly River's cottonwood forest increased by +52% between the photographs taken in 1951 and 1985. It may be very beneficial to research what caused the dramatic increase in cottonwood abundance. Perhaps the natural cause that increased the forest population may be artificially applied to cottonwood depleted rivers such as parts of the Waterton River and the cottonwood impoverished segments of the St. Mary River.

4.5 Continued monitoring

Although the outlook for the cottonwoods along the Waterton River is promising, continued monitoring is imperative to provide feedback into the dam management strategies. Ongoing field assessments should be completed alternating with aerial photography interpretation at regular intervals. Forests along the St. Mary River had collapsed following from approximately 40 years of irrigation dam management (Rood and Heinze-Milne, 1989; Rood et al., 1995). Therefore, it is recommended that a woodland observation should be undertaken every 5 years to provide sufficient time to detect and modify management strategies accordingly.

Aerial photography interpretation should follow the methodology presented in Chapter 2 allowing for historical comparisons over time. Attention should be placed on the woodland furthest away from the river because that is where the depth to the groundwater table is greatest and where cottonwoods are most susceptible to drought mortality (Harner and Stanford, 2003). An improvement to this analysis would be to qualify segments of the Waterton River based on the apparent land use practices, such as grazing or agricultural production, to better compare the impacts of Environmental Flows. With multiple aerial photography interpretation studies, the responses of the cottonwoods to dam management will be documented over time.

Field sampling should occur at similar locations as undertaken in Chapter 3, although sites are subject to river migration and avulsions that may make permanent transects impractical. Cottonwood sizes and densities should be measured and compared between sites and between studies over time. The Waterton River currently provides a positive case study for the Environmental Flow dam management implementation and continued monitoring is crucial to reinforcing the outcomes of these strategies. With the positive outcome observed as part of this current study, it is recommended that Environmental Flows continue to be implemented along the Waterton River.

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APPENDIX A

Aerial Photography Digitization Results

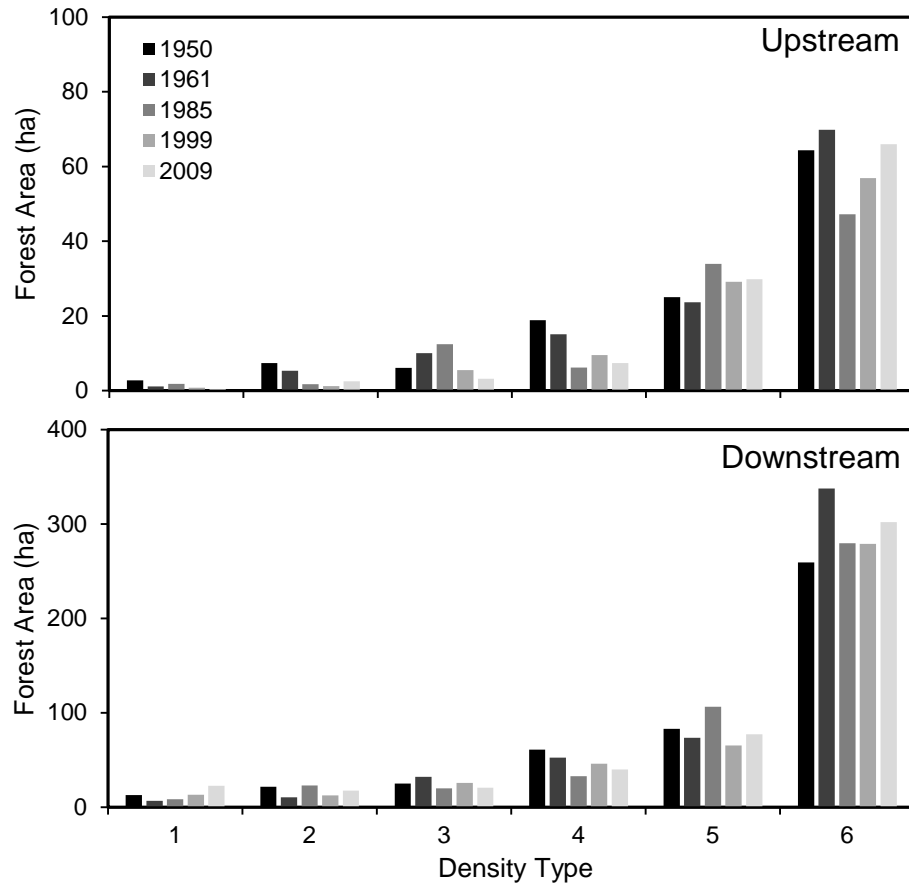


Figure A-1: Original six category density classification for the Waterton River. Note different y axis scales.

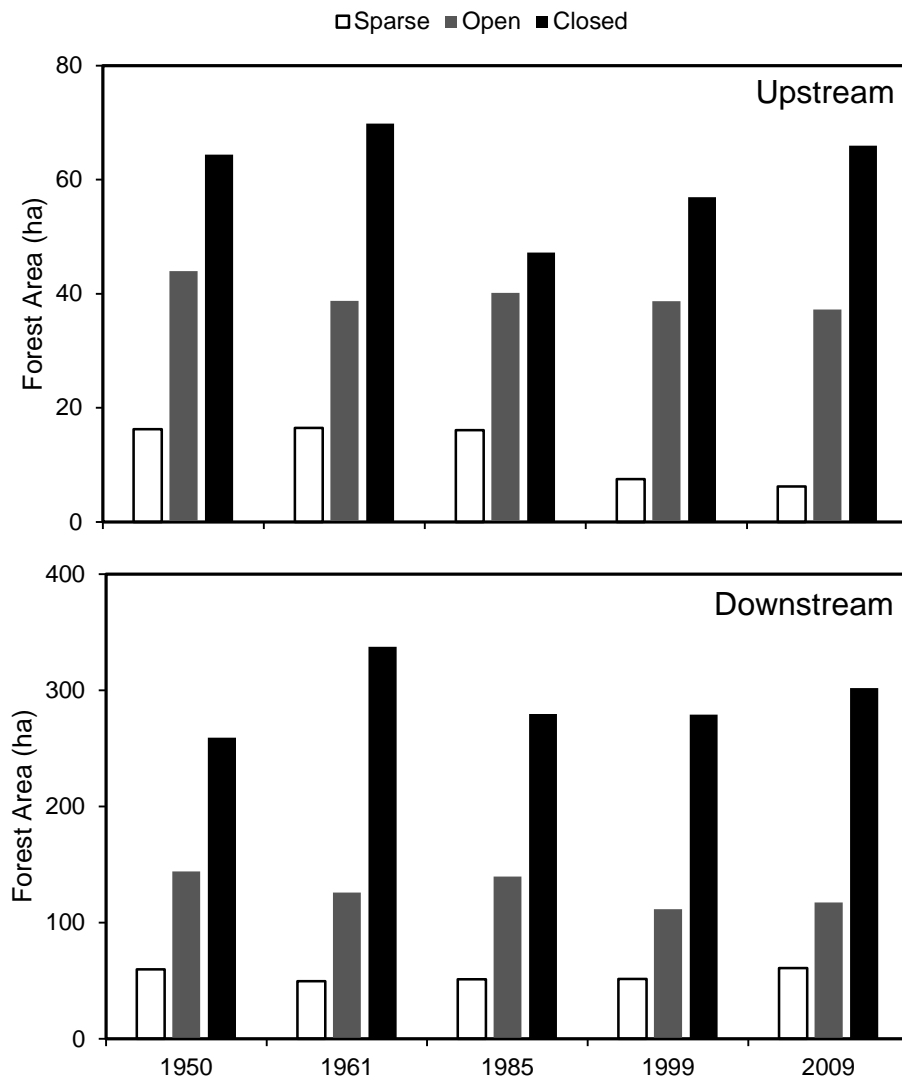


Figure A-2: Condensed density classification of forested area along the Waterton River. Note different y axis scales.

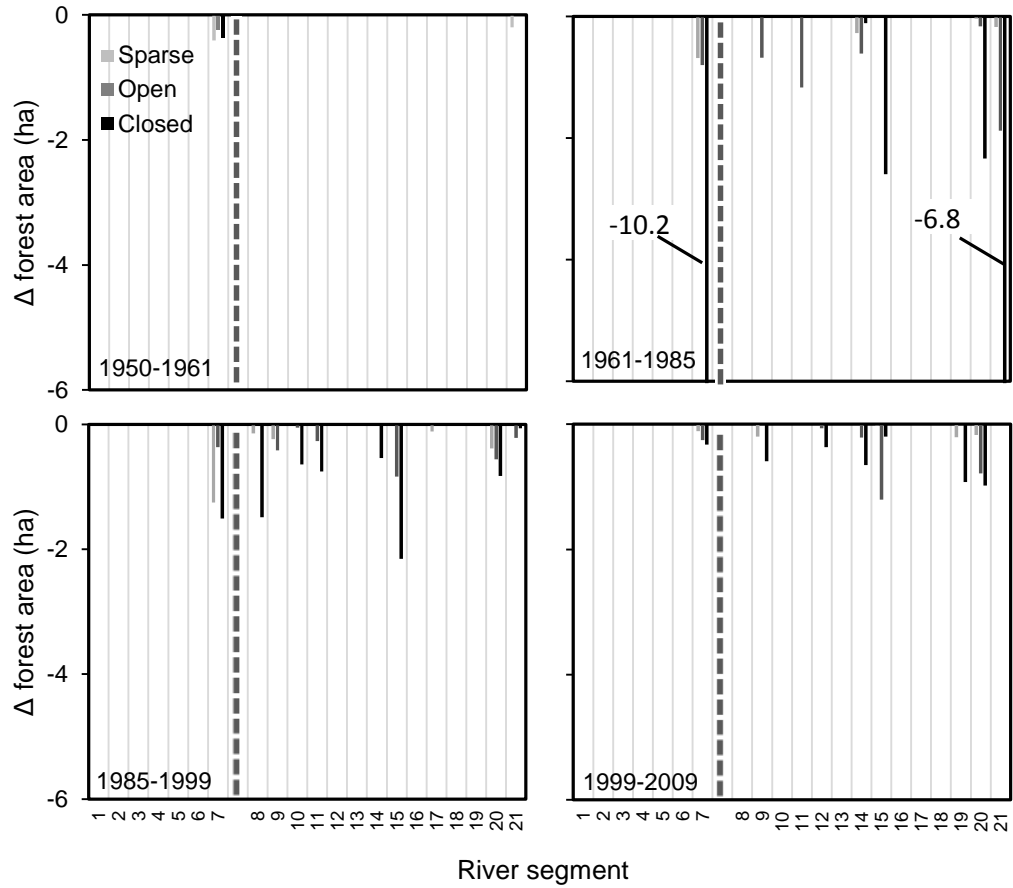
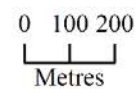


Figure A-3: Forested area removed by human floodplain development between photographed years. Segments 1-7 and 8-21 represent upstream and downstream reaches, respectively. The dashed line represents the location of the Waterton Reservoir.



Figure A-4: Woodland clearing along the Waterton River for crop agriculture purposes at the confluence with the Belly River. Photographs correspond with the 21st segment of the downstream study reach.



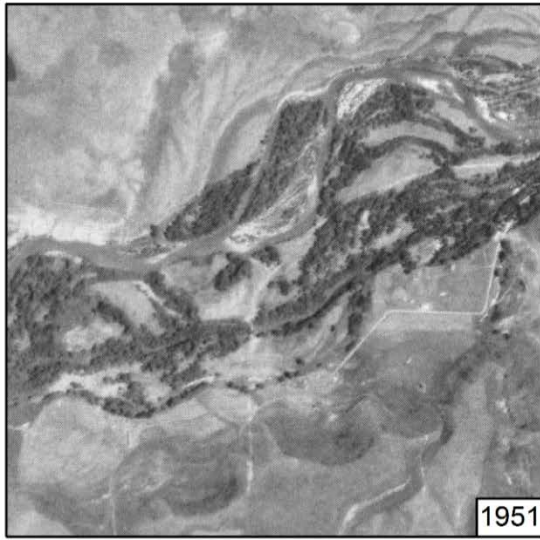


Figure A-5: Industrial feedlot and dairy ranching development along the upstream reach of the Waterton River. These photographs correspond with the 7th segment of the upstream study reach.

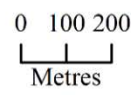


Table A-1: Coordinates and summary descriptions of changes between aerial photography digitizing segments for the Waterton River. This table continues on the next 4 pages.

Seg. #	Coordinates (Lat/ Long)	1950-1960	1960-1985	1985-1999	1999-2009	Comments
1	49.13 -113.83	Development of a small park. Noticeable recruitment prior to 1951.	Slightly more development of parks. Maturation of previously recruited trees.	Lots of maturation, Evidence of recruitment on gravel bars.	No substantial changes.	Confluence with Cottonwood Creek. Minor development and colonization. Substantial maturation in areas.
2	49.15 -113.79	No substantial changes.	No substantial changes.	No substantial changes.	No substantial changes.	No substantial changes. Very narrow floodplains except for one meander bend.
3	49.17 -113.77	No substantial changes.	No substantial changes.	No substantial changes.	No substantial changes.	No substantial changes. Mostly narrow floodplains except for two small meander bends.
4	49.20 -113.76	No substantial changes.	No substantial changes. A bridge was built with marginal effect on cottonwoods.	No substantial changes.	No substantial changes.	No substantial changes. Very narrow floodplains.
5	49.22 -113.75	No substantial changes.	No substantial changes.	No substantial changes.	No substantial changes.	Confluence with Dungarvan Creek. No significant changes. Mostly narrow canyons.

Seg. #	Coordinates (Lat/ Long)	1950-1960	1960-1985	1985-1999	1999-2009	Comments
6	49.23 -113.75	Slight amounts of erosion. Evidence of development prior to 1951.	Channel avulsions cause erosion of forest. Creation of abandoned channel. Established trees matured.	Some avulsions and migrating channel movement. Another abandoned channel created.	Lots of maturing of trees. Slight amounts of erosion.	Lots of channel movement with recruitment establishing in the abandoned channels. Beginning of broad floodplains.
7	Start: 49.25 -113.71 Finish: 49.26 -113.68	Minor amounts of erosion and the development of a road in the floodplain.	Extensive floodplain development (roads, feedlot, mining, berms). Channel migration causing tree erosion.	Further floodplain development. Noticeable thinning of forests. Some migration erosion. Recruitment on gravel bars.	Maturation of recruited trees. Deposition bars with recruitment. Development seems to have ceased.	Palmer Ranch. Waterton Hutterite Colony. Major channel movement. Extensive berms. New recruitment matured.
8	49.33 -113.66	Maturation of established trees. Evidence of some floodplain development prior to 1951 (household).	Dieback of some trees in narrow floodplains. Maturation of established trees. Evidence of recruitment bands.	Continued dieback in narrow floodplains. Floodplain development of a gravel pit. Evidence of recruitment bands.	Lots of new recruitment and maturing of trees. Slight amounts of erosion.	Some developed forests were lost in the narrow floodplains. A gravel pit was developed. Recruitment bands matured.
9	49.36 -113.66	Recruitment bands established prior to 1950 have substantially matured. Little change otherwise.	Maturation in broad floodplains. Dieback in narrow floodplains. Forest removal via channel avulsions, also creating abandoned channels.	Heavy dieback in narrow floodplains. Forest removal via channel migration. Abandoned channels become recruited.	Lots of maturation in broad floodplains. Continued dieback narrow floodplains. Maturation of new recruitment.	Susceptible to channel erosion. Abandoned channels recruited and experienced lots of maturation.

Seg. #	Coordinates (Lat/ Long)	1950-1960	1960-1985	1985-1999	1999-2009	Comments
10	49.38 -113.63	Maturation of recruitment. Episodic channel movement removed forest and created abandoned channels.	Heavy amounts of channel erosion. Recruitment of abandoned channels and continued maturation.	Further maturation and recruitment in abandoned channels. Minor amounts of development and channel erosion.	Lots of maturation, and arcuate fringe recruitment.	High amount of channel erosion followed by high amounts of recruitment and maturation.
11	49.40 -113.59	Lots of maturation and recruitment. High amounts of episodic erosion and creation of abandoned channels.	Continued channel erosion. High amounts of recruitment and maturation within abandoned channels.	Continued maturation of previously recruited zones. Minor amounts of erosion and development.	High amounts of maturation. High amounts of recruitment on point bars.	Confluence with Foothill Creek. Susceptible to channel erosion. Lots of recruitment in abandoned channels and point bars.
12	49.40 -113.57	Maturation of previously established trees. No substantial erosion or developments.	Forest removal via channel migration. Further maturation of established trees.	Slight amounts of continued erosion. No other substantial changes.	Thinning of forest probably caused by nearby development. Recruitment on point bars.	Lots of maturation of established trees. Mild erosion caused by channel migration.
13	49.41 -113.53	Noticeable tree removal via channel migration. Maturation of established trees.	Continued erosion via channel migration. Maturation of small recruitment patches.	Avulsions and migration. Recruitment of abandoned channels. Maturation of established trees.	Maturation of previously recruited abandoned channels. Heavy recruitment of point bars. Thinning of mature forests.	Lots of erosion over a large meander, lots of recruitment, noticeable dieback on meander bend.

Seg. #	Coordinates (Lat/ Long)	1950-1960	1960-1985	1985-1999	1999-2009	Comments
14	49.42 -113.50	Hwy 810 bridge established pre-1951. Maturation of established trees.	Floodplain development (revamped bridge, farms). Minor amounts of erosion.	Some maturation of established trees. Creation of campground. Minor channel erosion. Patches of recruitment.	Maturation of previous recruitment. Continued campground development.	Lots of maturation of established trees. Mild impact from floodplain developments.
15	49.43 -113.47	Pre-1951 floodplain development (Hutterite colony). Heavy maturation of established trees.	Floodplain development of Hutterite Colony. Slight maturation of established trees.	Extensive floodplain development of Hutterite Colony. Slight maturation of established trees. Some recruitment.	Continued development of Colony. Thinning of established trees. Extensive recruitment along gravel bars.	Riverside Hutterite Colony development has impacted adjacent forest. Apparent recruitment on gravel bars.
16	49.43 -113.43	Minor maturation of established trees. No other significant changes.	No substantial changes.	No substantial changes.	No substantial changes.	No substantial changes.
17	49.44 -113.41	Large pre-1951 floodplain farming. Minor maturation of established trees.	No substantial changes.	No substantial changes.	Minor amounts of recruitment bands. No significant changes.	No substantial changes despite large floodplain farm.
18	49.45 -113.38	Minor maturation of established trees. No substantial changes.	No substantial changes.	No substantial changes.	Minor amounts of recruitment bands and maturation of established trees.	No substantial changes. Narrow floodplains.

Seg. #	Coordinates (Lat/ Long)	1950-1960	1960-1985	1985-1999	1999-2009	Comments
19	49.47 -113.37	Tree removal via channel migration erosion. Large floodplain displaying maturation.	Extensive forest erosion due to channel migration. Lots of recruitment on large gravel bars.	Continued forest erosion due to channel migration. Maturation of recruitment.	Extensive maturation of recruitment. Minor forest removal via development and channel migration.	Evidence of substantial downstream meander migration pre-1951. Broad floodplain with channel erosion and recruitment.
20	49.49 -113.34	Large floodplain displaying maturation and recruitment. Tree removal via channel migration erosion. Some pre-1951 development.	Extensive forest erosion due to channel migration. Lots of recruitment on large gravel bars. Further development.	Forest erosion via channel migration. Abandoned channels. Extensive recruitment. Continued development.	Extensive floodplain development of RV campground. Further channel migration and gravel bar recruitment.	Hwy #2 bridge. Development of RV campground. Lots of erosion, deposition, and recruitment.
21	Start: 49.51 -113.30 Finish 49.52 -113.27	Forest erosion via channel migration. Maturation of established trees on broad floodplains.	Extensive erosion via channel migration. Extensive floodplain farm development. Lots of deposition and recruitment.	Further erosion and minor farming development. Continued deposition and recruitment.	Very little forest removal via erosion and development. Extensive recruitment and maturation of prior recruitment.	Broad floodplain. Extensive channel erosion and floodplain farming. Lots of fringe recruitment in arcuate bands.

Appendix B

Transect Representations

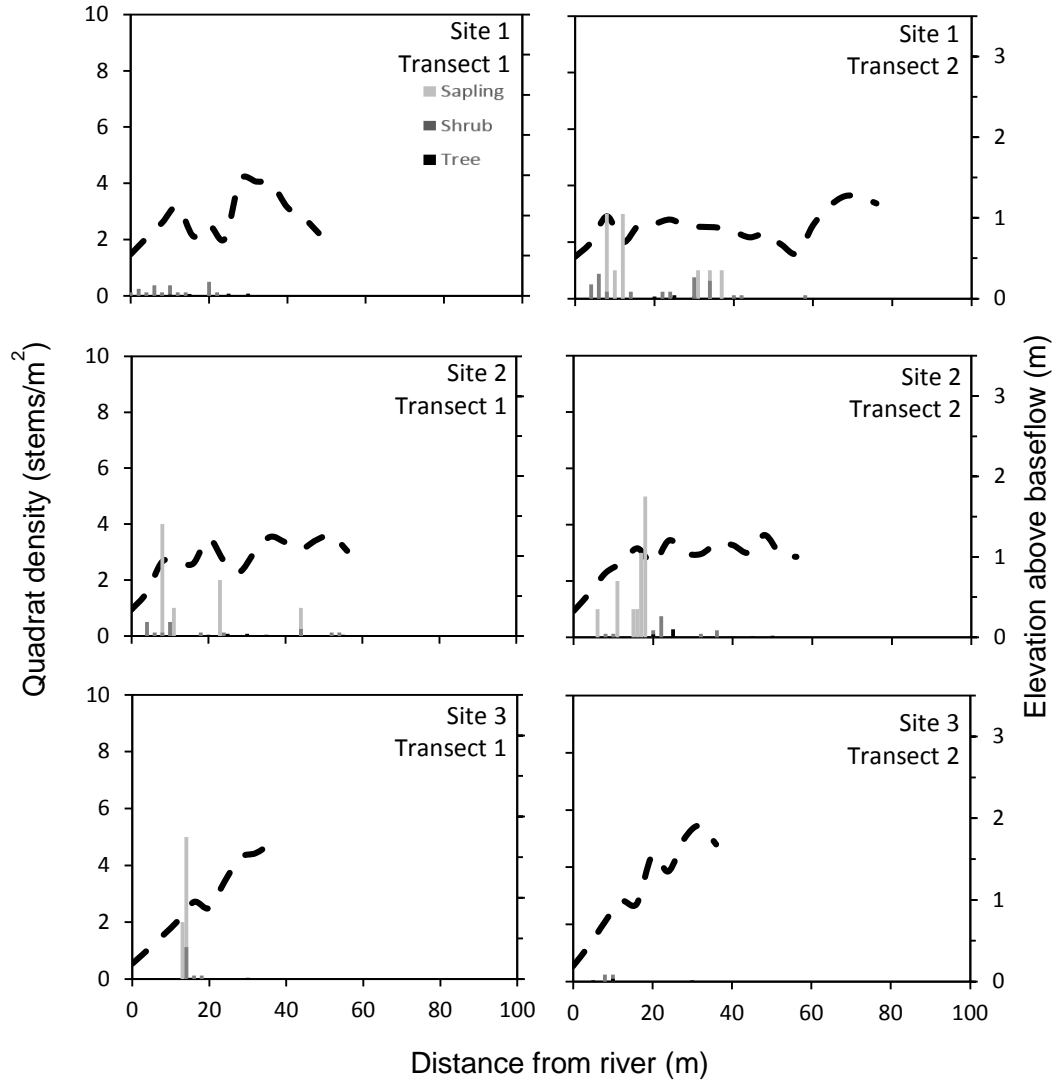
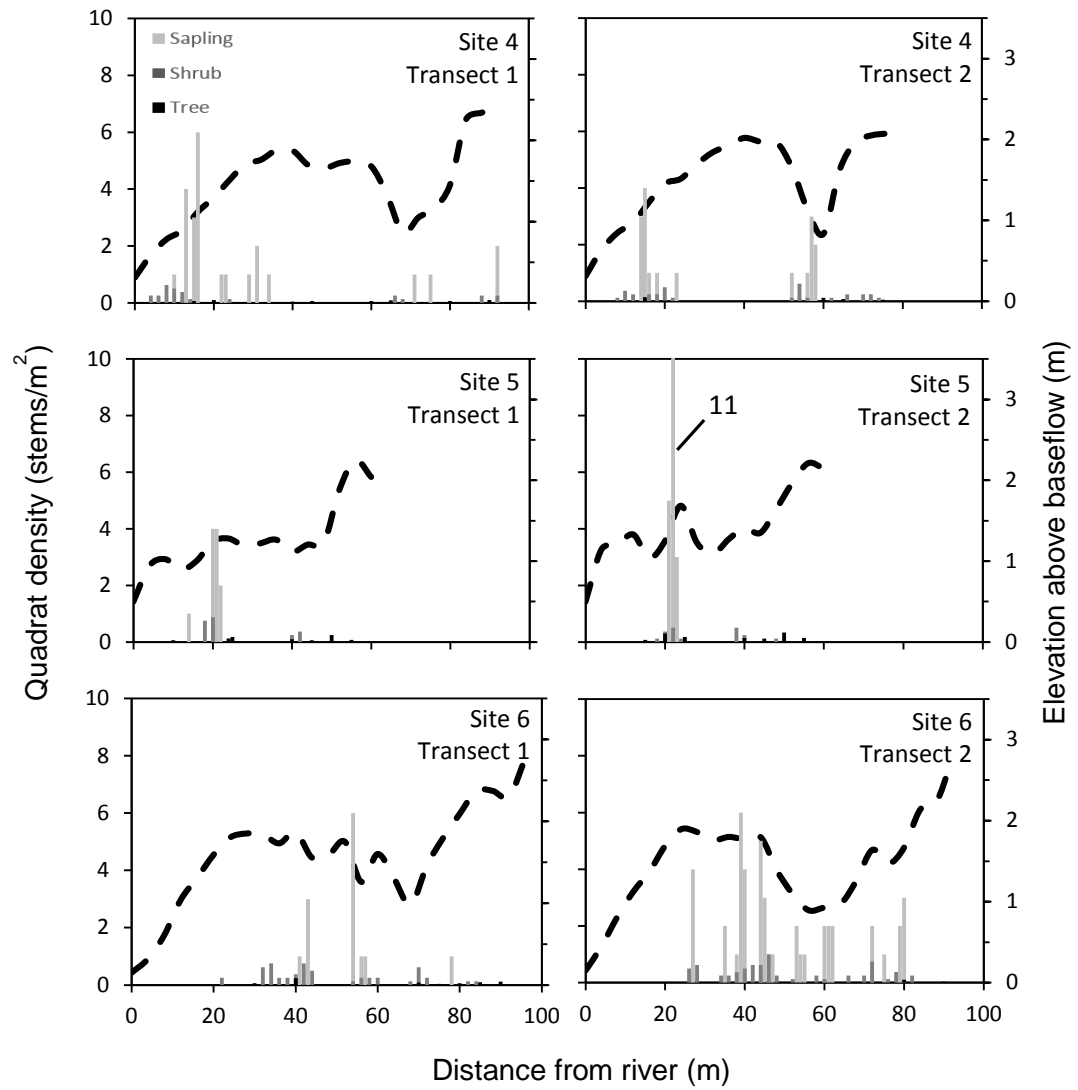
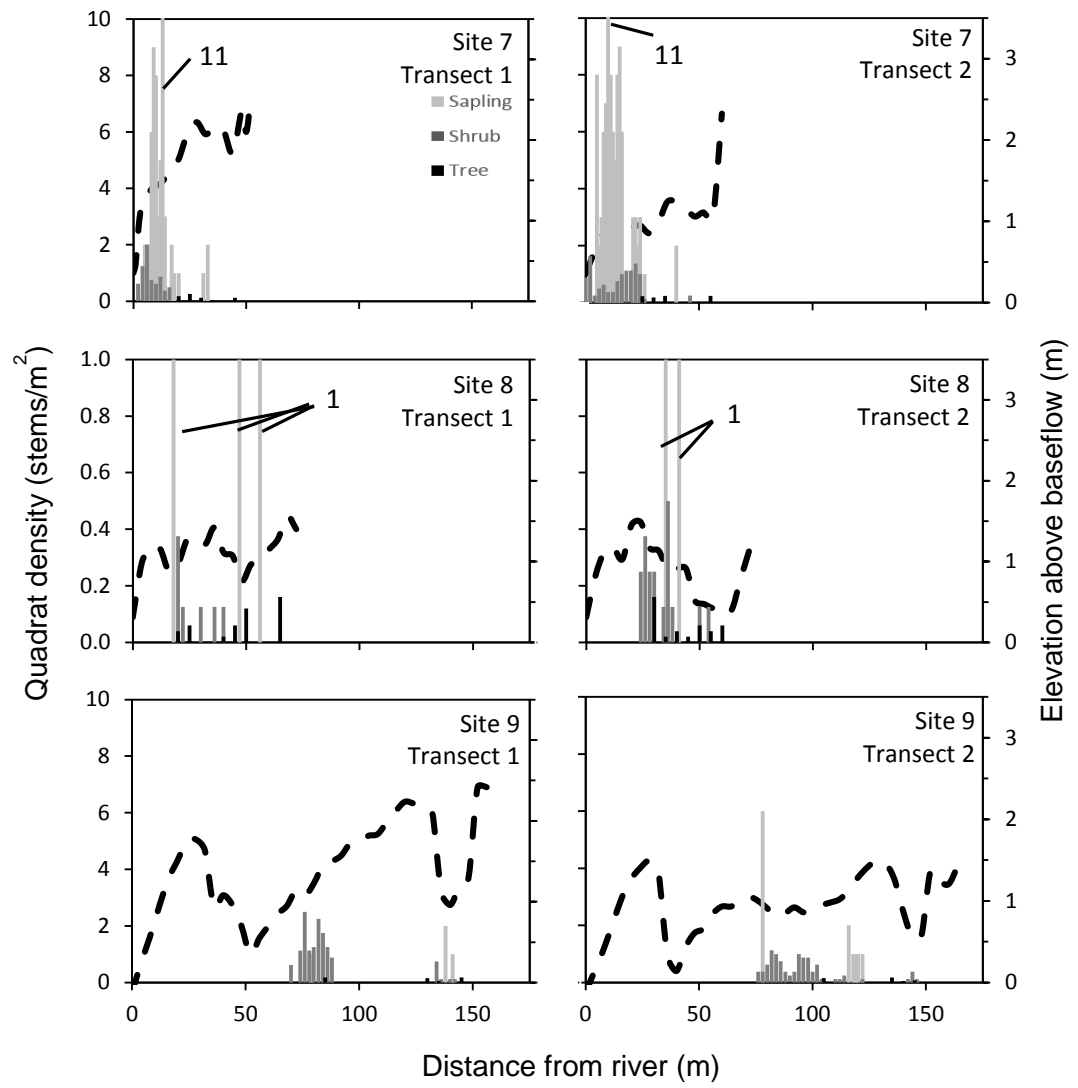
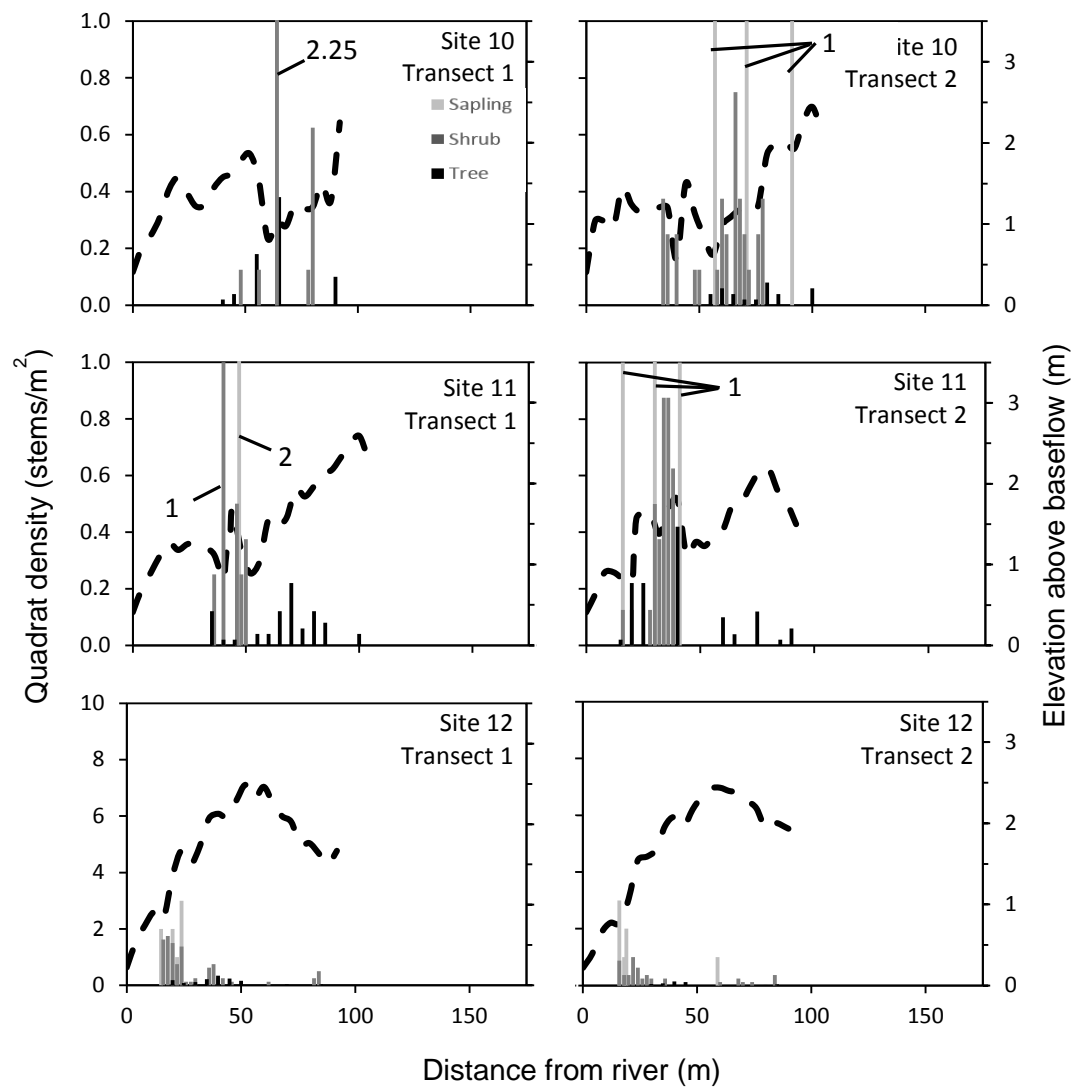
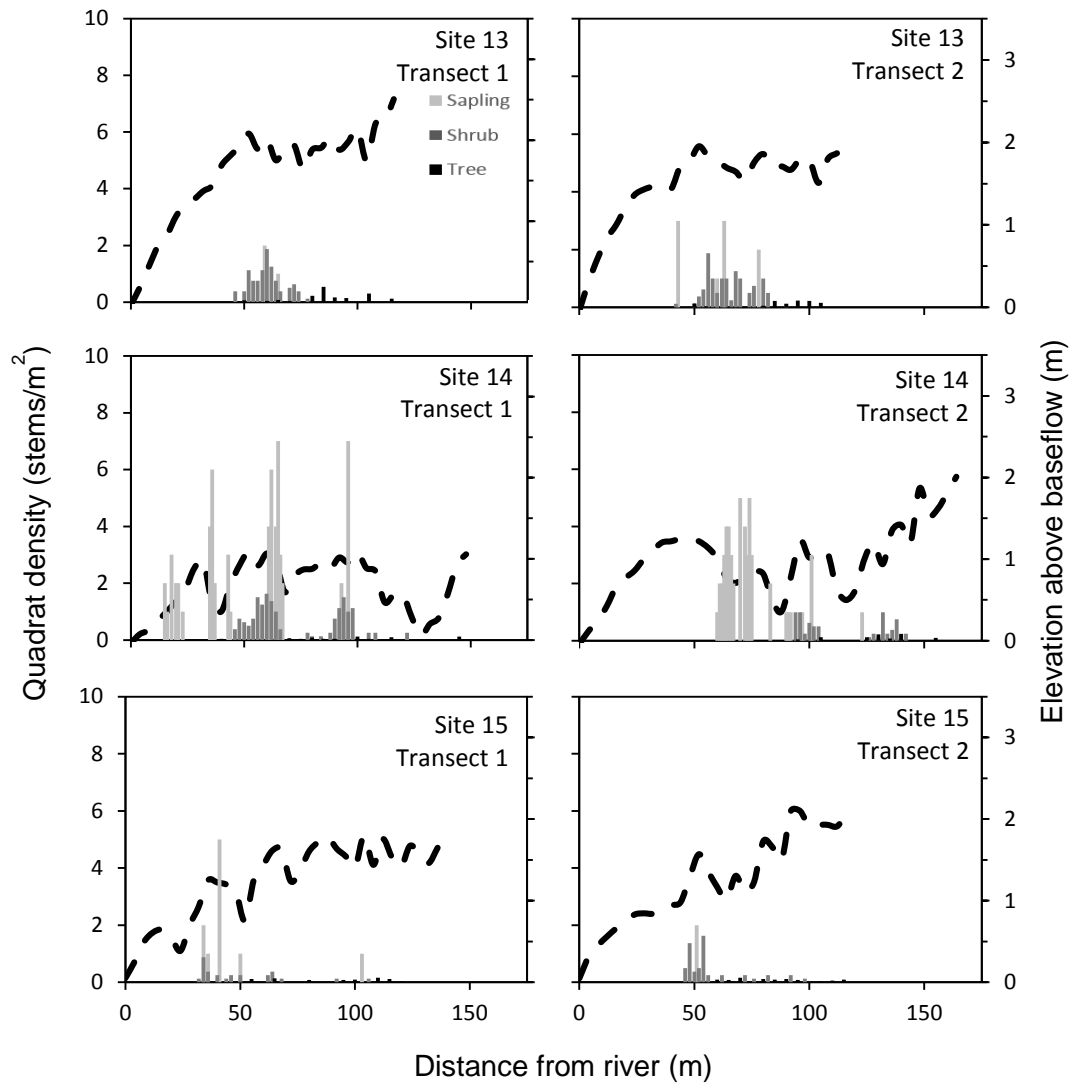


Figure B-1: Density of cottonwoods by distance from river and transect elevation above baseflow on the Waterton River. Dashed line represents transect cross-section. Note variable primary y axis scale. This figure continues on the next 4 pages.









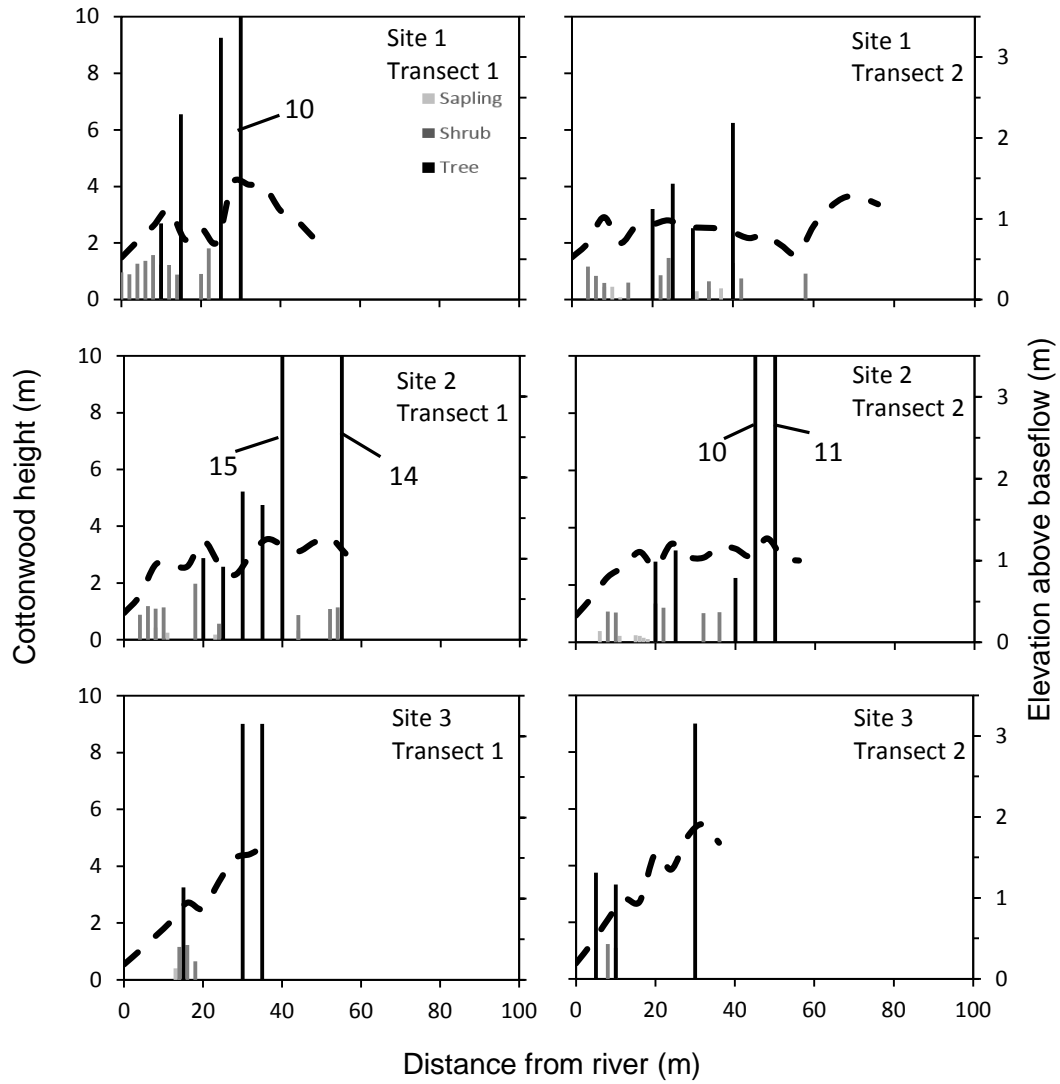
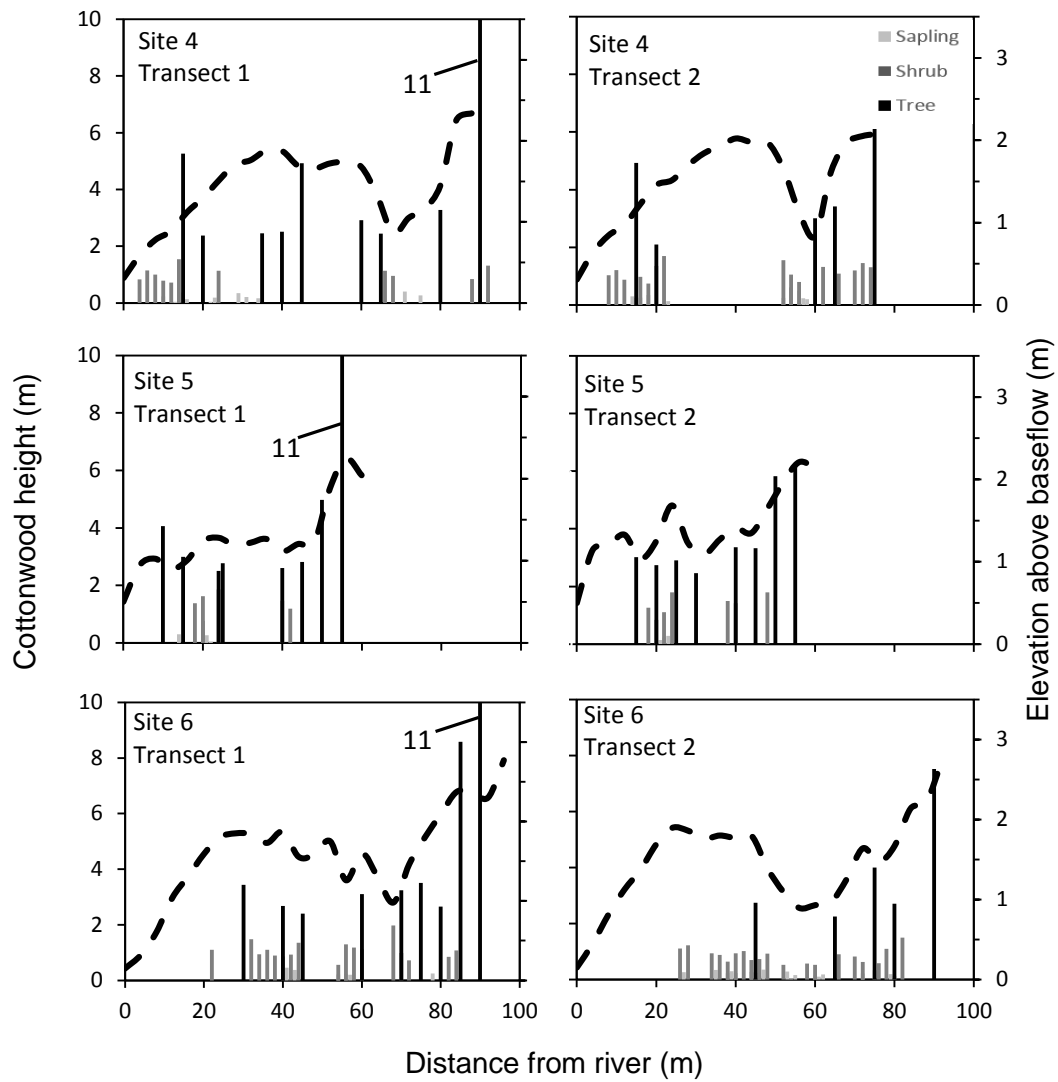
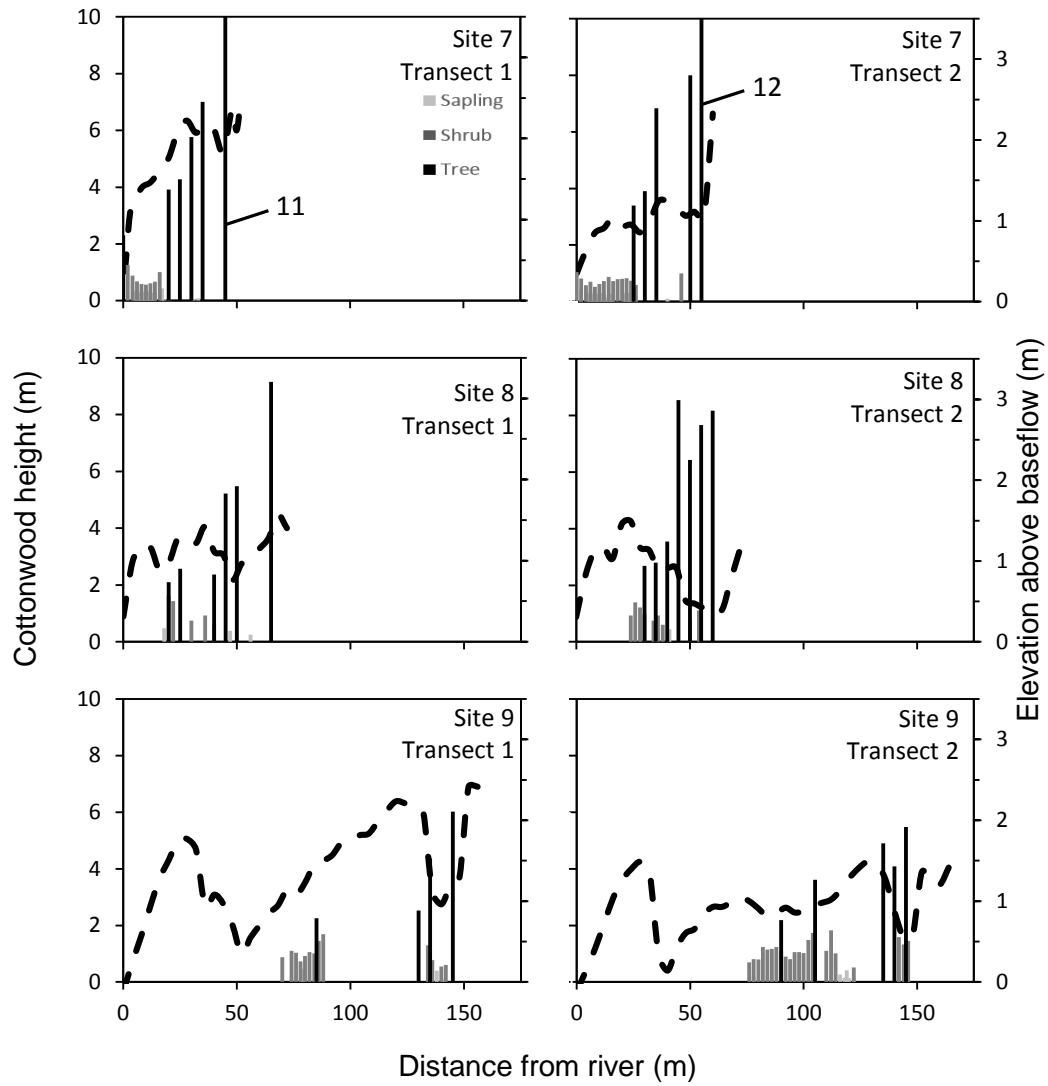
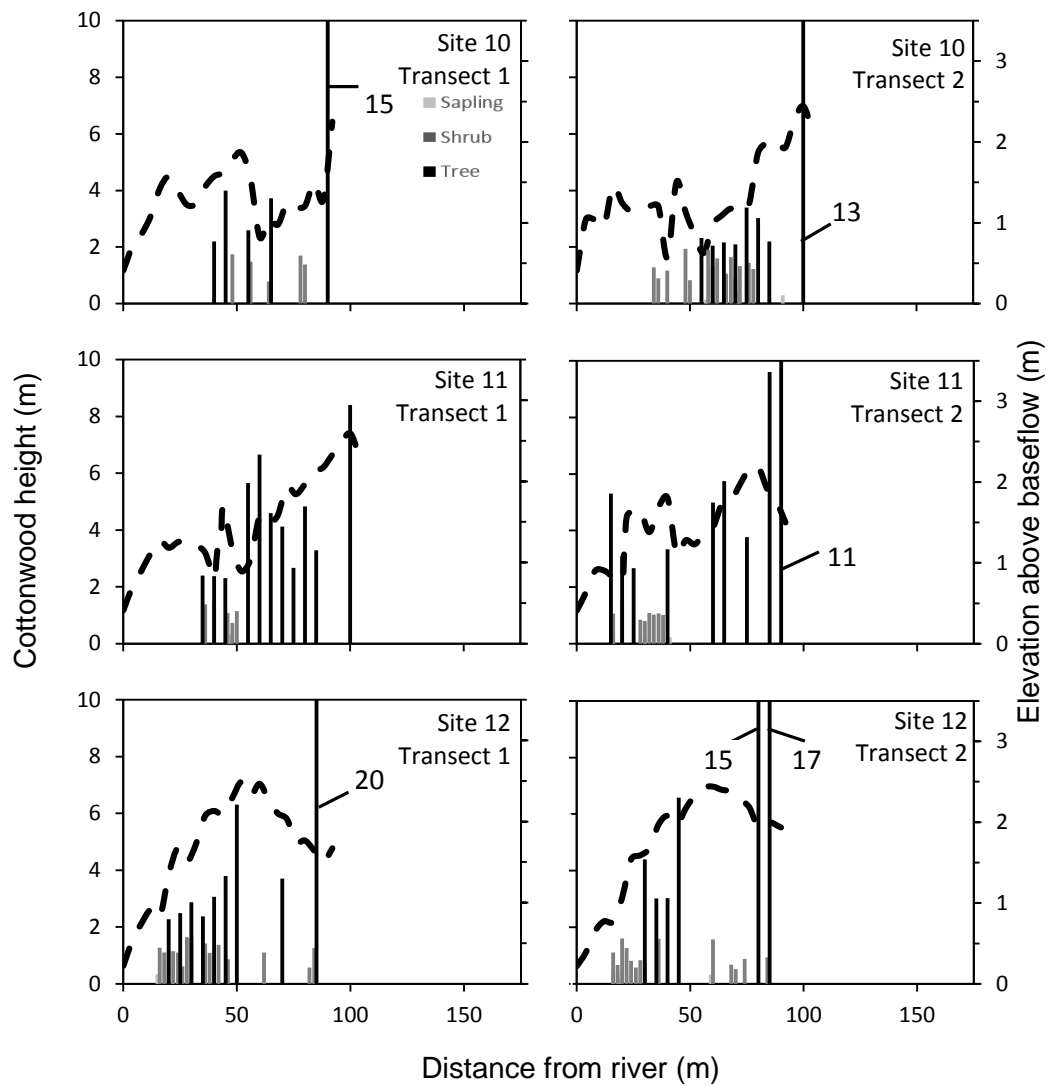
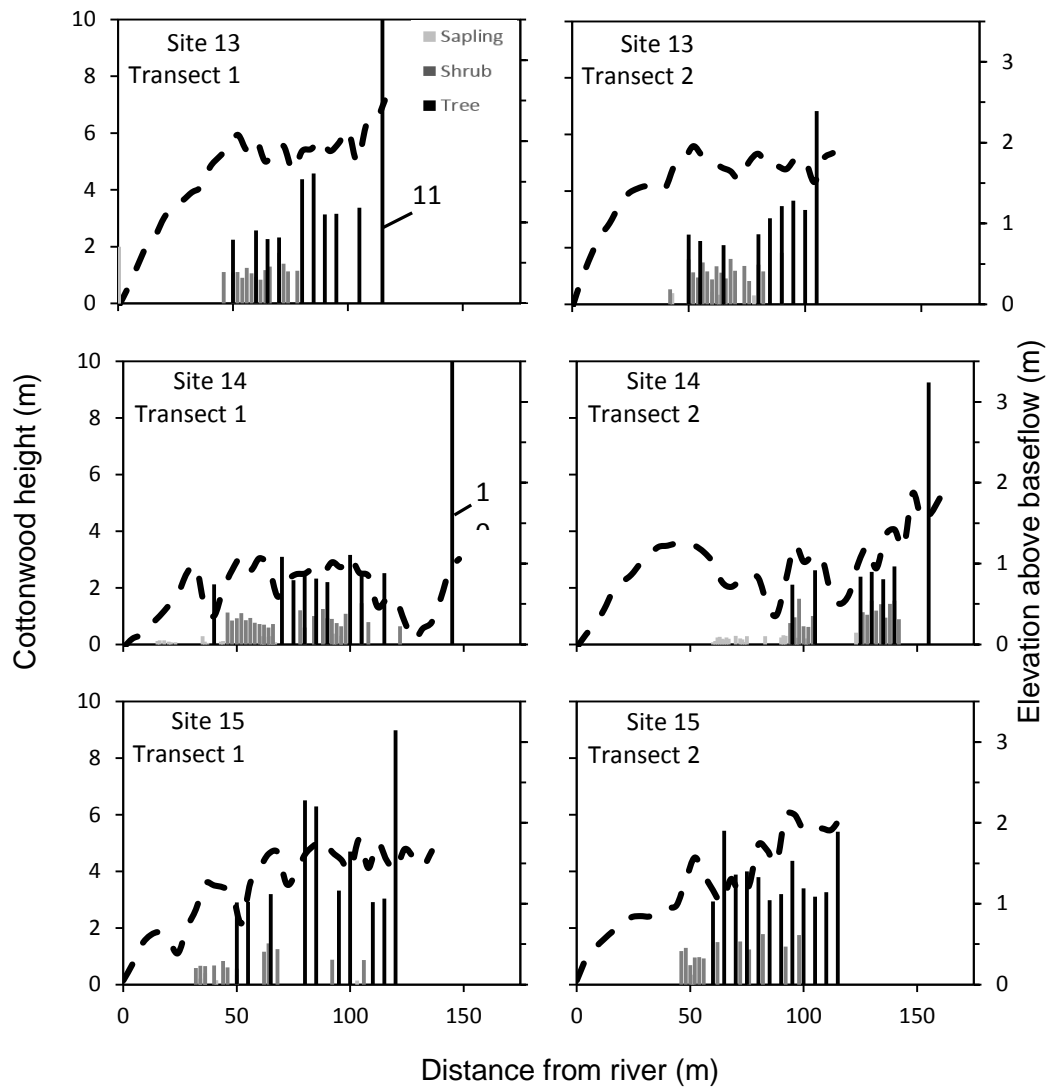


Figure B-2: Height of cottonwoods by distance from river and transect elevation above baseflow on the Waterton River. Dashed line represents transect cross-section. This figure continues on the next 4 pages.









Appendix C

Kendall's Tau Rank Order Correlation for Physical and Biological Attributes

Table C-1: Kendall's Tau correlations between physical (site width, slope, and sediment) and growth characteristics (height and diameter). * = $p < 0.05$; t = $p < 0.1$. Sample sizes vary between physical ($n = 8$) and biological ($n = 16$) characteristics.

	Tree Height	Tree Diameter	Shrub Height	Shrub Diameter	Sapling Height	Sapling Diameter
Distance	-0.449*	-0.320^t	-0.155	-0.256	-0.258	-0.066
Floodplain Width	-0.345^t	-0.251	-0.051	-0.330^t	-0.086	0.028
River Slope	0.207	0.112	-0.155	0.165	-0.155	-0.179
D ₁₆	0.034	0.008	-0.189	0.055	-0.362^t	-0.217
D ₅₀	0.310	0.077	0.017	0.275	0.120	-0.066
D ₈₄	0.414*	0.181	0.155	0.201	0.293	0.066
Heterogeneity	0.380*	0.008	0.258	0.201	0.431*	0.141
Tree Height		0.611*	-0.033	0.088	0.183	0.073
Tree Diameter			-0.075	0.115	0.058	0.009
Shrub Height				0.585*	0.183	0.365^t
Shrub Diameter					0.106	0.310
Sapling Height						0.548*

Appendix D

Particle Distribution Curves

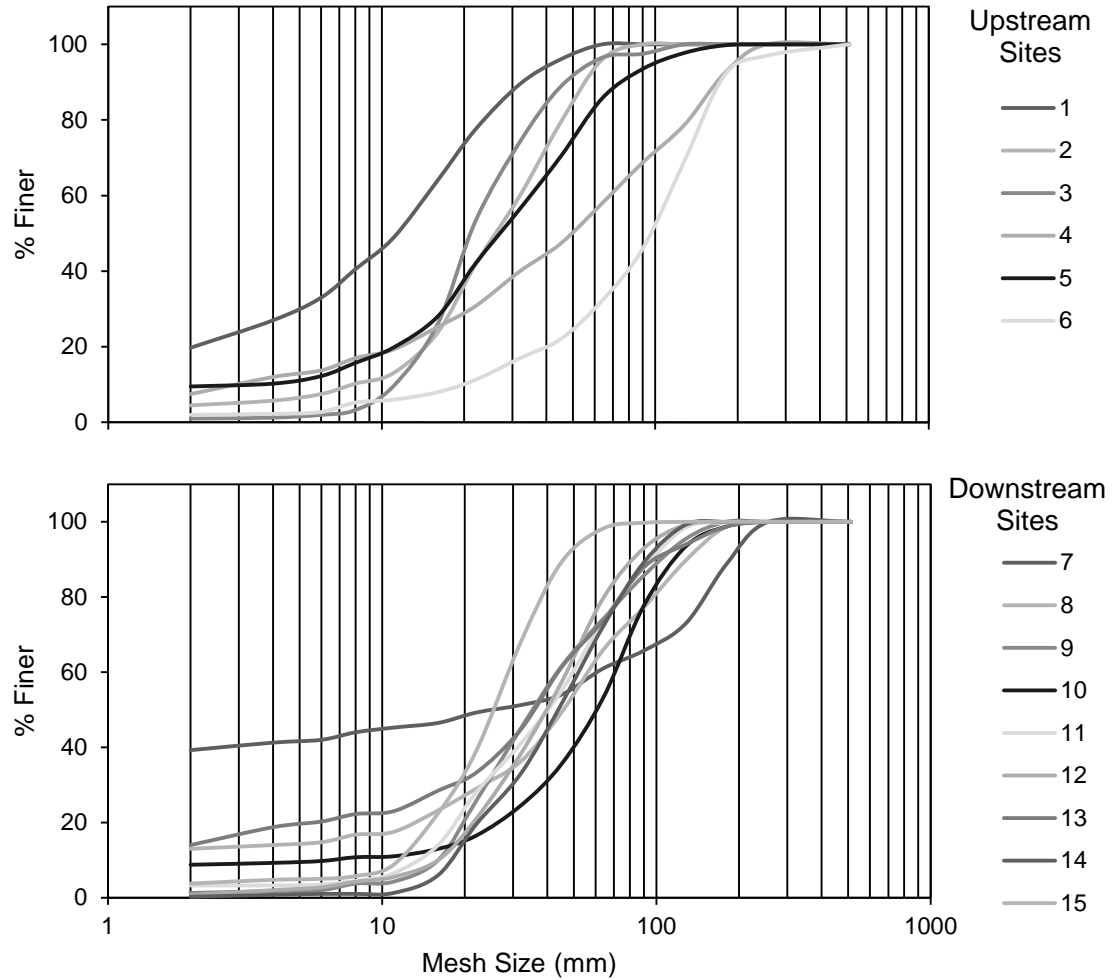


Figure D-1: Particle distribution curves for field sites located along the upstream (Sites 1-6) and downstream (Sites 7-15) reaches of the Waterton River. Curves were determined with a sampling of 400 clasts and measured using a gravelometer.