

**RIVER REGULATION AND RIPARIAN WOODLANDS ALONG THE
LOWER RED DEER RIVER, ALBERTA**

LAURENS J. PHILIPSEN
Bachelor of Science, University of Lethbridge, 2011

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

Environmental Science Program
University of Lethbridge
LETHBRIDGE, ALBERTA, CANADA

© Laurens J. Philipsen, 2017

RIVER REGULATION AND RIPARIAN WOODLANDS ALONG THE LOWER
RED DEER RIVER, ALBERTA

LAURENS J. PHILIPSEN

Date of Defence: April 4, 2017

Dr. Stewart B. Rood Supervisor	Professor	Ph.D.
-----------------------------------	-----------	-------

Dr. Cameron P. Goater Thesis Examination Committee Member	Professor	Ph.D.
--	-----------	-------

Dr. Stefan W. Kienzle Thesis Examination Committee Member	Professor	Ph.D.
--	-----------	-------

Dr. Lawrence B. Flanagan Chair, Thesis Examination Committee	Professor	Ph.D.
---	-----------	-------

ABSTRACT

This thesis investigates the historical trends and prospective future streamflow of the Red Deer River and the impacts of streamflow management on the reproduction and health of riparian cottonwood communities along the lower river. No common trends were detected in the historical streamflow data for the Red Deer River and its upper tributaries. Annual streamflow volumes and the onset of peak discharge have not changed from 1912 to 2012. Hydroclimatic modelling forecasted slight increases in annual streamflow volumes. Aerial photograph analysis, dendrochronology, and field transects of cottonwood communities along the lower river through Dinosaur Provincial park revealed no changes in tree growth and continued cottonwood recruitment despite the construction of the Dickson Dam in 1983. However, some improvements to the pattern of streamflow regulation, particularly flow ramping, are recommended to ensure the continued health of riparian cottonwood communities along the Red Deer River.

ACKNOWLEDGEMENTS

There are a number of people that I owe my gratitude to, as without their support, this thesis would not have been possible.

I would first like to thank my supervisor Dr. Stewart Rood for providing me with this research opportunity. Your expertise, guidance, continuous support, and numerous side projects, have made this journey an incredibly rewarding experience. I could not have asked for a better supervisor and mentor.

Thanks to the Rood Lab, affectionately known as the “Cottonwood Crew”, for all the advice, editing, thought-provoking discussion, and laughter during this process — Karen Zanewich, Soba Kaluthota, Evan Hillman, Stephen Foster, Kayleigh Nielson, and Sam Woodman, I owe you my deepest gratitude. I would especially like to thank Dr. David Pearce for answering my relentless stream of questions with patience and goodwill. Additionally, I would like to extend my gratitude to Dr. Stefan Kienzle and Dr. Cam Goater for graciously agreeing to be part of my thesis committee.

I must also thank my fellow graduate students and friends, Colin Langhorn, Ariel Belsheim, Gordon Logie, and Charmaine Bonifacio, I’m grateful that we could tackle the trials and tribulations of graduate school together. Your company has made this experience a little more bearable.

Lastly, I would like to thank my family for their endless love, support, and patience during this process. I can finally tell you that yes, I am finished.

TABLE OF CONTENTS

TITLE PAGE	i
THESIS EXAMINATION COMMITTEE MEMBERS PAGE	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF SYMBOLS & ABBREVIATIONS	xii
1. Chapter 1	
OVERVIEW OF COTTONWOODS AND RIVER REGULATION	
1.1 Introduction	1
1.2 Introduction to cottonwoods.....	2
1.3 Cottonwood collapse and water management.....	5
1.4 Functional flows	7
1.5 The Red Deer River.....	12
1.6 Significance of research	18
1.7 Thesis framework.....	19
1.8 References	21
2. Chapter 2	
HISTORIC AND PROSPECTIVE FUTURE FLOWS OF THE RED DEER RIVER AND ITS HEADWATER TRIBUTARIES	
2.1 Introduction	26
2.1.2 Hydroclimatic modelling.....	31
2.1.3 Historical streamflow projection.....	31
2.2 Methods.....	32
2.2.1 Historical trend analysis	32
2.2.1.1 Data preparation	33
2.2.1.2 Statistical analysis and trend projection.....	37
2.2.2 Hydroclimatic modelling.....	38

2.2.2.1	Model development.....	38
2.2.2.2	Future forecasting from down-scaled GCMs.....	41
2.2.3	Comparison of empirical trend and GCM predictions	42
2.3	Results	43
2.3.1	Naturalized data validation.....	43
2.3.2	Historical annual and monthly flow trends	46
2.3.3	Hydroclimatic model verification	51
2.3.4	Future flows as predicted with empirical trend projection and GCM modelling.....	55
2.4	Discussion	58
2.5	References	66

3. Chapter 3

COTTONWOOD RECRUITMENT AND STREAMFLOW MANAGEMENT ALONG THE LOWER RED DEER RIVER

3.1	Introduction	72
3.1.1	Study location.....	75
3.2	Methods.....	79
3.2.1	Aerial photograph analysis.....	79
3.2.2	Dendrochronology.....	85
3.2.3	Field survey	88
3.2.4	Hydrology.....	90
3.3	Results	91
3.3.1	Aerial photograph analysis.....	91
3.3.2	Dendrochronology.....	96
3.3.3	Field survey	101
3.3.4	Hydrology.....	105
3.4	Discussion	111
3.5	References	123

4. Chapter 4

COTTONWOOD GROWTH, CLIMATE, AND STREAMFLOW MANAGEMENT ALONG THE LOWER RED DEER RIVER

4.1	Introduction	129
4.1.1	Study site	132
4.2	Methods.....	134
4.2.1	Cottonwood core collection and processing	134

4.2.2	Hydrology and climate	137
4.3	Results	138
4.3.1	Tree growth	138
4.3.2	Correlations	142
4.3.3	Pre- and post-dam comparison	145
4.4	Discussion	147
4.4.1	Tree growth patterns.....	147
4.4.2	Streamflow and tree growth	151
4.4.3	Other climatic factors	152
4.4.4	Streamflow and climate reconstruction potential	154
4.5	Conclusion.....	158
4.6	References	159
5.	Chapter 5	
	SUMMARY AND KEY FINDINGS	
5.1	Historic and prospective future flows of the Red Deer River	166
5.2	Cottonwood recruitment and streamflow management along the lower Red Deer River	167
5.3	Cottonwood growth, climate, and streamflow management along the lower Red Deer River.....	169
5.4	References	172
	Appendix A	
	Naturalization correction equations	174
	Appendix B	
	Flow variability along the Red Deer River	176
	Appendix C	
	Streamflow trends P value table	179
	Appendix D	
	Transect locations.....	180
	Appendix E	
	Flood recurrence analysis.....	181

LIST OF TABLES

Table 2-1 – Annual and monthly temperature trends at meteorological stations around the upper Red Deer River Basin from 1912 to 2012	30
Table 2-2 – Pearson Product Moment correlation coefficients and Tau-b values of mean annual discharges, and monthly discharges, with time from 1912 to 2012.....	48
Table 2-3 – Average yearly percent change and percent change from 1912 to 2012 of mean annual and monthly discharges	49
Table 2-4 – Kendall’s tau coefficients for trends in precipitation and percent change in precipitation	64
Table 3-1 – Aerial photography used for the Red Deer River through Dinosaur Provincial Park for georeferencing and analysis	80
Table 3-2 – Bivariate correlation analyses for changes in hydrology, river morphology and cottonwood abundance between photo periods.	99
Table 3-3 – Comparison of Dickson Dam/Gleniffer Reservoir inflow and outflow monthly average discharges, monthly minimum discharges and max daily discharges from 1984 to 2013 using the Wilcoxon signed rank test	107
Table 4-1 – Pearson correlation analysis between radial increment growth (RI), basal area growth (BAI), basal area growth residuals (BAIR), log transformed annual discharge (Q), log transformed annual discharge 5-year moving average (Q_{5ma}), Hargreaves evapotranspiration (ETP), lag 1 evapotranspiration (ETPL), precipitation (PPT), and the Pacific Decadal Oscillation (PDO).....	143
Table 4-2 – Mean values of basal area increment growth, basal area increment residuals, annual discharge (Q), evapotranspiration (ETP), precipitation (PPT) and the Pacific Decadal Oscillation (PDO) index before (1953-1982) and after (1984-2013) the construction of the Dickson Dam	146
Table C-1 – P values of trends calculated using Pearson Product-Moment correlation and Mann-Kendall analysis of mean annual discharges, and monthly discharges, with time from 1912 to 2012	179
Table D-1 – Red Deer River seedling survey transect locations	180
Table E-1 – Comparison of flood recurrence probabilities, return interval and discharge in m^3/s for Generalized Extreme Value (GEV), Log Pearson Type III (LP3), Johnson SB and Log-normal distributions for max daily discharges from 1912 to 2013 for the Red Deer River at Red Deer	182

LIST OF FIGURES

Figure 1-1 – The ‘recruitment box,’ the temporal and spatial zone that cottonwood seedlings are likely to be successfully established if streamflow patterns are favorable	11
Figure 1-2 – Red Deer River Basin with natural regions.	14
Figure 1-3 – Annual precipitation (mm) within the Red Deer River Basin	15
Figure 1-4 – Average weekly naturalized flows of the Red Deer River as gauged at Red Deer, Bindloss and for the upper tributaries from 1912 to 2001	17
Figure 2-1 – Map of the upper Red Deer River Basin and major tributaries of the Red Deer River	29
Figure 2-2 – Gauging stations used in naturalization process	36
Figure 2-3 – Comparison of mean annual discharges (Q_a) of our naturalized data, Alberta Environment’s naturalized data and gauged data for the Red Deer River at Red Deer gauging station	45
Figure 2-4 – Comparison of mean monthly discharges (Q_m) of the generated naturalized data set and Alberta Environment’s naturalized data.....	45
Figure 2-5 – Average annual percent change in monthly discharge for the Red Deer River and the upper tributaries from 1912 to 2012.....	50
Figure 2-6 – Comparison of gauged and modelled mean monthly discharge (Q_m) for the Red Deer River at Red Deer for the validation period of 1960 to 1989	52
Figure 2-7 – Comparison of gauged and simulated annual discharge (Q_a) for the Red Deer River at Red Deer for the validation period of 1960 to 1989.	52
Figure 2-8 – Correlation between measured and modelled mean monthly discharges for the upper tributaries of the Red Deer River for the validation period of 1960 to 1989	54
Figure 2-9 – Change in annual (Q_a) and mean monthly discharge (Q_m) from around 1975 to around 2055 for the upper Red Deer River Basin as forecasted by empirical trend projection and four general circulation models	56
Figure 2-10 – Change in annual (Q_a) and mean monthly discharge (Q_m) from around 1975 to around 2055 for the Red Deer River below Burnt Timber Creek as forecasted by empirical trend projection and four general circulation models	56
Figure 2-11 – Change in annual (Q_a) and mean monthly discharge (Q_m) from around 1975 to around 2055 for the Little Red Deer River near the mouth as forecasted by empirical trend projection and four general circulation models	57
Figure 2-12 – Correlation between mean annual streamflow of the Red Deer River gauged at Red Deer and standardized values for Pacific Decadal Oscillation (PDO)	61
Figure 3-1 – Location of Dinosaur Provincial Park, the study area for this study, within the Red Deer River Basin and within Alberta	77

Figure 3-2 – Typical woodland and river reach through Dinosaur Provincial Park, summer 2016.....	78
Figure 3-3 – Methods for calculation of channel migration: (a) generating channel centreline, (b) migration area (shaded area) and (c) channel migration equation	84
Figure 3-4 – Regression analysis of age and diameter of <i>P. deltoides</i> along the Red Deer River through Dinosaur Provincial Park.....	87
Figure 3-5 – Regression analysis of age and height of <i>P. deltoides</i> along the Red Deer River through Dinosaur Provincial Park.....	87
Figure 3-6 – Typical belt transect sampling	89
Figure 3-7 – Average cottonwood woodland area recruited and lost for 8 floodplains between aerial photograph intervals in Dinosaur Provincial Park.....	93
Figure 3-8 – Map of the Red Deer River showing recruitment and losses in cottonwood areal extent from 1950 to 2012.	94
Figure 3-9 – Average migration, erosion and accretion rates of the Red Deer River, AB, as determined by aerial photograph analysis	97
Figure 3-10 – Average active channel widths for photo mosaics and 1935 topographic map of the Red Deer River, AB.....	97
Figure 3-11 – (a) Annual average discharges and (b) annual max daily discharges of the Red Deer River at Red Deer from 1935 to 2015	98
Figure 3-12 – Map showing age and distribution of cottonwoods within one floodplain at the study reach along the Red Deer River.	100
Figure 3-13 – Relative areas of each age group for cottonwoods along the Red Deer River study reach presented in figure 3-13	100
Figure 3-14 – Cottonwoods in Dinosaur Provincial Park, AB, established in (a) 2013, (b) 2014 and (c) 2005. Photo dates are indicated	103
Figure 3-15 – Density and elevation of cottonwood seedlings, saplings, and trees along transects in Dinosaur Provincial Park.....	104
Figure 3-16 – Comparison of inflow and outflow (a) median monthly discharges, (b) median monthly minimum discharges and (c) median monthly max discharges for the Dickson Dam/Gleniffer Reservoir from 1984 to 2013	108
Figure 3-17 – Comparison of inflow and outflow annual max daily discharges for the Dickson Dam/Gleniffer Reservoir from 1984 to 2013	109
Figure 3-18 – Ramping analysis of the 2013, 2005 and 1990 floods	110
Figure 3-19 – Hydrograph for the Red Deer River at Red Deer in 1952	113
Figure 3-20 – Comparison of average daily discharge (Q) of the Red Deer River at Red Deer (RDR) and the St. Mary River near Lethbridge (SMR) and the corresponding reservoir elevation for the Gleniffer Reservoir and St. Mary Reservoir	113
Figure 3-21 – Cottonwood losses along the Red Deer River in Dinosaur Provincial Park resulting from (a) beaver browsing and (b) fire; summer 2016.....	119

Figure 3-22 – Photograph comparison between 1912 and 2016 of a woodland at Steepleville, Alberta	120
Figure 4-1 – Plains cottonwood along the Red Deer River within Dinosaur Provincial Park, Autumn 2015	133
Figure 4-2 – Average basal area increment growth of cottonwoods growing along the Red Deer River in Dinosaur Provincial Park by age	139
Figure 4-3 – Average basal area of cottonwoods growing along the Red Deer River in Dinosaur Provincial Park by age	139
Figure 4-4 – Average basal area increment growth of cottonwoods older than 150 years growing along the Red Deer River in Dinosaur Provincial Park by age	140
Figure 4-5 – (a) Average radial increment growth and (b) average basal area increment growth of cottonwoods from 1842 to 2013 sampled along the Red Deer River	141
Figure 4-6 – Annual average discharge for the Red Deer River at Red Deer (1912-2013) and basal area increment growth residual chronology.....	144
Figure 4-7 – (a) Annual precipitation as gauged at Brooks, Alberta, (b) average summer daily evapotranspiration for Brooks, Alberta, and (c) 5-year moving average of the PDO index.....	144
Figure 4-8 – Average monthly minimum flows for the Red Deer River at Red Deer before (1953-1982) and after (1984-2013) the construction of the Dickson Dam	146
Figure 4-9 – Cottonwood in Dinosaur Provincial Park greater than 200 years of age with a large canopy displaying extensive shoot production	150
Figure 4-10 – Cottonwood in Dinosaur Provincial Park showing extensive shoot production in response to porcupine browsing	150
Figure 4-11 – Tree ring chronologies from the International Tree-Ring Data Bank (2012) extending before 1800 for North America	157
Figure 4-12 – Adjusted BAI growth for <i>P. deltoides</i> from 1842 to 2013 in Dinosaur Provincial Park along the lower Red Deer River.....	158
Figure A-1 – Relationship between the mean monthly discharges of the Red Deer River gauged at Red Deer and the mean monthly discharge of the upstream ‘tributary’ inputs grouped by seasons	174
Figure A-2 – Relationship between max values of the three-day moving average of the sum of daily discharges from the Dickson Dam, Medicine River and Little Red Deer River tributaries and max daily discharge of the Red Deer River at Red Deer for May, June and July.....	175
Figure B-1 – Comparison of mean weekly discharges of the three major tributaries of the South Saskatchewan River.....	177
Figure B-2 – Month of occurrence of annual max daily discharges for the Red Deer River, Bow River and Oldman River for the period of 1912 to 2014	178
Figure E-1 – Flood recurrence analysis of max daily discharges for the Red Deer River at Red Deer from 1912 to 2013	181

LIST OF SYMBOLS & ABBREVIATIONS

AENV	Alberta Environment
AR	Autoregressive model
ARMA	Autoregressive moving average model
BAI	Basal area increment
BAIR	Basal area increment residuals
CMIP3	Coupled Model Inter-comparison Project Phase 3
ENSO	El Niño Southern Oscillation
ETP	Evapotranspiration
ETPL	Lagged evapotranspiration
GCM	General circulation model
GCP	Ground control point
GIS	Geographic information system
HYDAT	Water Survey of Canada's hydrological database
IPCC	Intergovernmental Panel on Climate change
MTCLIM	Mountain Climate Modeller
PDO	Pacific Decadal Oscillation
PPT	Precipitation
Q	Discharge
Q_{5ma}	Discharge 5-year moving average
Q_a	Annual discharge
Q_m	Monthly discharge
RDR	Red Deer River
RI	Radial increment
RMSE	Root mean square error
SRES	IPCC Special Report on Emission Scenarios
SSRB	South Saskatchewan River Basin
UNESCO	United Nations Educational, Scientific, and Cultural Organization

CHAPTER 1: OVERVIEW OF COTTONWOODS AND RIVER REGULATION

1.1 Introduction

Water of adequate quality and quantity is essential for human development. Worldwide water use over the last century has grown at a rate of more than twice the population growth (UN Water, 2007). Unfortunately, renewable freshwater is in short supply in many regions of the world. In these regions, the ever-rising demand has placed stress on a limited resource and has increased the need for infrastructure for the conveyance and storage of water. Dams and diversions, principally for agriculture, have allowed people and economies to thrive in areas that were previously thought inhospitable. However, this infrastructure has come at a significant cost to the environment with dams and diversions becoming one of the foremost impacts on freshwater ecosystems (Nilsson et al., 2005; Rood et al., 2005).

Floodplains and riparian habitat play an important role in the overall health of rivers. Natural floodplains are among the most dynamic and biologically productive ecosystems in the world (Tockner and Stanford, 2002). In the semi-arid prairies of western North America, cottonwood trees are often the dominant and keystone species within floodplains, forming the foundation of the riparian woodland ecosystem (Braatne et al., 1996). Only small remnants of once abundant cottonwood populations remain with estimates of the magnitude of riparian vegetation loss and degradation in the southwestern United States ranging from 70 to 90 percent (Johnson and Haight, 1984). Dams and diversions have played a large role in these substantial losses.

Declines of cottonwood woodlands have been reported downstream of dams and diversions in Alberta, Montana, North Dakota, Wyoming, Colorado and Arizona (Bradley and Smith, 1986; Rood and Heinze-Milne, 1989; Rood and Mahoney, 1990). The loss of these cottonwood populations has a significant impact on the health of rivers throughout North America and the aquatic and terrestrial wildlife that depend on them.

In southern Alberta, the Red Deer River is the only river that has not been excessively used for irrigation water abstraction and is ecologically one of the least disturbed rivers in the semi-arid regions of western North America (Cordes et al., 1997). It marks the most northern extension of the plains cottonwood and flows through the iconic Canadian badlands. Cottonwood communities along the lower Red Deer River provide a haven for biodiversity that would not otherwise exist in the prairie landscape. In 1983, the Dickson Dam was completed in the upper basin of the Red Deer River, raising concerns about the future of woodlands along the Red Deer River. This study investigates streamflow trends within the upper Red Deer River Basin, assesses cottonwood health along the lower river through Dinosaur Provincial Park, and identifies the implications of management on riparian health as well as potential mitigation strategies.

1.2 Introduction to cottonwoods

Trees of the *Populus* genus are widely distributed over the northern hemisphere (Dickmann and Stuart, 1983). They are able to propagate vegetatively and are fast growing, making them desirable as a source of fuel, fibre, lumber and animal feed, and are commonly grown for use in shelter belts or for bank stabilization (Stettler et al., 1996). A common species found in North America, the eastern cottonwood (*Populus deltoides*), is the fastest growing native tree in North America and can average an early

height growth of over four metres/year under ideal conditions (Dickmann and Stuart, 1983). In their native environments, *Populus* species play an important role in the recolonization of sites after disturbances. Cottonwoods are particularly well adapted to the dynamic regimes of erosion and deposition found along streams (Rood et al., 2015). In the prairies of southern Alberta, cottonwood trees are often the dominant species along rivers and provide a haven for a diversity of plant and animal species not found elsewhere in the prairie landscape (Finch and Ruggiero, 1993; Knopf et al., 1988; Sabo et al., 2005). This makes cottonwood woodlands highly valued, not only for their ecological services and high productivity, but also for their recreational and aesthetic value.

Four different cottonwood species and their hybrids are found in Southern Alberta, *Populus angustifolia* James (narrow-leaf cottonwood), *P. balsamifera* L. (balsam poplar), *P. trichocarpa* Torrey and Gray (black cottonwood), and *P. deltoides* Bartr. ex Marsh (plains cottonwood). The geographic distribution of these species is largely associated with climatic factors, mainly temperature and precipitation (Rood et al., 2003a). Generally, balsam poplar and black cottonwood woodlands are found along the upper, gravel dominated, reaches of prairie rivers. These areas are typically at a higher elevation and receive greater precipitation. Plains cottonwood predominates along more arid, sandy, downstream reaches. Narrow-leaf cottonwoods are found along intermediate sites (Cordes et al., 1993). Complex hybrid zones with rich genetic diversity can exist where the ranges of the different species overlap (Floate, 2004).

Asexual reproduction is common in most cottonwoods with the exception of the *Aigeiros* section of species which includes *P. deltoides* (Braatne et al., 1996). Asexual reproduction occurs through suckering — the emergence of new shoots from existing

parental roots or shoots — and via branch propagation, whereby branch fragments buried in sediment can sprout and develop shoots (Rood et al., 1994; Rood et al., 2003c).

Cottonwoods are dioecious, with flowers for both male and female trees being clustered in catkins. During sexual reproduction, female flowers are pollinated producing small fluffy seeds that are dispersed by both wind and water (Braatne et al., 1996). Seed production by a single mature cottonwood tree may exceed 25 million seeds, however, only a small fraction of seeds successfully establish (Cain, 2007). As cottonwood seeds contain very little endosperm and are viable for only a short period of time, generally only 1-2 weeks, successful establishment is dependent on the availability of ideal microsites and conditions (Braatne et al., 1996). In semi-arid regions, these conditions are rare and only occur episodically along rivers following flood events (Mahoney and Rood, 1998).

Floods — or over-bank streamflow — mobilize, transport and deposit alluvial sediments, thereby creating optimal seed beds for cottonwoods. For many American rivers, overbank flows typically occur every two years (Leopold, 1994). For rivers at higher latitudes and elevation, such as those in Canada, channels are often enlarged by ice scour making overbank floods and the opportunity for recruitment events, less common. For these rivers, bankfull discharges may only occur every 1-in-5 years, or longer (Smith, 1979).

Cottonwoods are phreatophytic plants, requiring contact with the semi-saturated zone immediately above the water table for the majority of the growing season in order to survive (Rood et al., 2011; Rood et al., 2003a; Williams and Cooper, 2005). This moist, yet aerobic, zone is called the capillary fringe (Rood et al., 2011). Seedlings, in particular, require continued contact with this saturated zone (Mahoney and Rood, 1991). Following floods, root growth of established cottonwood seedlings must keep pace with

declining river stage and the associated water table. If the water table declines at a rate greater than root growth, seedlings will desiccate and die (Mahoney and Rood, 1991; Mahoney and Rood, 1998).

In addition to drought-induced mortality, seedlings, especially those established at lower elevations, may succumb to extended periods of inundation, erosion from subsequent high flow events, and ice scour. These factors combined make the prospect of large successful recruitment events occurring annually unlikely. Successful recruitment of cottonwoods only occurs every 5 to 10 years or longer depending on the river (Braatne et al., 1996).

1.3 Cottonwood collapse and water management

In southern Alberta, the South Saskatchewan River Basin (SSRB) is considered Canada's most threatened river system (WWF-Canada, 2009). The SSRB is composed of four major sub-basins, the Red Deer River sub-basin, the Bow River sub-basin, the Oldman River sub-basin, and the South Saskatchewan River sub-basin. Water licensing within these basins has been recognized as being unsustainable, with surface water allocations being reached or exceeded in three of the four sub-basins (Alberta Environment, 2006). This has created a significant gap between existing flows and the flows necessary to maintain long term functioning ecosystems (Alberta Environment, 2006). Only the Red Deer River system remains open to further allocation in the SSRB. Water scarcity in southern Alberta is, in part, due to seasonal changes in flow. Mountain snowmelt accounts for approximately 75% of annual discharge (Pentney and Ohrn, 2008). The result is a peak in spring resulting from snowmelt and a steady decrease in discharge through the summer and fall as snowpack declines. Dams and reservoirs regulate this temporal imbalance.

Most dams in southern Alberta function to attenuate and store spring flows while releasing water during low-flow periods, primarily for agricultural purposes (Mahoney and Rood, 1998; Rood et al., 2005). Unfortunately, management of dams often failed to recognize that the integrity of riverine ecosystems is largely dependent on natural river dynamics (Lytle and Poff, 2004; Poff et al., 1997). The quantity and timing of water supply is a critical component for the successful recruitment and maintenance of cottonwoods and alterations to the natural flow regime can be detrimental to tree survivorship.

Diminishing populations of riparian cottonwoods have been observed along several streams in southern Alberta. Rood and Heinze-Milne (1989) reported a rapid downstream reduction of riparian woodlands along the Waterton River and St. Mary River following damming, while the neighboring, free flowing, Belly River, remained relatively unchanged over the same period. Along the Milk River, Bradley and Smith (1986) reported that densities of cottonwoods recruited downstream from the Fresno Dam built in 1939 were significantly lower than floodplain sites surveyed upstream. An inventory of cottonwoods along the heavily dammed Bow River also revealed a deficiency in the recruitment of riparian poplars (Rood and Bradley, 1993). These reductions in the survival and recruitment of cottonwoods in southern Alberta are the result of a combination of many factors, most of which can be attributed to water management (Rood and Mahoney, 1990).

Dams trap sediments and stabilize river flows thereby reducing channel dynamics such as erosion, transportation and deposition of sediments (Rood et al., 1999). Cottonwoods are dependent on these disturbances for the creation of microsites for seed germination. Flow stabilization, principally flood attenuation, permits the encroachment of flood-intolerant

upland species such as grasses (Rood et al., 1999). These species easily outcompete the shade intolerant cottonwood seedlings and provide less erosional resistance to flooding (Braatne et al., 1996; Rood et al., 2015). Flow recession downstream of dams following high flow events can also result in drought induced seedling mortality after germination. Streamflow recession downstream from dams is often accelerated, which greatly reduces the survival of seedlings as root growth is often not adequate enough to remain in contact with groundwater (Mahoney and Rood, 1998; Rood and Heinze-Milne, 1989).

In addition to limiting seedling establishment, dams and diversional weirs can create artificial drought conditions that can greatly reduce plant vigour and health and even result in the mortality of mature trees (Reily and Johnson, 1982; Rood and Heinze-Milne, 1989). Compared to dams, diversional weirs have little capacity to attenuate floods, but can significantly reduce summer discharges. This can be problematic in areas such as southern Alberta where high water demands for irrigation coincide with low summer discharges. As alluvial groundwater is linked to river flows, a significant lowering in river stage in the summer can impose drought stress and mortality in mature riparian cottonwoods, which are dependent on shallow alluvial water supplies (Amlin and Rood, 2003; Scott et al., 2000; Scott et al., 1999). Fortunately, while cottonwoods in semi-arid regions are sensitive to water table depletion, their physiological recovery can be quite rapid if conditions improve (Amlin and Rood, 2003). Thus, lies the advantage of dams over diversional weirs; whereby weirs have little opportunity for management, dam operation can be quite flexible, allowing streamflow to be altered to mimic natural flow processes and improve riparian health.

1.4 Functional flows

Restoring riparian ecosystems can be difficult as degradation is typically the result of many different interacting stressors including impacts from urbanization, agriculture, deforestation, flow regulation and water extraction amongst others (Palmer et al., 2010). Despite this complexity, recovery efforts often only focus on physical channel characteristics. Local scale restoration attempts, such as adding boulders or woody debris, or re-creating channel morphological features commonly fail as underlying problem are not addressed (Jähnig et al., 2011; Palmer et al., 2010; Rood et al., 2003b). These underlying problems will inevitably limit any restoration attempts. A more systemic approach that addresses the overall ecosystem is necessary (Rood et al., 2005). For the recovery of cottonwood woodlands, the underlying problem is often the alteration of natural streamflow dynamics.

The stress, mortality or lack of recruitment of cottonwoods along a managed river system can be attributed to the pattern of streamflow management rather than simply the presence of a dam (Braatne et al., 2007; Mahoney and Rood, 1998). The application of different management strategies that better reflect natural processes can successfully restore riparian areas and cottonwood communities previously degraded by poor water management (Hall et al., 2011; Rood and Mahoney, 2000; Rood et al., 2003b; Rood et al., 2005). One such strategy is the complete removal of an existing dam. This has become a popular strategy in the US as many dams reach the end of their life span (Stanley and Doyle, 2003). While the rate and level recovery varies greatly within and between different ecosystems, overall, the restoration of an unregulated flow regimes has resulted in increases in biodiversity and ecosystem function (Bednarek, 2001; Doyle et al., 2005).

The obvious problem with this strategy is that in water-scarce regions, such as southern Alberta, dams and reservoir storage support populations and economies that would not otherwise exist, making the removal of dams an impractical strategy.

An alternative to the removal of a dam is an implementation of 'functional flows', which refers to the deliberate regulated artificial flow pattern implemented to support one or more natural ecological processes (Rood et al., 2016). This strategy recognizes that a certain level of streamflow must be allocated for human and economic uses and aims to satisfy these demands while efficiently allocating the remaining streamflow to mimic natural flow patterns that enable the conservation and restoration of ecosystems and ecological functions.

There are four major instream components for cottonwood recruitment (adapted from Bradley et al. (1991):

1. High flows enable erosion, transport and deposition of sands and gravels for the development of new surfaces suitable for seedling colonization.
2. Flow recession coinciding with poplar seed release permits seedling establishment at appropriate elevations.
3. Gradual decline/tapering in river stage and the associated groundwater level following germination allows elongating roots to maintain contact with saturated soil.
4. Sufficient late summer and autumn flows reduces cottonwood seedling and tree stress and mortality.

Not all these components can be implemented every year. Functional flows aim to capitalize on high flow years to maximize environmental benefit and minimize stress in low flow years. During wet years, there is more streamflow readily available and the goal may be to facilitate cottonwood seedling colonization. In these years, streamflow should be managed to target the ‘recruitment box’ for cottonwoods (Figure 1-1) (Amlin and Rood, 2002; Mahoney and Rood, 1998). The recruitment box defines the timing and flow requirements to permit seedling establishment. The box is delineated by the time of seed release by mature cottonwoods, and by the recruitment band — the elevation at which seedlings are above the zone scoured by ice but below an elevation where seedlings root elongation would not be sufficient enough to access ground water. This area typically extends from 0.6 to 1.5 metres above base stage (Mahoney and Rood, 1998). Following seedling establishment, elongating roots must remain in contact with the capillary fringe and the rate of river stage decline should be limited to 4 cm per day or less to prevent drought-induced seedling mortality (Mahoney and Rood, 1998). This gradual reduction in streamflow is called ‘flow ramping’. In drier years, managing flows for cottonwood recruitment is not a likely option, but it may be possible to maintain summer flows at a level that minimizes stress on mature trees and limits seedling mortality. Increasing summer minimum flows also has an auxiliary benefit to aquatic life and for maintaining water quality.

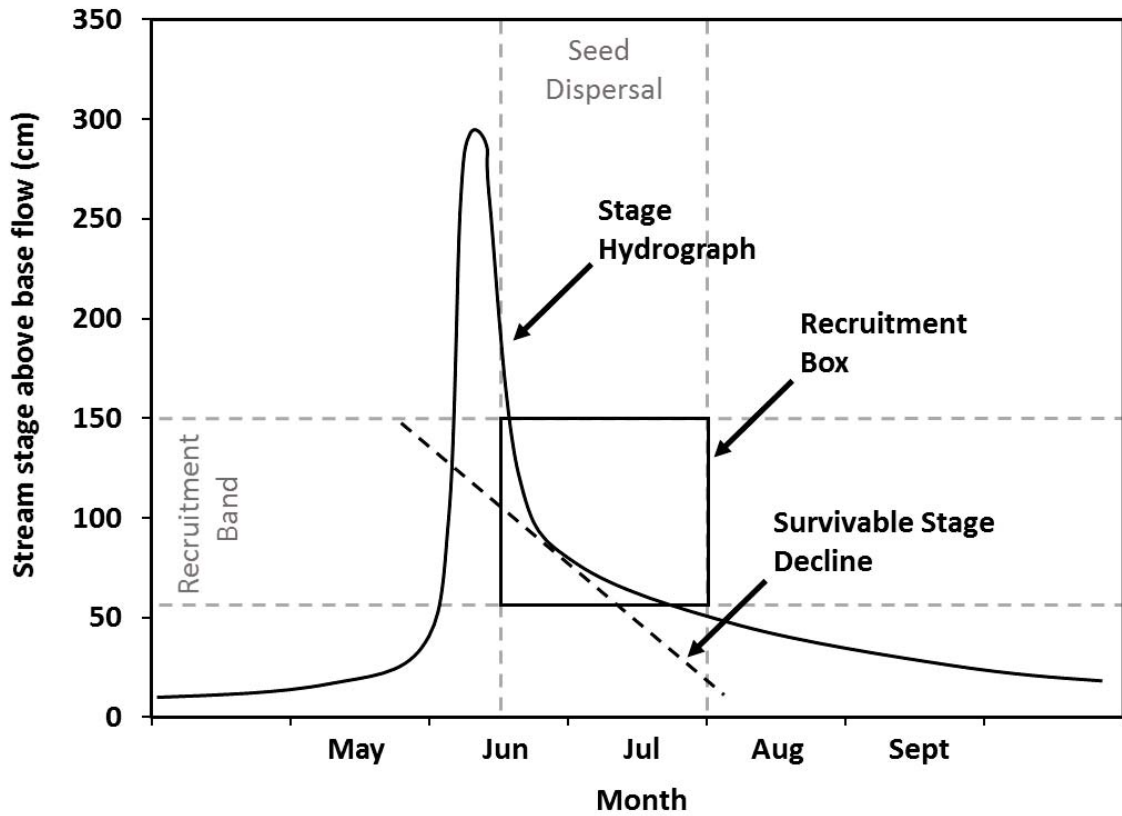


Figure 1-1: The 'recruitment box,' the temporal and spatial zone that cottonwood seedlings are likely to be successfully established if streamflow patterns are favorable. The box is delineated by the time of seed release and by the recruitment band, the elevation above base flow ideal for seedling survival. Figured modified from Mahoney and Rood (1998).

Intentional flow ramping was first adopted within the Oldman River Basin in southern Alberta. In 1995, following an exceptional 1-in-100 year flood, ramping flows were implemented downstream from the Oldman River Dam resulting in the successful establishment of billions of cottonwood seedlings along the Oldman and South Saskatchewan Rivers (Rood et al., 1998). Also within the Oldman River Basin, the tripling of minimum flows and the introduction of ramping on the St. Mary River led to the extensive recruitment of cottonwoods and willows, many of which have subsequently survived exceptionally dry years and reached sexual maturity (Rood et al., 2003b). Outside of Alberta, the collapsed Truckee River ecosystem in Nevada slowly recovered after increased spring flows were provided to the severely dewatered river system in the 1980s. While this flow enhancement was initially intended to enhance fish spawning, it had the unanticipated collateral benefit of extensive recruitment of native willows and cottonwoods (Rood et al., 2003b). In 1995, the introduction of the recruitment box model and ramping flows further enabled the recovery of cottonwood and willow populations. The re-establishment of native riparian vegetation led to the formation of a narrower and deeper main channel, which, combined with shading, lowered water temperatures and improved conditions for both fish and wildlife (Rood et al., 2003b).

1.5 The Red Deer River

The Red Deer River Basin is the most northern and largest basin in the SSRB and contributes on average 20% of the annual flow of the South Saskatchewan River (Clipperton et al., 2003). With its origins in the Sawridge Range of the Rocky Mountains within Banff National Park, the uppermost regions of the Red Deer River can be traced to near Lake Louise. The Red Deer River flows through more natural regions than any other

river in Alberta. From the mountains, the Red Deer River stretches over 700 kilometres east through foothill, boreal, parkland and grassland natural regions before flowing into Saskatchewan where it joins the South Saskatchewan River (Figure 1-2). These ecoregions reflect the significant climatic differences across the basin including precipitation differences, which vary from nearly 500 mm/year at the City of Red Deer to around 330 mm/year near Empress (Figure 1-3) (Cordes et al., 1997). Mountain and foothills form a relatively small proportion of the Red Deer River Basin but contribute the majority of the annual flow. The area upstream of the city of Red Deer accounts for approximately 85% of the annual naturalized discharge of the Red Deer River as measured near the Saskatchewan border.

The topography of the Red Deer River varies greatly along its extent. The upper river, running through mountains and foothills, is of a relatively steep gradient and is predominately gravel with a highly dynamic channel. From the Dickson dam eastward toward the town of Drumheller, the river is less dynamic, with narrow, partially incised channels that have little floodplain development. The lower river from Drumheller downstream to Empress is characterized by a sand dominated, meandering channel with numerous alluvial islands and point bars (Cordes et al., 1997). These features support large stands of riparian woodlands, including those in Dinosaur Provincial Park, a UNESCO world heritage site. The riparian poplar communities in the lower reach are primarily represented by *P. deltoides*, and by *P. balsamifera* in the upper reach, with an extensive hybrid zone between stretching from about Dry Island Buffalo Jump Provincial Park to Dinosaur Provincial Park (Floate, 2004).

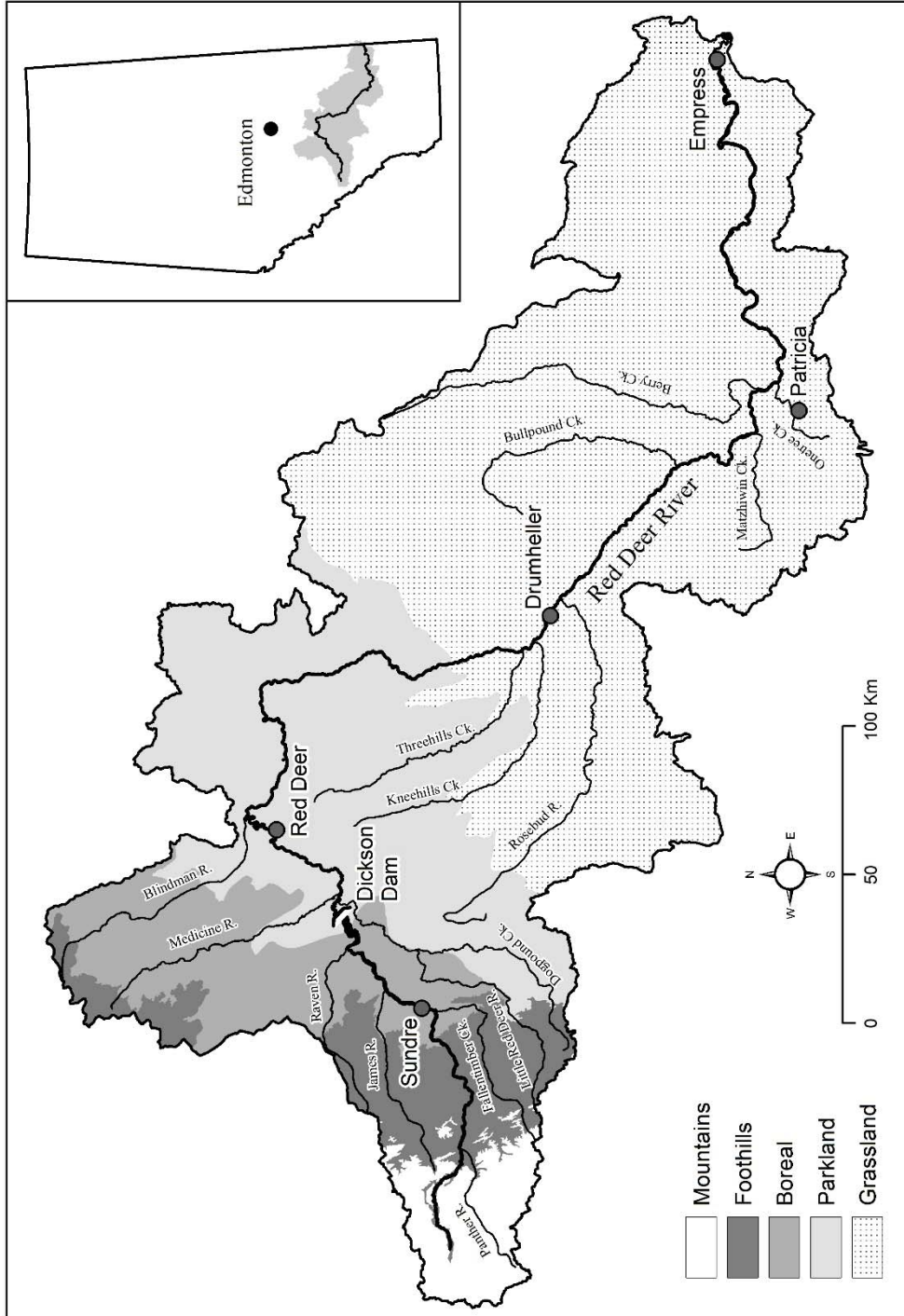


Figure 1-2: Red Deer River Basin with natural regions. Basin location within Alberta shown (top-right)

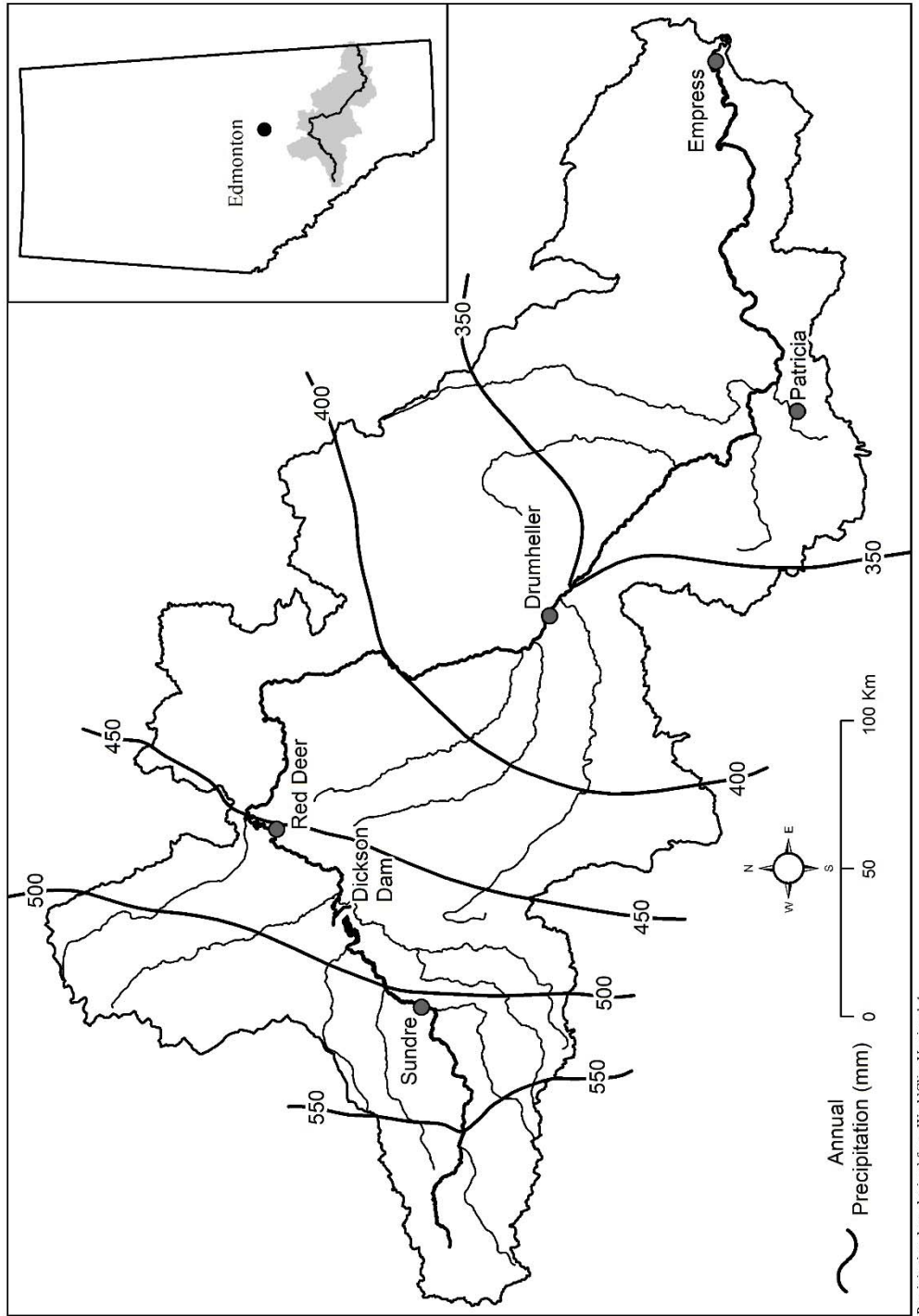


Figure 1-3: Annual precipitation (mm) within the Red Deer River Basin. Basin location within Alberta shown (top-right)

The average naturalized annual discharge for the Red Deer River is 48 m³/s as gauged at Red Deer and 58 m³/s at Bindloss near the mouth. The Red Deer River has a typical hydrograph for a major river in southern Alberta with peak flows occurring in June and July and quickly diminishing into the late summer and autumn (Figure 1-4). The hydrograph of the Red Deer River at Bindloss also has a significant peak occurring in March to April resulting from prairie snowmelt. Because of the relatively small proportion of the basin in the high elevation Rocky Mountains, peak flows from prairie snowmelt can often exceed the peak generated by contributions from mountain snowmelt and rain in June and July. This is less common along other major rivers in southern Alberta (Appendix B).

The Red Deer River is the last river in southern Alberta that has not been highly regulated and has not been heavily allocated for irrigation. The Dickson Dam is a low capacity dam forming the Gleniffer Reservoir. It is situated about midway between Sundre and Red Deer and is the only dam along the Red Deer River. Prior to the construction of the Dickson Dam in 1983, dissolved oxygen levels would occasionally fall dangerously low during the winter months due to heavy loading of organic substances, particularly during ice cover (Baker and Telang, 1985). The operations of the Dickson Dam were designed to address this issue by sustaining winter flows at 16 m³/s (Clipperton et al., 2003). This type of management is different from most dams in southern Alberta, which are primarily operated for power generation and to supply water for agricultural purposes.

In addition to water quality, the Dickson Dam and Gleniffer Reservoir is also managed to control flooding and erosion, provide opportunities for recreation, and to a smaller extent generate hydroelectric power (Cordes et al., 1997).

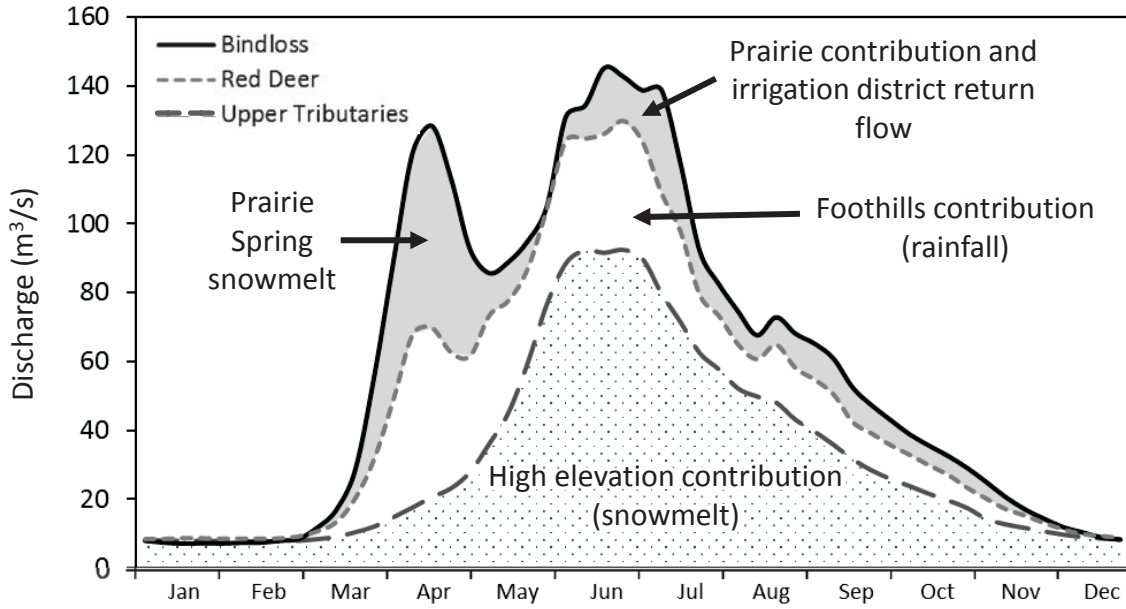


Figure 1-4: Average weekly naturalized flows of the Red Deer River as gauged at Red Deer, Bindloss and for the upper tributaries (Red Deer River at Sundre + James River + Raven River) from 1912 to 2001. Adapted from Figliuzzi and Richmond (1989)

1.6 Significance of research

This project was undertaken to investigate streamflow trends within the upper Red Deer River Basin, assess cottonwood health along the lower river through Dinosaur Provincial Park, and identify any implications management may have on riparian health and suggest mitigation strategies. In terms of the impact of streamflow management on downstream riparian areas, the Red Deer River has been studied substantially less than other rivers in southern Alberta. This is likely the direct result of the lack of water regulation and allocation along the Red Deer River. Cordes et al. (1997) is one of few studies on the Red Deer River that links cottonwood health with water management from the Dickson Dam. They concluded that construction of the Dickson Dam in 1983 has led to the attenuation of floods and has subsequently reduced the likelihood of the occurrence of extensive poplar regeneration. However, these conclusions were based on field studies performed in the early 1990s and air photo analyses from 1950 to 1989. While that study provides a thorough analysis of past recruitment and makes many valid recommendations regarding instream flow needs, the short temporal scale of the study likely makes any conclusions on the implications of management on riparian woodlands limited. A more encompassing study is now possible with over 30 years since the construction of the Dickson Dam, a significant period of drought in 2001 and 2002, and two substantial floods in 2005 and 2013.

The availability of water licenses within the Red Deer River Basin also provides the opportunity to identify problems and experiment with mitigation strategies before the system is fully allocated. Identifying management issues and potential impacts on riparian

and aquatic health early will allow managers to avoid some of the problems experienced on other river systems within southern Alberta.

1.7 Thesis framework

This thesis is composed of five chapters, including an introduction, three body chapters in the form of standalone research papers and a concluding chapter.

Chapter 1, the introductory chapter, provides a summary of cottonwood ecology, the importance of cottonwood woodlands in semi-arid regions, the collapse of riparian woodlands throughout North America with a focus on streamflow management, and lastly, the significance of the findings presented in this study.

Chapter 2 provides an analysis of historical streamflow trends and prospective future flows of the Red Deer River. Two complimentary approaches are presented, hydroclimatic modelling and empirical trend projection. Changes in the quantity and pattern of streamflow resulting from global warming will have economic and environmental implications, especially as water demands increase.

Hydroclimatic modeling following projections from four global circulations was largely undertaken by Dr. Anita Shepherd as a post-doctoral fellow with Professor Rood. In chapter 2, those projections are compared with the empirical trend analyses that were completed by Laurens Philipsen as part of his MSc thesis project. Laurens Philipsen undertook all of the research components in chapters 3 and 4.

Chapter 3 presents a hydrological, dendrochronological, field, and aerial photograph analysis of the lower Red Deer River with the intent of identifying the implications of water management on the recruitment of cottonwoods. An analysis of pre- and post-dam

recruitment is presented and the impact of the Dickson Dam on natural streamflow processes key to cottonwood recruitment are explored. Mitigation strategies and opportunities for better management practices are also presented.

In Chapter 4, dendrochronology is used to analyze the impact construction of the Dickson Dam has on cottonwood growth along the lower Red Deer River. Pre- and post-dam minimum flows and differences in tree growth are assessed. The relationship between tree growth and other climatic factors, including precipitation, evapotranspiration and the Pacific Decadal Oscillation, is also assessed.

Chapter 5, the concluding chapter, summarizes the impacts of water management other activities on the reproduction and health of riparian woodlands along the lower Red Deer River.

1.8 References

- Alberta Environment, 2006. Approved Water Management Plan for the South Saskatchewan River Basin, Edmonton, Alberta, Canada.
- Amlin NM, Rood SB, 2002. Comparative tolerances of riparian willows and cottonwoods to water-table decline. *Wetlands*, 22(2): 338-346. DOI:10.1672/0277-5212(2002)022[0338:ctorwa]2.0.co;2
- Amlin NM, Rood SB, 2003. Drought stress and recovery of riparian cottonwoods due to water table alteration along Willow Creek, Alberta. *Trees*, 17(4): 351-358. DOI:10.1007/s00468-003-0245-3
- Baker BL, Telang SA, 1985. Abundances of oxygen and organics in the Red Deer River: Comparison with Marmot Basin streams. *Canadian Water Resources Journal*, 10(2): 19-27. DOI:10.4296/cwrj1002019
- Bednarek TA, 2001. Undamming rivers: A review of the ecological impacts of dam removal. *Environmental Management*, 27(6): 803-814. DOI:10.1007/s002670010189
- Braatne JH, Jamieson R, Gill KM, Rood SB, 2007. Instream flows and the decline of riparian cottonwoods along the Yakima River, Washington, USA. *River Research and Applications*, 23(3): 247-267. DOI:10.1002/rra.978
- Braatne JH, Rood SB, Heilman PE, 1996. Life history, ecology, and conservation of riparian cottonwoods in North America, *Biology of Populus and its implications for management and conservation*. NRC Research Press, Ottawa, ON, Canada, pp. 57-85.
- Bradley CE, Reintjes F, Mahoney JM, 1991. The biology and status of riparian poplars in southern Alberta. *Alberta Forestry, Lands and Wildlife*, 85 pp.
- Bradley CE, Smith DG, 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. *Canadian Journal of Botany*, 64(7): 1433-1442. DOI:10.1139/b86-195
- Cain K, 2007. *The Cottonwood Tree: An American Champion*. Big Earth Publishing.
- Clipperton G, Koning C, Locke A, Mahoney J, Quazi B, 2003. Instream flow needs determinations in the South Saskatchewan River Basin, Alberta. Alberta Environment and Sustainable Resource Development, Pub No T/719, Calgary, Alberta, Canada: 271.
- Cordes LD, Getty MA, Hughes F, 1993. Red Deer River instream flow studies: riparian vegetation component, Alberta Environmental Protection, Edmonton, 125 pp.

- Cordes LD, Hughes FMR, Getty M, 1997. Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: The Red Deer River, Alberta, Canada. *Journal of Biogeography*, 24(5): 675-695. DOI:10.1111/j.1365-2699.1997.tb00077.x
- Dickmann DI, Stuart KW, 1983. The culture of poplars in eastern North America. Department of Forestry, Michigan State University, East Lansing, Michigan.
- Doyle MW, Stanley EH, Orr CH, Selle AR, Sethi SA, Harbor JM, 2005. Stream ecosystem response to small dam removal: Lessons from the Heartland. *Geomorphology*, 71(1-2): 227-244. DOI:10.1016/j.geomorph.2004.04.011
- Figliuzzi S, Richmond D, 1989. Red Deer River Basin - Physical system. Unpublished, in house document for Alberta Environment
- Finch DM, Ruggiero LF, 1993. Wildlife habitats and biological diversity in the Rocky Mountains and northern Great Plains. *Nat Area J*, 13(3): 191-203.
- Floate KD, 2004. Extent and patterns of hybridization among the three species of *Populus* that constitute the riparian forest of southern Alberta, Canada. *Canadian Journal of Botany*, 82(2): 253-264. DOI:10.1139/B03-135
- Hall AA, Rood SB, Higgins PS, 2011. Resizing a River: A Downscaled, Seasonal Flow Regime Promotes Riparian Restoration. *Restoration Ecology*, 19(3): 351-359. DOI:10.1111/j.1526-100X.2009.00581.x
- Jähnig SC, Lorenz AW, Hering D, Antons C, Sundermann A, Jedicke E, Haase P, 2011. River restoration success: A question of perception. *Ecological Applications*, 21(6): 2007-2015. DOI:10.1890/10-0618.1
- Johnson RR, Haight LT, 1984. Riparian problems and initiatives in the American Southwest: A regional perspective. In: Warner, R.E., Hendrix, K.M. (Eds.), *California riparian systems: Ecology, conservation and productive management*. University of California Press, Berkeley CA, pp. 404-412.
- Knopf FL, Johnson RR, Rich T, Samson FB, Szaro RC, 1988. Conservation of riparian ecosystems in the United States. *The Wilson Bulletin*, 100(2): 272-284.
- Leopold LB, 1994. *A View of the River*. Harvard University Press.
- Lytle DA, Poff NL, 2004. Adaptation to natural flow regimes. *Trends in Ecology & Evolution*, 19(2): 94-100. DOI:10.1016/j.tree.2003.10.002
- Mahoney JM, Rood SB, 1991. A device for studying the influence of declining water table on poplar growth and survival. *Tree Physiology*, 8(3): 305-314. DOI:10.1093/treephys/8.3.305

- Mahoney JM, Rood SB, 1998. Streamflow requirements for cottonwood seedling recruitment—An integrative model. *Wetlands*, 18(4): 634-645. DOI:10.1007/bf03161678
- Nilsson C, Reidy CA, Dynesius M, Revenga C, 2005. Fragmentation and flow regulation of the world's large river systems. *Science*, 308(5720): 405-408. DOI:10.1126/science.1107887
- Palmer MA, Menninger HL, Bernhardt E, 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biology*, 55: 205-222. DOI:10.1111/j.1365-2427.2009.02372.x
- Pentney A, Ohrn D, 2008. Navigating from history into the future: The water management plan for the South Saskatchewan River Basin in Alberta. *Canadian Water Resources Journal*, 33(4): 381-396. DOI:10.4296/cwrj3304381
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC, 1997. The natural flow regime. *BioScience*, 47(11): 769-784. DOI:10.2307/1313099
- Reily PW, Johnson WC, 1982. The effects of altered hydrologic regime on tree growth along the Missouri River in North Dakota. *Canadian Journal of Botany*, 60(11): 2410-2423. DOI:10.1139/b82-294
- Rood S, Mahoney J, 2000. Revised instream flow regulation enables cottonwood recruitment along the St. Mary River, Alberta, Canada. *Rivers*, 7(2): 109-125.
- Rood SB, Bigelow SG, Hall AA, 2011. Root architecture of riparian trees: river cut-banks provide natural hydraulic excavation, revealing that cottonwoods are facultative phreatophytes. *Trees*, 25(5): 907-917. DOI:10.1007/s00468-011-0565-7
- Rood SB, Bigelow SG, Polzin ML, Gill KM, Coburn CA, 2015. Biological bank protection: trees are more effective than grasses at resisting erosion from major river floods. *Ecohydrology*, 8(5): 772-779. DOI:10.1002/eco.1544
- Rood SB, Braatne JH, Hughes FM, 2003a. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology*, 23(16): 1113-1124. DOI:10.1093/treephys/23.16.1113
- Rood SB, Bradley CE, 1993. Assessment of riparian cottonwoods along the Bow River downstream from Calgary, Alberta. Final Report to Trout Unlimited Canada, University of Lethbridge, Calgary, Alberta.
- Rood SB, Gourley CR, Ammon EM, Heki LG, Klotz JR, Morrison ML, Mosley D, Scoppettone GG, Swanson S, Wagner PL, 2003b. Flows for floodplain forests: A successful riparian restoration. *BioScience*, 53(7): 647-656. DOI:10.1641/0006-3568(2003)053[0647:ffffas]2.0.co;2

- Rood SB, Heinze-Milne S, 1989. Abrupt downstream forest decline following river damming in southern Alberta. *Canadian Journal of Botany*, 67(6): 1744-1749. DOI:10.1139/b89-221
- Rood SB, Hillman C, Sanche T, Mahoney JM, 1994. Clonal reproduction of riparian cottonwoods in southern Alberta. *Canadian Journal of Botany*, 72(12): 1766-1774. DOI:10.1139/b94-217
- Rood SB, Kalischuk AR, Mahoney JM, 1998. Initial cottonwood seedling recruitment following the flood of the century of the Oldman River, Alberta, Canada. *Wetlands*, 18(4): 557-570. DOI:10.1007/bf03161672
- Rood SB, Kalischuk AR, Polzin ML, Braatne JH, 2003c. Branch propagation, not cladogenesis, permits dispersive, clonal reproduction of riparian cottonwoods. *Forest Ecology and Management*, 186(1-3): 227-242. DOI:10.1016/S0378-1127(03)00276-7
- Rood SB, Kaluthota S, Gill KM, Hillman EJ, Woodman SG, Pearce DW, Mahoney JM, 2016. A twofold strategy for riparian restoration: Combining a functional flow regime and direct seeding to re-establish cottonwoods. *River Research and Applications*, 32(5): 836-844. DOI:10.1002/rra.2919
- Rood SB, Mahoney JM, 1990. Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. *Environmental Management*, 14(4): 451-464. DOI:10.1007/BF02394134
- Rood SB, Samuelson GM, Braatne JH, Gourley CR, Hughes FM, Mahoney JM, 2005. Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment*, 3(4): 193-201. DOI:10.2307/3868463
- Rood SB, Taboulchanas K, Bradley CE, Kalischuk AR, 1999. Influence of flow regulation on channel dynamics and riparian cottonwoods along the Bow River, Alberta. *Rivers*, 7(1): 33-48.
- Sabo JL, Sponseller R, Dixon M, Gade K, Harms T, Heffernan J, Jani A, Katz G, Soykan C, Watts J, 2005. Riparian zones increase regional species richness by harboring different, not more, species. *Ecology*, 86(1): 56-62. DOI:10.1890/04-0668
- Scott ML, Lines GC, Auble GT, 2000. Channel incision and patterns of cottonwood stress and mortality along the Mojave River, California. *Journal of Arid Environments*, 44(4): 399-414. DOI:10.1006/jare.1999.0614
- Scott ML, Shafroth PB, Auble GT, 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management*, 23(3): 347-358. DOI:10.1007/s002679900191

- Smith DG, 1979. Effects of channel enlargement by river ice processes on bankfull discharge in Alberta, Canada. *Water Resources Research*, 15(2): 469-475. DOI:10.1029/WR015i002p00469
- Stanley EH, Doyle MW, 2003. Trading off: the ecological effects of dam removal. *Frontiers in Ecology and the Environment*, 1(1): 15-22. DOI:10.1890/1540-9295(2003)001[0015:Toteeo]2.0.Co;2
- Stettler R, Bradshaw HJ, Heilman P, Hinckley T, 1996. *Biology of Populus and its Implications for Management and Conservation*. Preface. NRC Research Press, 542 pp.
- Tockner K, Stanford JA, 2002. Riverine flood plains: Present state and future trends. *Environmental conservation*, 29(03): 308-330. DOI:10.1017/S037689290200022X
- UN Water, 2007. *Coping with water scarcity: challenge of the twenty-first century*. Prepared for World Water Day.
- Williams CA, Cooper DJ, 2005. Mechanisms of riparian cottonwood decline along regulated rivers. *Ecosystems*, 8(4): 382-395. DOI:10.1007/s10021-003-0072-9
- WWF-Canada, 2009. *Canada's rivers at risk: Environmental flows and canada's freshwater future*, World Wildlife Fund Canada.

CHAPTER 2: HISTORIC AND PROSPECTIVE FUTURE FLOWS OF THE RED DEER RIVER AND ITS HEADWATER TRIBUTARIES

2.1 Introduction

A warming climate is predicted to have the greatest impact on the hydrological cycle of snow-dominated basins at higher latitudes (Barnett et al., 2005; Huntington and Niswonger, 2012; Nogués-Bravo et al., 2007). Changes, such as earlier snowmelt and earlier peak runoffs, have already been observed in many river basins in North America (Cayan et al., 2001; Mote et al., 2005; Rood et al., 2016). In addition to changing seasonality, there is potential for changes in the overall supply of water. Water supply is primarily dependent on precipitation. While trends and predictions of warming appear to be relatively consistent, regional changes in the volume and pattern of precipitation, and consequently water supply, are less certain (Stephens et al., 2010; Stevens and Bony, 2013)

In Alberta, many rivers have experienced a gradual decline in annual discharge as a result of climate change (Rood et al., 2008; Rood et al., 2005; St. Jacques et al., 2010). The overlap of potential decreasing supply with growing demand threatens Alberta's future water security. In southern Alberta, the South Saskatchewan River Basin (SSRB) is considered Canada's most threatened river system (WWF-Canada, 2009). The SSRB is comprised of four major sub-basins, the Oldman River, South Saskatchewan River, Bow River, and Red Deer River basins. Water licensing has been recognized as unsustainable within these basins with surface water allocations being reached or exceeded in three of four of the basins. This has created a significant gap between existing flows and the flows necessary to maintain long term functioning ecosystems (Alberta Environment, 2006).

Only the Red Deer River system remains open to further allocation. The availability of further licensing has renewed interest in the Red Deer River as a future water source. Potential changes in the volume and seasonality of streamflow under a changing climate will pose challenges to water management as water demands increase. The object of this study is to provide an analysis of the historic and prospective future hydrology of the Red Deer River and its headwater tributaries. Understanding the past and predicting future changes in streamflow will allow for improved decision making on how to balance both the economic and ecological needs within the Red Deer River Basin.

The Red Deer River Basin is the most northern and largest basin in the South Saskatchewan River system, but is third in volume, contributing, on average, only 20% of the annual flow of the South Saskatchewan River (Clipperton et al., 2003). The headwaters of the Red Deer River lie in the Rocky Mountains within Banff National Park, with the uppermost regions originating near Lake Louise (Figure 2-1). From the mountains, the river flows east through foothill, boreal and parkland natural regions before passing through Red Deer and eventually into Saskatchewan where it joins the South Saskatchewan River. Mountain and foothills form a relatively small proportion of the Red Deer River Basin but contribute the majority of the annual flow. The area upstream of the city of Red Deer accounts for approximately 85% of the annual naturalized discharge of the Red Deer River as measured near the Saskatchewan border.

Regional studies have found that summer temperatures in the western prairies have remained relatively unchanged over the past century; however, winter and spring temperatures, especially minimum temperatures, have increased significantly (Cutforth et al., 1999; Millett et al., 2009). The upper Red Deer River is no exception with most

warming occurring in January, February and March (Table 2-1). It is expected that this warming will continue (Barnett et al., 2005). To analyze the impacts of a potential future climate on the volume and seasonality of streamflow in the Red Deer River Basin, we applied two complimentary approaches, hydroclimatic modelling and projection of historical streamflow trends.

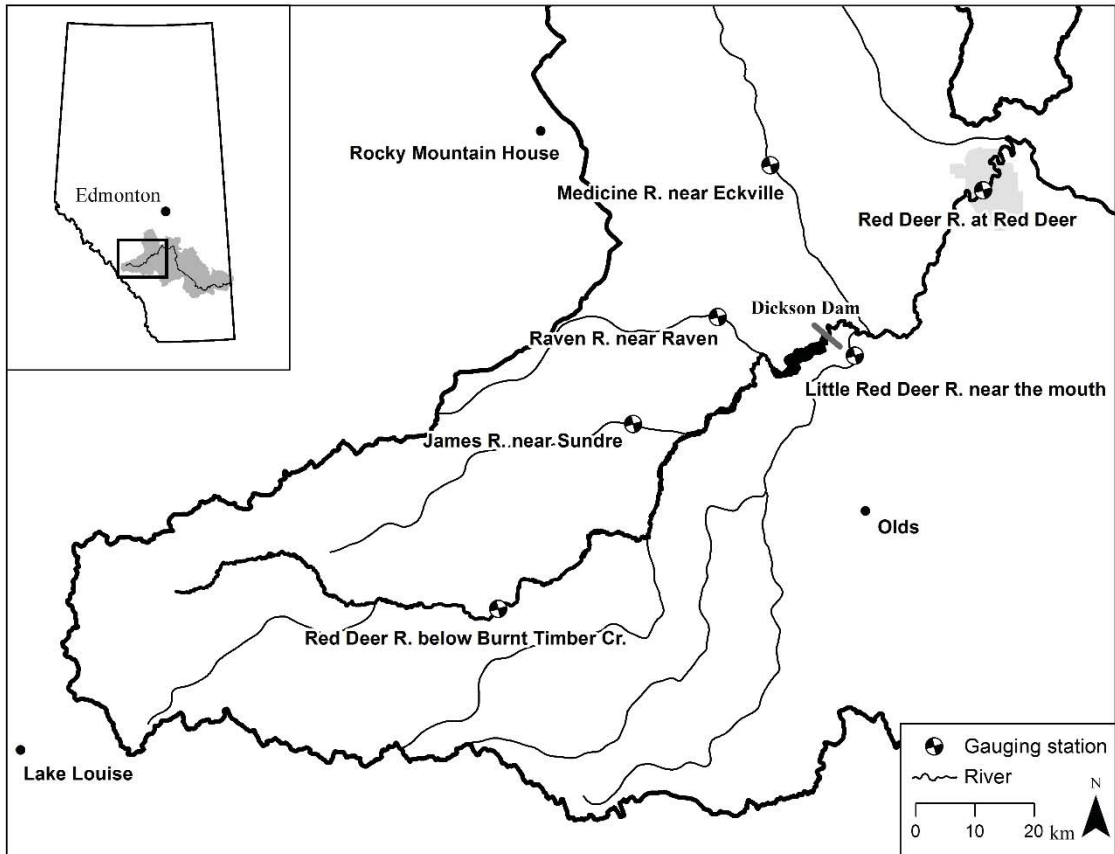


Figure 2-1: Map of the upper Red Deer River Basin and major tributaries of the Red Deer River. Gauging station locations where trends were analyzed are depicted along each tributary.

Table 2-1: Annual and monthly temperature trends at meteorological stations around the upper Red Deer River Basin from 1912 to 2012. Kendall's tau coefficients are shown. Significance distinguished using three levels of confidence: a probable trend (*t*) for $p < 0.1$, a significant pattern (*) for $p < 0.05$ and a highly significant pattern (**) for $p < 0.01$. Missing data were infilled using regression equations obtained by plotting climatological stations with missing monthly data with the nearest climatological station with data ($r^2 \geq 0.97$). Data for Rocky Mountain House and Olds were obtained from Environment and Climate Change Canada's Second Generation Homogenized Surface Air Temperature Database (Vincent et al., 2012). Data for Lake Louise and Red Deer were obtained from the National Climate Data Archive (Environment and Climate Change Canada, <http://climate.weather.gc.ca/>, data accessed up to Dec. 2015).

	Lake Louise	Rocky Mountain House	Olds	Red Deer
Annual	0.208 **	0.160 *	0.216 **	0.171 *
January	0.153 *	0.150 *	0.119 <i>t</i>	0.114 <i>t</i>
February	0.179 **	0.149 *	0.145 *	0.114 <i>t</i>
March	0.241 **	0.160 *	0.133 *	0.131 <i>t</i>
April	0.104	0.007	- 0.008	- 0.006
May	0.068	- 0.007	0.049	0.058
June	0.045	0.084	0.171 *	0.182 **
July	0.082	0.065	0.083	- 0.016
August	0.183 **	0.127 <i>t</i>	0.121 <i>t</i>	0.071
September	0.133 *	0.138 *	0.150 *	0.129 <i>t</i>
October	- 0.011	0.007	- 0.045	- 0.039
November	- 0.017	- 0.007	- 0.030	- 0.058
December	- 0.008	0.016	0.025	- 0.008

2.1.2 Hydroclimatic modelling

General circulation models (GCMs) are the most advanced tools available for simulating environmental responses to atmospheric changes (Mearns et al., 2001). GCMs represent computer models that blend energy inputs and flow of many physical processes in order to understand and forecast climate. GCMs can model climatic changes under various scenarios such as increased atmospheric greenhouse gases. Unfortunately, these models are sometimes limited in their applicability due to their coarse spatial resolution.

Hydrological models in particular, often consider catchment areas at a much smaller spatial resolution than those available from GCMs (Wilby and Wigley, 1997). This challenge can be overcome by downscaling the data output of GCMs. Downscaled GCM data can be used to assess changes in climatic variables at a regional level under various climate scenarios (Shepherd and McGinn, 2003). Climate projections can be input to environmental models for snowpack accumulation and melt to simulate future streamflows.

2.1.3 Historical streamflow projection

The detection and understanding of past trends and variability in hydrological variables is fundamental to understanding the impacts of climate change and is prudent for water management, especially in semi-arid regions (Jacques et al., 2011). As the near future often extends the recent past, trends in the seasonality and volume of gauged streamflow can provide insight into probable future flows. This is called empirical trend analysis (Shepherd et al., 2010). In empirical trend analysis, parametric and non-parametric rank order tests can be used to detect and quantify historical patterns in streamflow data. The direction and magnitude of these trends can then be extended into the future.

The analysis and projection of historical trends and hydroclimatic modelling are largely independent strategies for analyzing the impacts of climate change on streamflow. A combined approach of these methods can provide a stronger analysis than each independently. Changes in the hydrologic record that are consistent with modelled projections can lend credibility to the modelling process (Burn, 1994).

Our historical analysis and modelling of the Red Deer River is an extension of our work investigating prospective river flows within the Oldman River Basin (Shepherd et al., 2010). Our methods and results have been modified and updated from our technical report *Historic and prospective future flows of the Red Deer River and its headwater tributaries* (Gill et al., 2008).

2.2 Methods

2.2.1 Historical trend analysis

Trends in mean annual discharge (Q_a) and mean monthly discharge (Q_m) were analyzed from 1912 to 2012 for the Red Deer River at Red Deer and the major upstream tributaries (Figure 2-1). Streamflow data were obtained from HYDAT, the Water Survey of Canada's Hydrological Database (<http://wateroffice.ec.gc.ca/>) and Alberta Environment's Natural Flow Database (Alberta Environment, 1998). Only data not impacted by water diversion and management or data that has had these influences removed was considered. Long data sets (>100 years) were used to absorb natural climatic variation.

2.2.1.1 Data preparation

Annual trends for the Red Deer River at Red Deer were analyzed using gauged daily stream discharge data. Despite river regulation following the construction of the Dickson

Dam and formation of the Gleniffer Reservoir in 1983, Q_a volumes are likely unaltered due to a small reservoir with limited year-to-year carryover. To account for reservoir evaporation, an adjustment of $0.105 \text{ m}^3/\text{s}$, obtained from Alberta Environment's Natural Flow Database, was applied to the post-dam period (Alberta Environment, 1998). The gauged dataset was also supplemented with data from the Natural Flow Database for years with missing data from 1931 to 1935. Water removal was not considered in this study since consumptive water use along the Red Deer River is low, especially in the upper reaches, and has little effect on annual flow volumes (AMEC, 2009).

The most recent Alberta Environment naturalized dataset provides discharge data for the period of 1912 to 2009. To analyze naturalized Q_m trends for the Red Deer River at Red Deer up to 2012, we derived a new monthly naturalized flow dataset. The approach for constructing naturalized flows was to first coordinate the discharge from the Dickson Dam and the main downstream tributaries with the discharge at Red Deer from 1984 to 2012 (Figure 2-2). Outflow Q_m data for the Dickson Dam provided by Alberta Environment were summed with the downstream Q_m of the unmanaged Medicine and Little Red Deer Rivers. This provided a Q_m value that included the majority of the flow gauged at Red Deer, termed the 'tributary' discharge. Other flow not contributed by the main tributaries was then accounted for with a correction factor derived by linear regression. Gauged Q_m at Red Deer and the calculated 'tributary' Q_m were log-transformed to normalize the data, grouped seasonally, plotted, and fit with linear equations (Appendix A, Figure A-1). These equations were applied to the sum of the Medicine River, Little Red Deer River, and the inflow into the Dickson Dam (Gleniffer Reservoir) rather than the outflow, to produce naturalized monthly mean discharges at

Red Deer. The Alberta Environment naturalized Q_m was used for 1983 as no inflow data were available. The naturalized Q_m values from 1983 to 1984 were then combined with the free-flowing data gauged at Red Deer for trend analysis from 1912 to 2012.

A similar naturalization process as described above was applied to the tributary annual maximum daily discharge for May, June and July from 1984 to 2012 in order to analyze trends in peak discharges for the Red Deer River at Red Deer. A linear correction equation accounting for other flow was generated by plotting the annual maximum discharge of the three-day moving average of the sum of daily discharges from the Dickson Dam, Medicine River and the Little Red Deer River with the corresponding daily discharge for the Red Deer River at Red Deer. A three-day moving average of daily 'tributary' discharge was used as it provided a better fit than daily discharges. This is likely the result of differences in flow routing and time of travel of different flood magnitudes between the upstream tributaries and the Red Deer gauge. Discharges were log-transformed to normalize the data. The correction equation was then applied to the annual maximum discharge of the three day moving average of the sum of the daily inflow into the Dickson Dam and the corresponding discharges for the Medicine and Little Red Deer Rivers. This produced naturalized annual max daily discharge values for the Red Deer River at Red from 1984 to 2012. These naturalized values were joined with gauged annual peak discharges before the construction of the Dickson Dam for trend analysis from 1912 to 2012.

Peak discharges were limited to May, June and July to best represent annual max daily discharges with a significant contribution from mountain snow melt. Timing of annual max daily discharge is highly variable on the Red Deer River (Appendix B, Figures B-1,

B-2). High flows from prairie snowmelt or late summer rains can exceed the more common peak flows that occur in May, June and July. Peak flows resulting from these different meteorological causes represent statistically different populations and should be considered separately (Gordon et al., 1992).

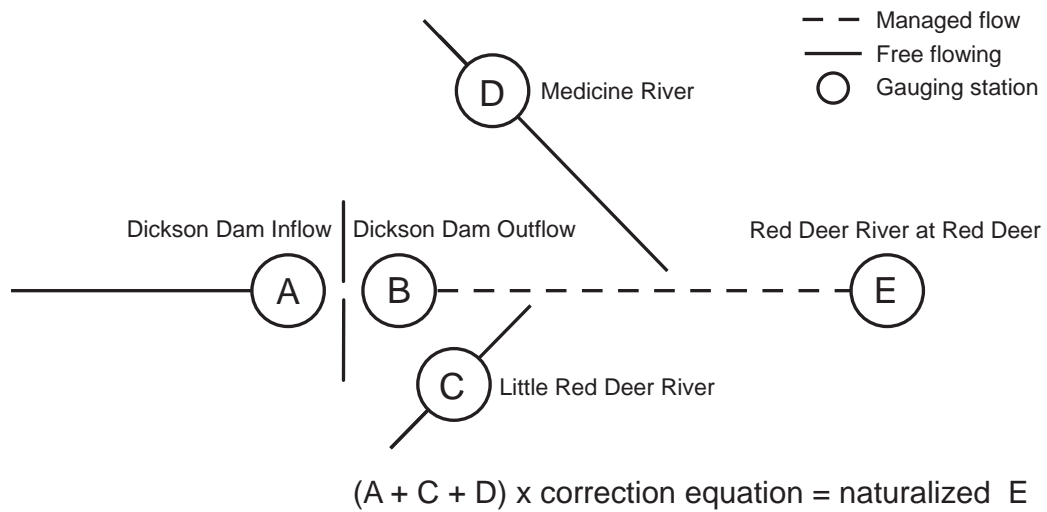


Figure 2-2: Gauging stations used in naturalization process. The sum of the discharges at B, C and D (tributary discharges) were plotted against the discharge at E to derive a correction equation that accounts for other flow contributions downstream from the dam other than C and D. The sum of A, C and D multiplied by the correction equation provides naturalized flow discharges at E.

Discharge data for the upper tributaries of the Red Deer River were limited with most records commencing around 1970. To generate a complete dataset for the upper tributaries, the Alberta Naturalized Dataset (1912-2009) was converted from weekly to daily discharges and supplemented with daily gauged HYDAT data. This extended the data to cover the period from 1912 to 2012. Daily discharges were then averaged to Q_a and Q_m values for trend analysis. Peak discharges were not analyzed for the upper tributaries.

2.2.1.2 Statistical analysis and trend projection

Statistical analyses were carried out using SPSS v.19 (IBM, Armonk, NY). The significance of trends was determined using the parametric Pearson product moment correlation coefficient and the more conservative non-parametric Mann-Kendall test.

The Mann-Kendall test requires that data is not autocorrelated (Yue and Wang, 2004).

Autocorrelation is the correlation of values with past or future values. This is common in hydroclimatic datasets as snow and ice, groundwater and other stored water can persist across multiple years (Huntington and Niswonger, 2012; McCuen, 2003). Kulkarni et al.

(1995) demonstrated that autocorrelation can increase the probability of the Mann-

Kendall test to erroneously signal a trend. They suggest data be “pre-whitened” to remove autocorrelation before trend analysis; however, this can remove a portion of the trend independent from the effect of autocorrelation (Yue et al., 2002). To avoid this

underestimation of a significant trend, when lag-one autocorrelation was detected, the

Mann-Kendall test was preceded by a trend-free pre-whitening process, whereby the trend

was first removed from the time series and then re-introduced after the removal of

autocorrelation (Yue and Wang, 2002). Our procedure is described by Burn et al. (2004).

Parametric tests were conducted on log-transformed data in order to best normalize the distributions. Statistically meaningful patterns were distinguished using three levels of confidence: a probable trend (*t*) for $p < 0.1$, a significant pattern (*) for $p < 0.05$ and a highly significant pattern (**) for $p < 0.01$.

The non-parametric Sen's slope (Sen, 1968) was used to calculate percent change in annual and mean monthly streamflow on an annual (yearly) basis and for the entire period from 1912 to 2012. Sen's slope was then also subsequently used to extend trends for each stream to project monthly and annual streamflow to the year 2055.

2.2.2 Hydroclimatic modelling

Our procedure integrated several modified computer models which process topographical and climate data through several stages. These models are termed 'lumped models' and aggregate general processes within a basin through the application of statistical methods to describe quantitative associations. These models have an advantage over more process-based models as they require less watershed data (Bingeman et al., 2006; Kouwen et al., 2002; Pietroniro et al., 2006).

2.2.2.1 Model development

Mountain climate modeller (MTCLIM), a mountain microclimate model developed by the USDA-Forest Service (Hungerford et al., 1989), was used to transform temperature and precipitation from base locations to mountain sites via regressions with physical parameters. Historical base weather station data from 1960 to 1989 were obtained from Agriculture & Agri-Food Canada and downscaled to a 50-x-50 km grid of Alberta via the inverse distance squared method developed by McGinn et al. (1999). Climate grid points

nearest the headwaters of each sub-basin within the upper Red Deer River were extracted and input with site parameters such as elevation, slope and aspect derived from digital elevation models, and other physical parameters such as latitude and local adiabatic lapse rate. The precipitation module of MTCLIM was modified from the original procedure to derive precipitation from base sites rather than from isohyet maps, which were unavailable for some locations. Monthly precipitation values were calculated using quadratic polynomials derived through regression analysis of various mountain sites against elevation and aspect. To verify the modified MTCLIM model, simulated temperature and precipitation outputs were compared with meteorological data gauged at two sites, Ricinus ($52^{\circ}27'N$, $115^{\circ}00'W$) and Cuthead Lake ($51^{\circ}27'N$, $115^{\circ}46'W$). Pearson correlation was used to compare the degree of correspondence between the simulated and observed data.

Outputs from MTCLIM were subsequently inputted into a snowpack and snowmelt module, which involved modifications to an existing model called SNOPAC (Lapp et al., 2005; Pipes and Quick, 1977; Wyman, 1995). Areas of each watershed in the headwaters of the Red Deer River were categorized by combinations of different elevation, slope and aspect to provide 48 topographical classes. Temperature and precipitation values from MTCLIM were assigned to these 48 topographic classes and input into SNOPAC. SNOPAC then determined whether precipitation fell as rain, snow or a combination, based on a minimum and maximum projected air temperature. Above a threshold, snowmelt was determined based on temperature, a point melt factor and reference dew point. Throughout the winter, snowpack rises and falls reflecting the balance between rain, snowfall and melt. The snow model was previously modified to analyze regional

snowpack patterns (Lapp et al., 2005), and subsequently expanded to analyze snowmelt. The snowmelt model computed snowmelt water yield for the different topographic classes for each watershed. This was then aggregated with rainfall to provide water yields for each watershed. The accuracy of the snowpack modelling was determined by comparing simulated results with historic snowpack data recorded from Alberta Environment's Limestone Ridge snow pillow site (<http://environment.alberta.ca/apps/basins>, data accessed December 2007).

Water yields from rain and snowmelt were translated into stream discharge using a river flow routing module called RIVRQ developed by Shepherd et al. (2010). RIVRQ divides stream discharge into two major components: stream contributions arising from a relatively stable perennial baseflow, and a more dynamic component arising from large rain and snowmelt events. Baseflow discharge is likely the result of inputs from riparian groundwater such as those from an alluvial aquifer. This is evidenced by persistent stream discharge during weeks without rainfall or snowmelt. To provide a constant baseflow, aquifers require gradual recharge during rain or snowmelt periods to compensate for drier periods. To account for this dynamic, we first defined baseflow for each tributary as the typical annual low flow rate during the ice-free period. In RIVRQ, when water yield exceeded the determined baseflow, the first priority was to provide the baseflow. Aquifer recharge was the second priority of RIVRQ. Recharge involved a consistent contribution from water yield into the aquifer during all wet periods throughout the year (i.e. when $\text{yield} > \text{baseflow}$). The number of days in a year where water yield was below the associated baseflow provided the volume of water yield required to compensate the aquifer. We acknowledge that recharge is likely variable and not consistent with the

extent of drawdown, but other recharge options were found to have little impact on seasonal hydrographs.

Water yield during large rain and snowmelt events raises stream discharge above baseflow and the aquifer recharge contribution. For the conversion of high water yields to streamflow, a lag component of 1 to 3 days was applied depending on the size of the watershed. The lag component resulted in daily water yields being contributed to the discharge of the current day and the following 1 to 3 days. This represented the transit time for water to flow from the water yield location to the location of the hydrometric gauge on the stream.

The model sequence neglected most water losses, transpiration in particular. As the magnitude and timing of these losses is unknown, the final step after RIVRQ was the application of a quadratic regression correction equation in order to maximize the correspondence between simulated and measured river discharges.

Before the model sequence was applied to predict future flows, it was evaluated by plotting simulated flows with gauged discharges to determine the correlation between the two datasets. We analyzed correlations between individual mean monthly data points, averaged mean monthly data and mean annual flows from 1960 to 1989. Coefficients of determination (r^2) were determined using the Pearson correlation.

2.2.2.2 Future forecasting from down-scaled GCMs

Future scenarios were investigated using 4 GCMs, HadCM3, NCAR-CCM3, ECHAM4 and the CGCM1-A models. The IPCC Special Report on Emission Scenarios (SRES) provides likely future atmospheric conditions (Nakicenovic and Swart, 2000). The

HadCM3, NCAR-CCM3 and ECHAM4 models are based on the SRES A2 scenario that anticipates a high population growth of 15 billion by the year 2100 with relatively slow economic technological development. The Canadian CGCMI-A model is based on the IS92a scenario which predicts slightly greater greenhouse gas emissions and aerosol loading. These GCMs have all been commonly applied and produce moderate and consistent projections for North America (Coquard et al., 2004; Gray and Hamann, 2013; Shepherd et al., 2010; Shepherd and McGinn, 2003). While the models are based on the older CMIP3 (Coupled Model Intercomparison Project phase 3) scenarios and have been superseded by the more recent CMIP5 scenarios, they have been found to produce very similar spatial patterns of temperature and precipitation change (Knutti and Sedláček, 2013; Wuebbles et al., 2014).

Daily maximum and minimum temperatures and precipitation for each watershed were downscaled from GCMs for the historical base period 1960 to 1989 and for the period 2040 to 2069 using methods described in Shepherd and McGinn (2003) and Shepherd et al. (2010). These values were then inputted into the hydroclimatic model sequence to determine change in the monthly and annual streamflow for each tributary. The tributaries were then aggregated and a correction equation was applied to determine future flows for the entire upper basin.

2.2.3 Comparison of empirical trend and GCM predictions

Changes in annual and mean monthly discharge were forecasted from the three decades around 1975 (1960 to 1989) to the three decades around 2055 (2040 to 2069). Predicted changes in annual and mean monthly discharge from empirical trend analysis were compared for the Red Deer River below Burnt Timber Creek, the Little Red Deer River

near the mouth and the upper basin as a whole as gauged for Red Deer River at Red Deer. For empirical trend analysis, the non-parametric slopes generated from the trend-free pre-whitened series were applied to the actual historical series to generate annual and monthly discharge values for 1975 and 2055. Slopes were applied whether they were determined to be significant or not. Values forecasted for 2055 were then subtracted from the 1975 base period to calculate the magnitude of change in annual and mean monthly discharge. Using simulations produced under GCM scenarios, future changes in streamflow were generated by subtracting the mean derived flow for the baseline period, 1960 to 1989, from the mean modelled streamflow forecast for the period from 2040 to 2069. For changes in annual and mean monthly discharge, the empirical future was compared to the empirical past and the modelled future was compared to the modelled past. These comparisons were made due to differences between the recorded and modelled historic datasets.

2.3 Results

2.3.1 Naturalized data validation

The seasonal linear regressions used to naturalize mean monthly flows at Red Deer provided strong fits (Spring $r^2 = 0.97$, Summer $r^2 = 0.99$, Fall $r^2 = 0.98$), with the exception of the winter regression equation ($r^2 = 0.57$) (Appendix A, Figure A-1). Our naturalized data and Alberta Environment's naturalized data were generated using independent methods and produced comparable results with both annual and mean monthly discharges being very similar (Figures 2-3 and 2-4). The 2005 flood year annual and monthly mean discharges were somewhat greater for our dataset compared to Alberta

Environments. A strong fit was also produced for the correction equation for the naturalization of max daily discharges ($r^2 = 0.97$) (Appendix A, Figure A-2).

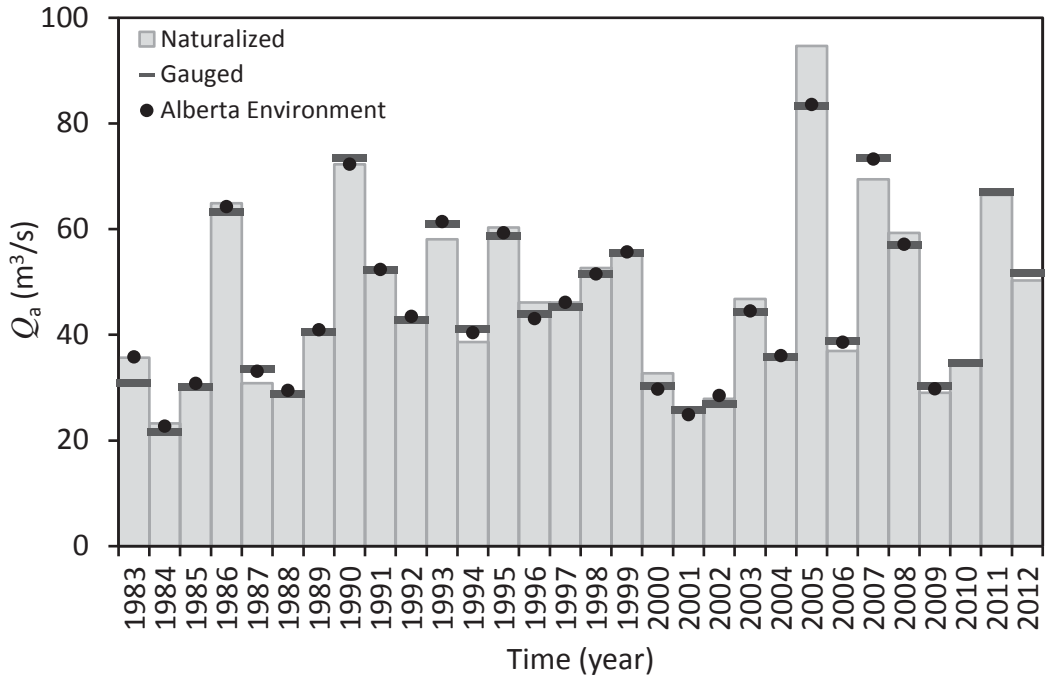


Figure 2-3. Comparison of mean annual discharges (Q_a) of our naturalized data, Alberta Environment's naturalized data and gauged data for the Red Deer River at Red Deer gauging station.

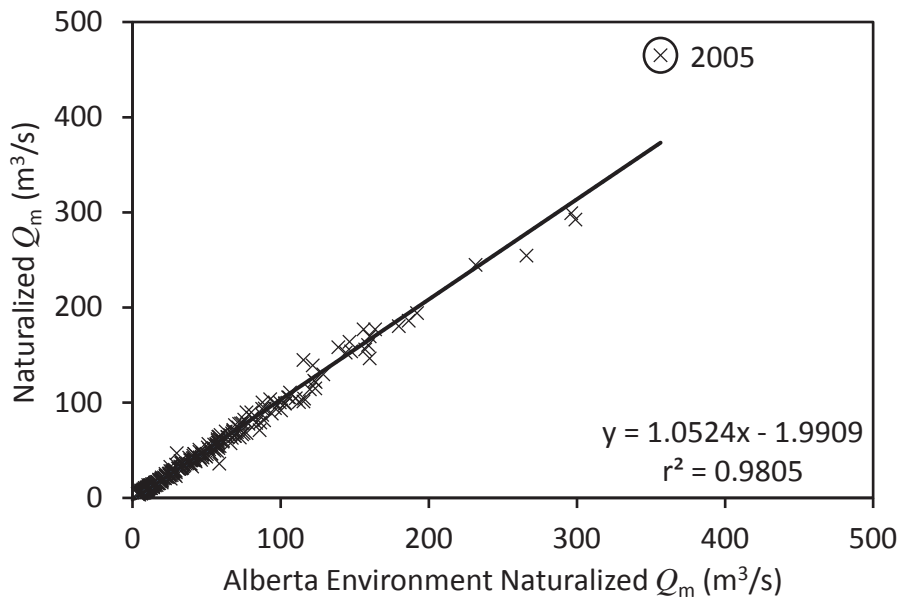


Figure 2-4: Comparison of mean monthly discharges (Q_m) of the generated naturalized data set and Alberta Environment's naturalized data. Data points represent the managed period between 1983 and 2009.

2.3.2 Historical annual and monthly flow trends

Results from the parametric Pearson product moment correlation coefficient analysis and the pre-whitened non-parametric Mann-Kendall test were similar when determining the significance of trends (coefficients, Table 2-2; p-values, Appendix C, Table C-1). Only the results from the Mann-Kendall test are presented.

No trends in annual average discharge were found from 1912 to 2012 for the Red Deer River at Red, Red Deer River below Burnt Timber Creek, James River near Sundre, Raven River near Raven or the Little Red Deer River near the mouth. Only the Medicine River near Eckville showed a significant trend in mean annual flow with an increase of approximately 0.28% per year from 1912 to 2012 (Table 2-3).

No trends in mean monthly discharge were detected for the Red Deer River at Red Deer with the exception of March. March showed an increase of 0.26% per year or an increase of 39% from 1912 to 2012.

Overall there were no consistent patterns in mean monthly discharge between the tributaries (Figure 2-5). The Red Deer River below Burnt Timber Creek showed an increasing trend in February discharge (0.12% per year) and decreases in April (0.24% per year) and August (0.20% per year). The most trends were found on the Raven River. Decreasing mean monthly discharges were found for January (0.37% per year), February (0.22% per year), November (0.33% per year) and December (0.45% per year), and an increasing trend in March (0.21% per year). The Medicine River only showed an increase in July mean monthly discharge (0.51% per year). The Little Red Deer River had

increasing trends in September (0.37% per year) and October (0.43% per year). No trends were found for the James River.

No trends were found for annual max daily discharges for either magnitude or day of occurrence. Peak discharges do not appear to be occurring earlier or increasing in volume along the Red Deer River.

Table 2-2: Pearson product moment correlation coefficients and Tau-b values of mean annual discharges, and monthly discharges from 1912 to 2012. Statistically meaningful patterns are bold and distinguished using three levels of confidence: a probable trend (t) for $p < 0.1$, a significant pattern (*) for $p < 0.05$ and a highly significant pattern (**) for $p < 0.01$.

	RDR at Red Deer		RDR below Burnt Timber Creek		James River		Raven River		Medicine River		Little Red Deer River	
	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ
Annual	-0.124	-0.041	-0.132	-0.060	-0.051	-0.002	0.055	0.009	0.164	0.121^t	-0.072	-0.016
Jan	-0.060	-0.031	0.028	0.022	-0.390^{**}	-0.277^{**}	-0.179^t	-0.070	-0.049	-0.034	-0.049	-0.034
Feb	0.001	-0.018	0.195^t	0.142[*]	-0.185^t	-0.173[*]	-0.156[*]	0.073	0.073	0.043	0.073	0.043
Mar	0.168^t	0.120^t	-0.023	-0.006	0.261^{**}	0.128^t	0.249	0.111	0.000	0.049	0.000	0.049
Apr	-0.013	-0.020	-0.297^{**}	-0.231^{**}	0.149	0.079	0.093	0.061	-0.052	-0.037	-0.052	-0.037
May	-0.074	-0.059	-0.058	-0.041	-0.067	-0.101	-0.096	-0.047	-0.044	-0.044	-0.047	-0.044
Jun	-0.086	-0.052	-0.001	0.009	0.050	-0.099	0.000	-0.140	-0.098	-0.098	-0.140	-0.098
Jul	-0.056	0.009	-0.141	-0.087	0.019	-0.068	0.298^{**}	0.005	0.035	0.035	0.005	0.035
Aug	-0.158	-0.016	-0.235[*]	-0.134[*]	-0.079	-0.026	0.115	0.070	-0.042	0.027	-0.042	0.027
Sep	-0.139	0.033	-0.170^t	-0.045	0.048	0.069	-0.081	-0.054	0.031	0.118^t	0.031	0.118^t
Oct	-0.122	0.053	-0.120	-0.044	0.113	0.102	-0.148	-0.060	0.176^t	0.164[*]	0.176^t	0.164[*]
Nov	-0.102	0.027	-0.134	-0.057	-0.254[*]	-0.215^{**}	0.043	0.080	-0.095	0.059	-0.095	0.059
Dec	-0.102	-0.024	0.053	0.060	-0.364^{**}	-0.276^{**}	-0.034	0.009	-0.034	0.001	-0.034	0.001

Table 2-3: Average yearly percent change and percent change from 1912 to 2012 of mean annual and monthly discharges. Significant patterns are bold and distinguished using three levels of confidence: a probable trend (*t*) for $p < 0.1$, a significant pattern (*) for $p < 0.05$ and a highly significant pattern (**) for $p < 0.01$.

	RDR at Red Deer		RDR below Burnt Timber Creek		James River		Raven River		Medicine River		Little Red Deer River	
	Yearly	1912-2012	Yearly	1912-2012	Yearly	1912-2012	Yearly	1912-2012	Yearly	1912-2012	Yearly	1912-2012
Annual	-0.06	-10.41	-0.09	-11.97	-0.01	-1.00	0.01	1.33	0.28	43.88^t	-0.04	-6.33
Jan	-0.07	-7.15	0.02	2.36			-0.37^{**}	-31.25^{**}	-0.22	-23.09	-0.12	-13.39
Feb	-0.04	-4.29	0.12[*]	13.49[*]			-0.22[*]	-20.47[*]	-0.27	-26.57	0.17	24.89
Mar	0.26^t	39.45^t	0.00	-0.44			0.21^t	26.13^t	0.28	60.59	0.10	27.51
Apr	-0.04	-5.09	-0.24^{**}	-22.98^{**}	0.01	0.72	0.12	13.60	0.19	30.73	-0.07	-9.86
May	-0.13	-15.23	-0.07	-7.43	0.06	7.97	-0.17	-17.45	-0.12	-17.44	-0.12	-15.48
Jun	-0.14	-17.41	0.03	3.17	-0.13	-15.24	-0.28	-28.91	-0.08	-17.34	-0.36	-46.63
Jul	0.03	3.52	-0.19	-18.76	-0.13	-15.77	-0.13	-14.87	0.51^{**}	352.0^{**}	0.13	23.95
Aug	-0.03	-4.17	-0.20[*]	-19.23[*]	-0.13	-15.79	-0.05	-5.22	0.30	73.63	0.08	14.12
Sep	0.07	10.47	-0.08	-8.65	0.13	22.93	0.12	14.79	-0.17	-29.12	0.37^t	90.91^t
Oct	0.14	21.96	-0.08	-8.27	0.10	15.33	0.15	18.35	-0.22	-30.14	0.43[*]	82.94[*]
Nov	0.06	7.35	-0.08	-8.06			-0.33^{**}	-29.81^{**}	0.24	34.62	0.17	28.81
Dec	-0.06	-6.85	7.79	7.79			-0.45^{**}	-37.14^{**}	0.05	5.86	0.01	0.74

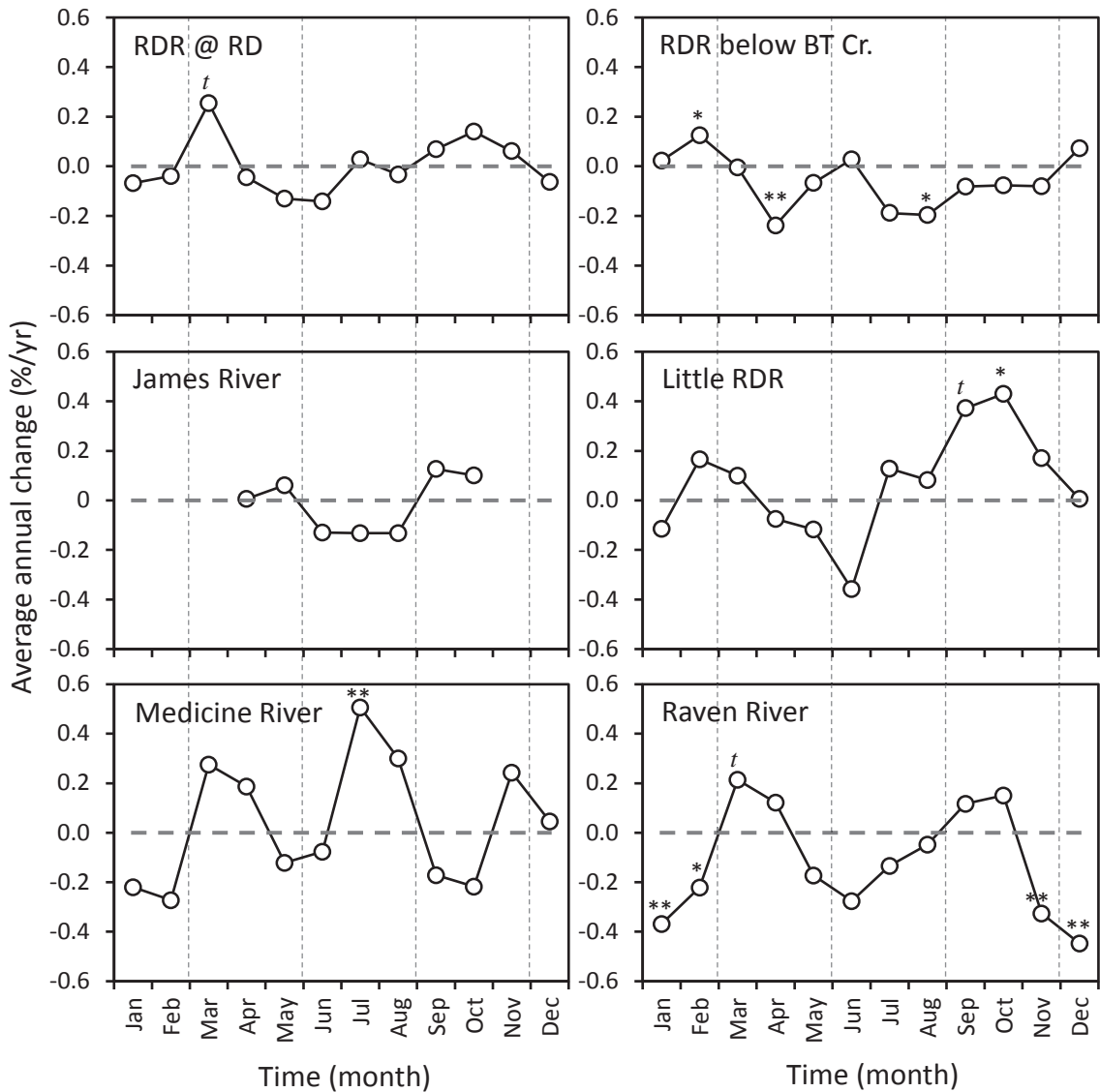


Figure 2-5: Average annual percent change in monthly discharge for the Red Deer River and the upper tributaries from 1912 to 2012. Percent change was calculated using Sen's slope (slope / mean · 100). Statistically meaningful patterns are distinguished using three levels of confidence: a probable trend (*t*) for $p < 0.1$, a significant pattern (*) for $p < 0.05$ and a highly significant pattern (**) for $p < 0.01$. Vertical dashed lines represent seasons.

2.3.3 Hydroclimatic model verification

Simulated mean monthly maximum and minimum temperatures were very similar to values observed at the Ricinus meteorological station ($r^2 = 0.997$ max temp, $r^2 = 0.996$ min temp) for the period of June 1986 to October 1987. There was also a strong correlation at the Cuthead Lake meteorological station ($r^2 = 0.958$ max temp, $r^2 = 0.934$ min temp) for the period January 1999 to January 2005. Simulated monthly precipitation at the Ricinus station was also closely correlated with observed values ($r^2 = 0.789$). Correlation between simulated and observed precipitation was weaker at the Cuthead Lake site ($r^2 = 0.340$). Simulated snowpack validated satisfactorily against measured snow pillow data obtained from Alberta Environment Water Management Operations Branch (not shown).

Overall, simulated average monthly discharges were fairly well modelled when compared to gauged data for the upper Red Deer River Basin for the period from 1960 to 1989 ($r^2 = 0.786$). April, May and June discharges were, however, significantly underestimated. Modelling appears to have delayed spring peak flows (Figure 2-6). Overall, simulated and observed average annual discharges were significantly correlated ($r^2 = 0.275$, $p = 0.002$), but the simulated discharges appear to be more conservative and do not fully capture the variability in the observed data (Figure 2-7). The correlation between simulated and measured results was particularly weak for the period from 1960 to 1970. This is likely the result of the underestimation of peak flows in years of high annual discharge such as in 1964. The decade from 1980 to 1990 was best modelled for the validation period.

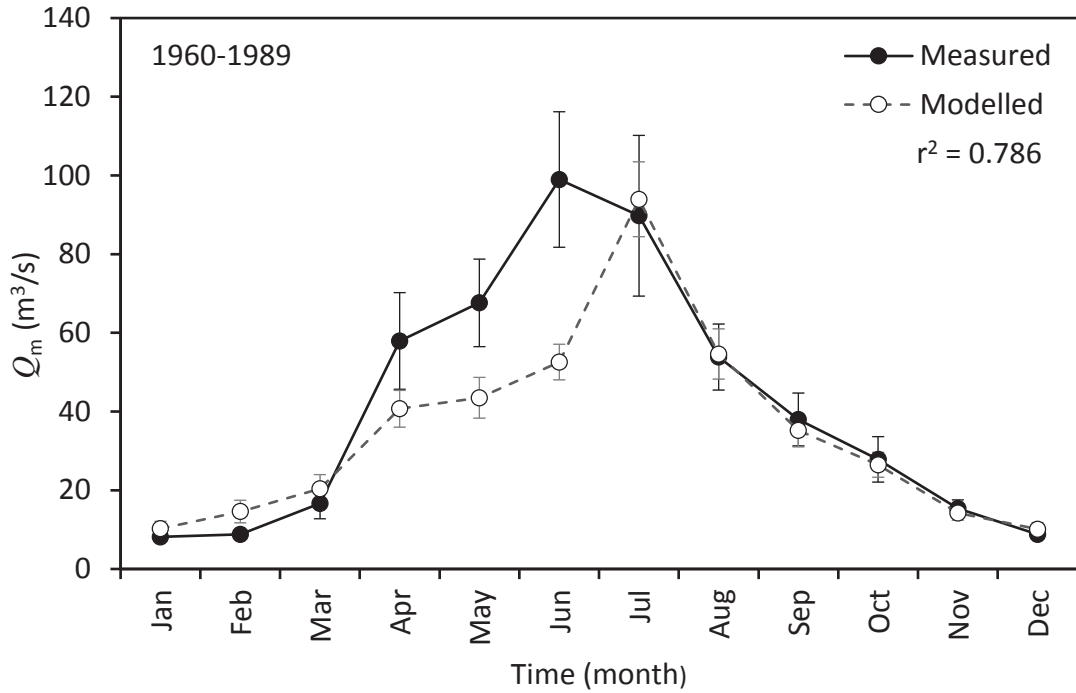


Figure 2-6: Comparison of gauged and modelled mean monthly discharge (Q_m) for the Red Deer River at Red Deer for the validation period of 1960 to 1989. Bars represent 95% confidence intervals about the mean, $n=30$.

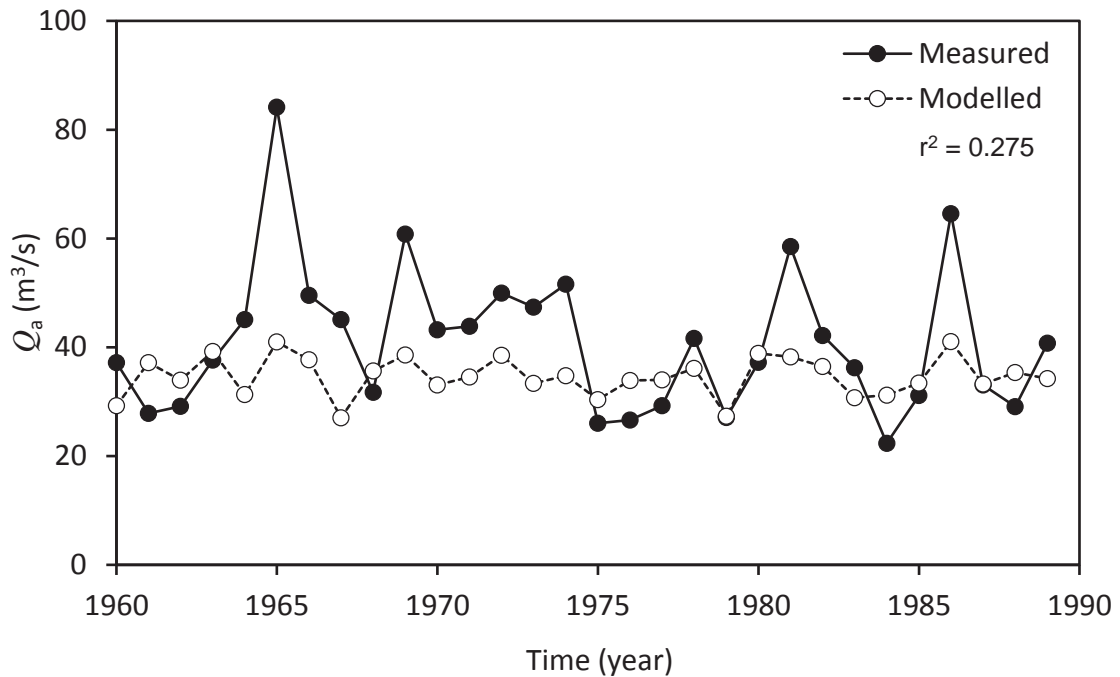


Figure 2-7: Comparison of gauged and simulated annual discharge (Q_a) for the Red Deer River at Red Deer for the validation period of 1960 to 1989.

Similar to modelled flows for the Red Deer River at Red Deer, modelled peak discharges of mean monthly flow for all the tributaries occurred later than what was reported at gauging stations. Peak discharge was modelled to occur in July for all the tributaries. The Red Deer River below Burnt Timber Creek, and to a lesser extent, the James River near Sundre, receive a greater proportion of discharge from higher elevations than the other tributaries and thus typically have a later peak discharge which occurs in June. The lower tributaries, the Little Red Deer River, Medicine River and the Raven River typically have a typical peak discharge which occurs in April resulting from lower elevation snowmelt. The model appears to have underestimated the contribution of this spring snowmelt. Measured and modelled mean monthly discharges were more highly correlated for the Red Deer River below Burnt Timber Creek ($r^2 = 0.729$). The majority of this basin is fed by higher elevation mountainous regions. The lower tributaries, which fall mainly in boreal/foothills regions, were less well modelled (Figure 2-8). The James River near Sundre ($r^2 = 0.480$) was best modelled for the lower tributaries followed by the Medicine River near Eckville ($r^2 = 0.416$), the Little Red Deer near the mouth ($r^2 = 0.395$) and the Raven River near Raven ($r^2 = 0.113$).

Overall, correlation between simulated and gauged annual discharges were less strong compared to mean monthly discharges. Simulated discharges were best correlated with gauged discharges for the Medicine River near Eckville ($r^2 = 0.418$), followed by the James River near Sundre ($r^2 = 0.272$), the Raven River near Raven ($r^2 = 0.249$), the Little Red Deer River near the mouth ($r^2 = 0.176$) and the Red Deer River below Burnt Timber Creek ($r^2 = 0.172$).

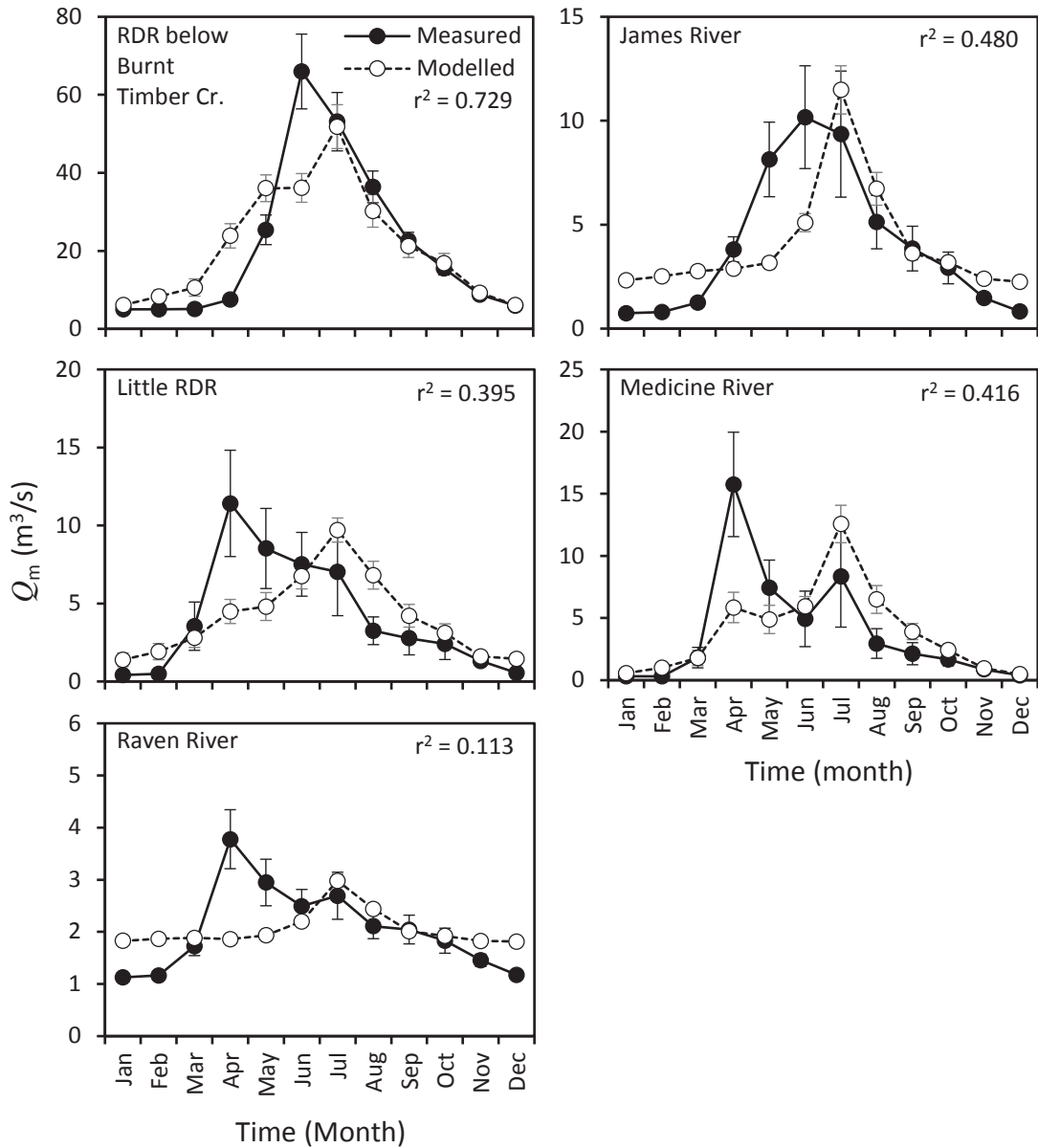


Figure 2-8: Correlation between measured and modelled mean monthly discharges for the upper tributaries of the Red Deer River for the validation period of 1960 to 1989. Bars represent 95% confidence intervals about the mean, $n=30$.

2.3.4 Future flows as predicted with empirical trend projection and GCM modelling

Forecasted changes in annual and mean monthly discharge from empirical trend analysis were compared for the upper basin as a whole as gauged at Red Deer, the Red Deer River below Burnt Timber Creek and for the Little Red Deer River near the mouth (Figures 2-9, 2-10 and 2-11). All of the GCMs, HadCM3, NCAR-CCM3, ECHAM4 and the CGCM1-A models, provided similar results with a forecast of slightly more water in the system on an annual basis. Empirical trend projection forecasted slight decreases in annual discharge for the period around 2055, but none of the past trends were determined to be significant.

For the entire upper basin as gauged at Red Deer, the empirical trend projection forecasted a 5% decrease in annual discharge while the average of the GCM climate-derived streamflow data show a 14% increase in annual discharge. For the Red Deer River below Burnt Timber Creek, a 7% reduction in discharge was forecasted using the empirical trend and an increase of 1% was forecasted by the models. The empirical trend analysis forecasted a 3% decrease in discharge for the Little Red Deer River near the mouth while the models forecasted a slight increase of 0.5%.

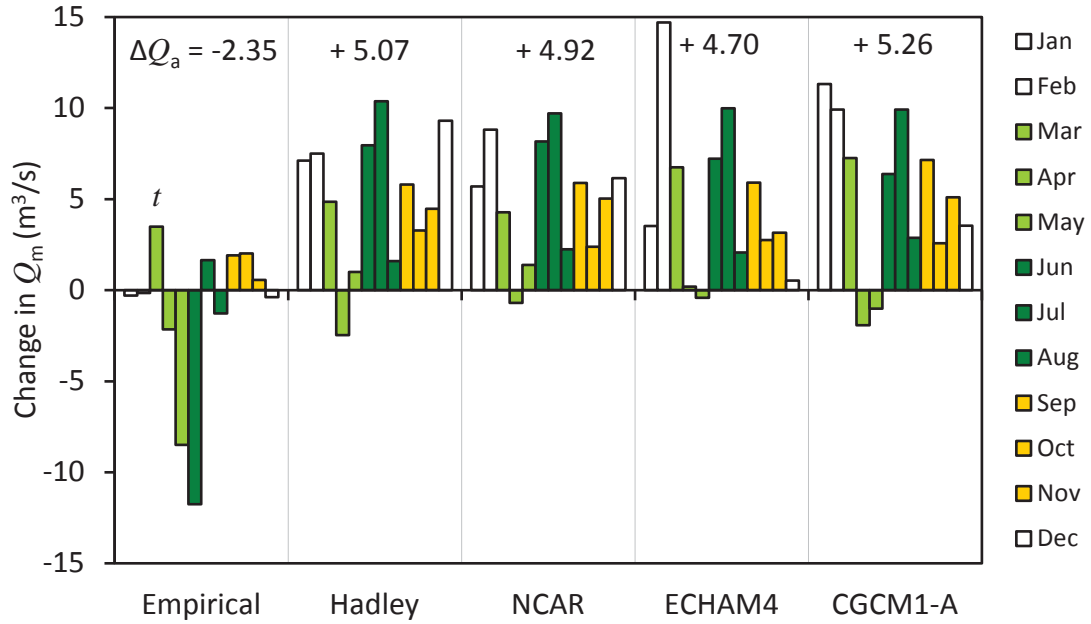


Figure 2-9: Change in annual (Q_a) and mean monthly discharge (Q_m) from around 1975 to around 2055 for the upper Red Deer River Basin as forecasted by empirical trend projection and four general circulation models. Significant empirical trends are indicated (Mann-Kendall test, $t = p < 0.10$)

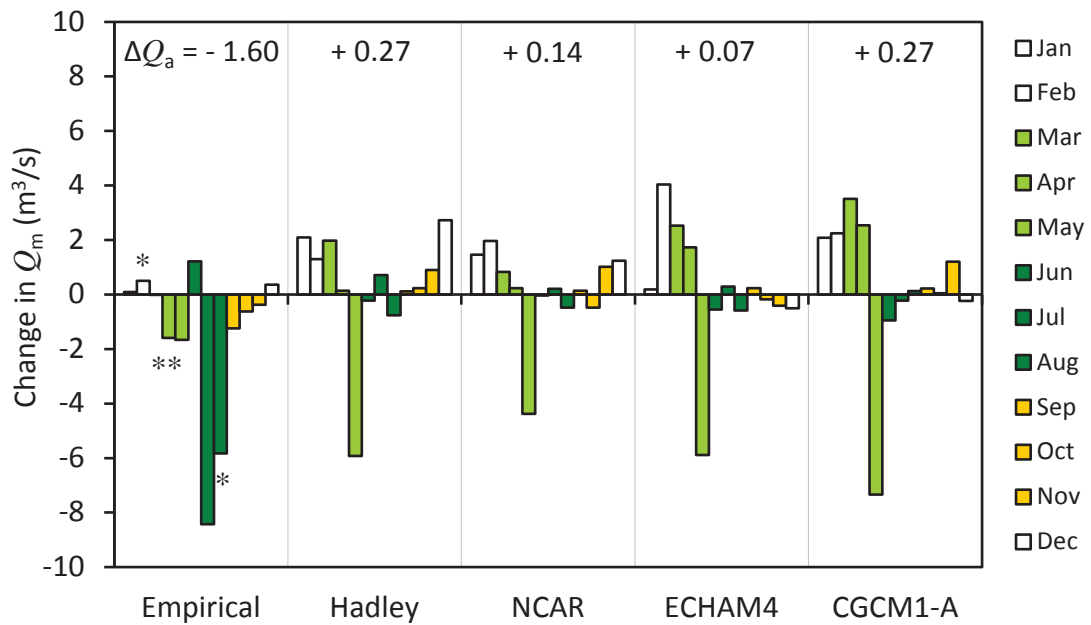


Figure 2-10: Change in annual (Q_a) and mean monthly discharge (Q_m) from around 1975 to around 2055 for the Red Deer River below Burnt Timber Creek as forecasted by empirical trend projection and four general circulation models. Significant empirical trends are indicated (Mann-Kendall test, * = $p < 0.05$, ** = $p < 0.01$)

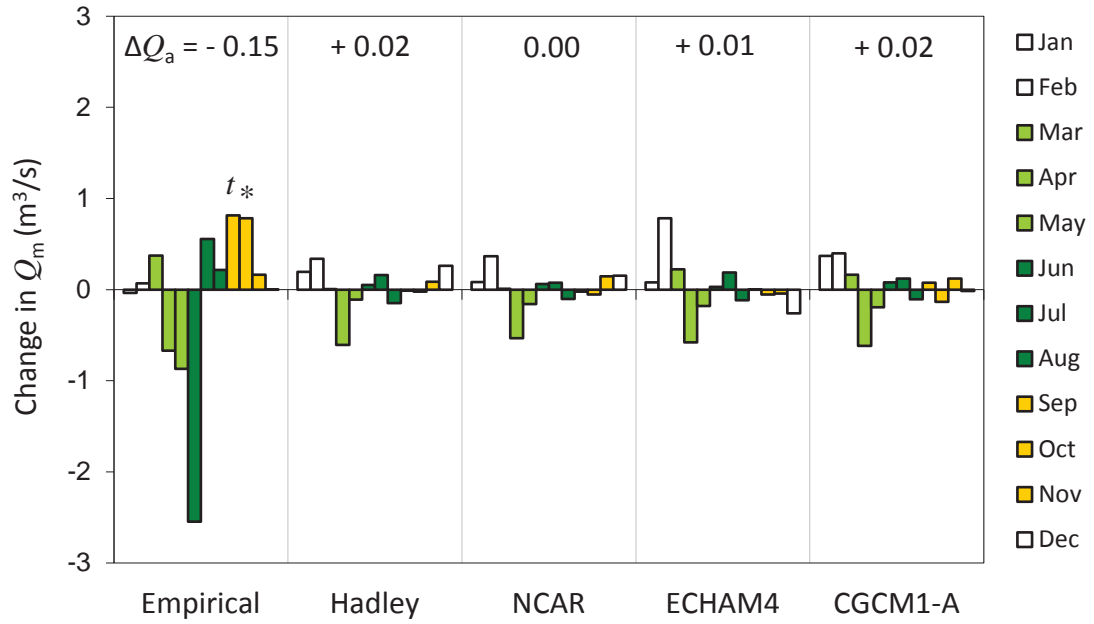


Figure 2-11: Change in annual (Q_a) and mean monthly discharge (Q_m) from around 1975 to around 2055 for the Little Red Deer River near the mouth as forecasted by empirical trend projection and four general circulation models. Significant empirical trends are indicated (Mann-Kendall Test, $t = p < 0.10$, $* = p < 0.05$)

For the upper Red Deer River Basin, the empirical trend analysis and the GCM climate-derived streamflow all predict an increase in March and a decrease in April. All the projections also show an increase in autumn flows. While the modelled streamflow under climate projections predict an increase in summer flows, the empirical trend analysis overall forecasts a decrease, especially for June. Overall there was a forecast of greater annual streamflow and some monthly fluctuations that included decreases in April and sometimes May, but the shape of the future hydrograph remained relatively unaltered from the modelled historic baseline condition with little shift in the seasonality of flows. For the Red Deer River below Burnt Timber Creek, the greatest decrease in discharge was forecasted by empirical trend projection to occur in the summer. In contrast, the modelled streamflow under climate projections predicted little change in summer discharges. The models predicted the greatest reduction in discharge to occur in May for the Red Deer River below Burnt Timber Creek. Overall the GCMs forecast little change for the Little Red Deer River near the mouth, with modest increases in winter discharge and a decline in spring discharge. Empirical trend projections forecast a decrease in late spring and early summer flows with an increase in late summer and autumn discharges.

2.4 Discussion

Both the empirical trend analysis and hydroclimatic modelling have advantages and disadvantages. The strength of projecting historical trends is the use of actual historical data and the relatively straightforward analysis. A potential weakness is the assumption that the near future will extend the past. This assumption may not always be valid as changes such as a warming climate may accelerate with time. The response of some climate parameters to a warming climate may also be nonlinear. Dynamics such as

thresholds and positive and negative feedbacks may result in unexpected future scenarios as the climate continues to change (Shepherd et al., 2010). Modelling using GCM climate projections has the advantage of being able to make predictions using novel future conditions such as increased levels of greenhouse gases. A weakness lies in the coarseness of the GCMs. GCMs are intended for large scale global processes and may not be accurate for regional analysis even when downscaled.

For hydroclimatic models to be accurate at forecasting future streamflow, they must be able to successfully simulate historical flows. Our model appears to be more suited to simulating streamflow in watersheds dominated by snowmelt than those with a greater rainfall component. Consequently, the higher elevation mountain tributaries were better simulated than watersheds with a significant proportion of streamflow originating from the lower elevation boreal and foothill regions.

The strength of empirical trends projection lies in its simplicity, but there are some important considerations that must first be made. The most important may be the need for a long complete record of streamflow. Climatic cycles in sea surface temperatures such as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) can greatly influence the hydrometeorology of western North America (Dettinger et al., 2001; Mantua et al., 1997; Mote, 2006; St. Jacques et al., 2010). Short-term trend analyses of streamflow may reflect phases in these oscillations rather than long-term trends (Cayan et al., 1998; Rood et al., 2005). The cycles of the PDO in particular, can pose a challenge for trends applied to shorter records. Warm PDO cycles have occurred from 1925 to 1946, and 1977 through to at least the mid-1990s. These warm cycles generally resulted in drier conditions and lower streamflows. Cooler cycles from 1890 to 1924 and 1947 to 1976

generally resulted in greater streamflows (Mantua and Hare, 2002; Whited et al., 2007). While the relationship is not as strong as the more southern basins, annual discharges of the Red Deer River are significantly correlated with the PDO (Rood et al., 2013; St. Jacques et al., 2010) (Figure 2-12). When assessing hydrological trends resulting from climate change, it is important to recognize this natural climatic variability. Long periods of record (≥ 80 years) that span at least two warming and cooling phases of the PDO can reduce the confounding effects of this climatic cycle (Shepherd et al., 2010). Unfortunately, time series of a sufficient length are often not available. Other than the century of record for the Red Deer River at Red Deer, most records for the upper tributaries of the Red Deer River do not commence until the 1970s. This lack of data increased our reliance on Alberta Environment's naturalized data to ensure we had a time series that encompassed multiple PDO cycles. While interpolated data is no replacement for actual gauged data and should be interpreted cautiously, the Alberta naturalized dataset represented the best data available to extend the record for the upper tributaries and allowed for us to analyze trends over multiple PDO cycles without manipulating the existing gauged data.

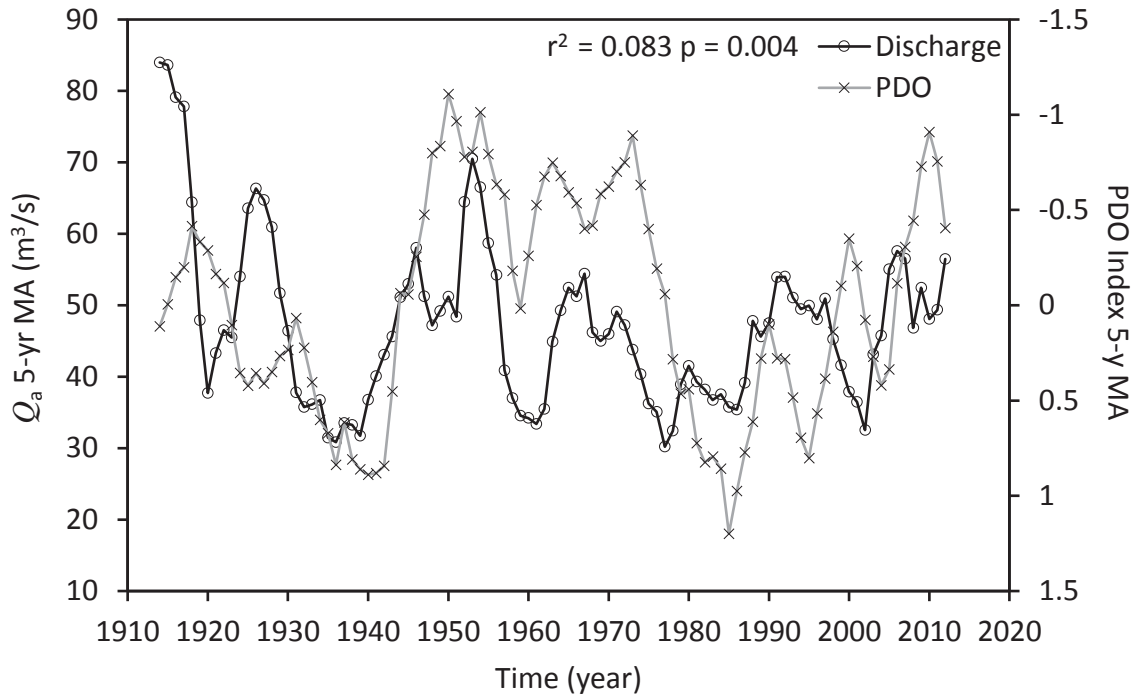


Figure 2-12: Correlation between mean annual streamflow of the Red Deer River gauged at Red Deer and standardized values for Pacific Decadal Oscillation (PDO). A five-year moving average of mean annual discharge (Q_a) is plotted with a five-year moving average of PDO index from 1912 to 2012. Greater streamflows are correlated with a lower (cooler) PDO index. PDO values were obtained from the PDO directory constructed by Mantua (2000) (<http://research.jisao.washington.edu/pdo/>, data accessed up to Dec. 2015). Streamflow data obtained from the Water Survey of Canada's Hydrological Database (<http://wateroffice.ec.gc.ca/>, data accessed up to Dec. 2015).

The accuracy of the naturalization process is another important consideration in empirical trend analysis. Water management and use can have a significant impact on the magnitude and direction of annual and seasonal trends. Fortunately, there is little water use in the upper Red Deer River Basin and the Dickson Dam is the only structure for management. This made the naturalization process relatively easy and gives us confidence in our results. The seasonally-grouped linear regressions for naturalization provided strong fits, with the exception of the winter regression. The weakness in the winter regression is most likely the result of gauging inaccuracies due to ice. Overall there is little contribution to the annual discharge during the winter months and the inaccuracy of the winter regression likely does not impact our annual results. Trends in the winter months should, however, be interpreted cautiously. Although our naturalization process provided only 3 more years of discharge data than the Alberta Environment naturalized dataset, it produced similar Q_a and Q_m discharges and provided a simple methodology that can allow the naturalized data to be easily and accurately extended without the use of computer modelling.

We predicted that with increasing winter and spring temperatures, the Red Deer River would undergo similar changes to those that have been observed along other rivers in southern Alberta. These potential changes included, increased winter flows as a greater proportion of precipitation falls as rain than snow, earlier peak flows and reduced summer and early autumn flows (Rood et al., 2008). The empirical trend analysis revealed that while there was a trend of increasing March discharge, a possible sign of earlier snow melt and more late winter precipitation falling as rain, there were no other streamflow trends for the Red Deer River at Red Deer. Additionally, peak flows did not appear to be

occurring earlier and summer flows were not decreasing. There were also no common significant trend amongst the tributaries. Declining flows in August for the Red Deer River below Burnt Timber Creek may be the result of reduced snow pack, but this late summer trend did not continue to the Red Deer gauge. The lack of a common streamflow trend along the Red Deer River could mean that either a warming climate did not have a substantial impact on the Red Deer River basin or that there may be feedbacks that were diminishing the expected trends. While summer streamflow at the higher elevation Red Deer River below Burnt Timber Creek gauge appeared to be declining, summer streamflow for the Medicine River and autumn streamflow for the Little Red Deer River were increasing overall. This was supported by the precipitation data. Precipitation data recorded at Rocky Mountain House near the Medicine River and Olds near the Little Red Deer River showed an increasing trend in the summer (Table 2-4). The increased streamflow in the lower tributaries resulting from more summer precipitation could be compensating reduced inputs from the higher elevation tributaries thereby diminishing any trends recorded at the Red Deer River at Red Deer gauge. This is further supported by the results of the hydrological modelling, with greater increases in summer streamflow being forecasted for the Red Deer River at Red Deer gauge compared to the upstream higher elevation Red Deer River below Burnt Timber gauge. A similar trend has been observed on an annual basis in the Athabasca watershed suggesting that there is a larger trend in central Alberta of a diminished runoff contribution to streamflow from the mountains but an increasing contribution from the foothill and boreal regions (Rood et al., 2015).

	Rocky Mountain House		Olds	
	1917 - 2012		1914 - 2012	
	Kendall's τ	% Change	Kendall's τ	% Change
Month				
January	0.070	29.40	0.086	21.63
February	- 0.009	- 3.14	- 0.022	- 9.809
March	- 0.030	- 10.28	- 0.004	- 1.914
April	- 0.005	- 2.27	- 0.039	- 16.92
May	0.159 *	61.21	0.078	23.83
June	0.115	42.34	0.148 *	57.6
July	0.147 *	50.18	0.138 *	50.5
August	- 0.320	- 8.85	- 0.033	- 9.004
September	0.010	4.25	0.089	41.34
October	0.001	0.00	- 0.093	- 33.39
November	0.096	40.18	0.017	5.918
December	0.041	16.41	0.057	22.05
	n = 91 - 94		n = 90 - 95	

Table 2-4: Kendall's tau coefficients for trends in precipitation and percent change in precipitation for Rocky Mountain House and Olds. Significant trends are indicated (Mann-Kendall test, * = $p < 0.05$) Missing data were not infilled and the number of years used for trend analysis varies by month. Data were obtained from Environment and Climate Change Canada's adjusted precipitation data (Mekis and Vincent, 2011).

Our hydroclimatic models projected modest increases in streamflow annually and for most months for the upper Red Deer River Basin. This is in contrast to the more southern tributaries of the South Saskatchewan Basin where streamflow volumes are projected to decrease (St. Jacques et al., 2013). Other attempts at modelling future flows of the Red Deer River have produced variable results. Applying the physical-based MISBA model, Tanzeeba and Gan (2012) forecasted a general decrease in streamflow for the entire Red Deer River Basin, concluding that increases in air temperature over the 21st century would likely offset projected increases in precipitation. Similarly, a decrease in average annual discharge (-12.6%) was also predicted by Lapp, Sauchyn and Toth (2009) by combining different GCM estimates of future temperature and precipitation with the WATFLOOD hydrologic model. Conversely, similar to our study, more recent modelling efforts using regional climate models have forecasted an increase of 13% in streamflow for the base period of 1971-2001 to 2041-2070 (WaterSMART, 2015). The variation of results between and within the different models highlights the high degree of uncertainty in climate and streamflow forecasting. The degree of variability between models may be greater in the Red Deer River basin as it lies in a transition zone between the drier south, where streamflow is projected to decrease, and the boreal region to the north, where streamflow is projected to increase (Intergovernmental Panel on Climate, 2013).

2.5 References

- Alberta Environment, 1998. South Saskatchewan River Basin historical natural flows 1912 to 1998, Edmonton, Alberta, Canada.
- Alberta Environment, 2006. Approved Water Management Plan for the South Saskatchewan River Basin, Edmonton, Alberta, Canada.
- AMEC, 2009. South Saskatchewan River Basin in Alberta: Water Supply Study, Alberta Agriculture and Rural Development, Lethbridge, Alberta.
- Barnett TP, Adam JC, Lettenmaier DP, 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066): 303-9. DOI:10.1038/nature04141
- Bingeman AK, Kouwen N, Soulis E, 2006. Validation of the hydrological processes in a hydrological model. *Journal of Hydrologic Engineering*, 11(5): 451-463. DOI:10.1061/(ASCE)1084-0699(2006)11:5(451)
- Burn DH, 1994. Hydrologic effects of climatic change in west-central Canada. *Journal of Hydrology*, 160(1): 53-70. DOI:10.1016/0022-1694(94)90033-7
- Burn DH, Cunderlik JM, Pietroniro A, 2004. Hydrological trends and variability in the Liard River basin. *Hydrological Sciences Journal*, 49(1): 53-67. DOI:10.1623/hysj.49.1.53.53994
- Cayan DR, Dettinger MD, Diaz HF, Graham NE, 1998. Decadal variability of precipitation over western North America. *Journal of Climate*, 11(12): 3148-3166. DOI:10.1175/1520-0442(1998)011<3148:Dvopow>2.0.Co;2
- Cayan DR, Dettinger MD, Kammerdiener SA, Caprio JM, Peterson DH, 2001. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, 82(3): 399-415. DOI:10.1175/1520-0477(2001)082<0399:CITOOS>2.3.CO;2
- Clipperton G, Koning C, Locke A, Mahoney J, Quazi B, 2003. Instream flow needs determinations in the South Saskatchewan River Basin, Alberta. Alberta Environment and Sustainable Resource Development, Pub No T/719, Calgary, Alberta, Canada: 271.
- Coquard J, Duffy PB, Taylor KE, Iorio JP, 2004. Present and future surface climate in the western USA as simulated by 15 global climate models. *Climate Dynamics*, 23(5): 455-472. DOI:10.1007/s00382-004-0437-6
- Cutforth HW, McConkey BG, Woodvine RJ, Smith DG, Jefferson PG, Akinremi OO, 1999. Climate change in the semiarid prairie of southwestern Saskatchewan: Late winter–early spring. *Canadian Journal of Plant Science*, 79(3): 343-350. DOI:10.4141/P98-137

- Dettinger MD, Battisti DS, Garreaud R, McCabe G, Bitz C, 2001. Interhemispheric effects of interannual and decadal ENSO-like climate variations on the Americas, in V. Markgraf (ed.), *Interhemispheric climate linkages: Present and past climates in the Americas and their societal effects*. Academic Press: 1-16.
DOI:10.1016/B978-012472670-3/50004-5
- Gill KM, Shepherd A, Romuld M, Rood SB, 2008. *Historic and prospective future flows of the Red Deer River and its headwater tributaries*, Prepared for the Red Deer River Watershed Alliance and Alberta Ingenuity Centre for Water Research, University of Lethbridge, Lethbridge, Alberta.
- Gordon ND, Finlayson BL, McMahon TA, 1992. *Stream hydrology: an introduction for ecologists*. John Wiley and Sons, New York.
- Gray LK, Hamann A, 2013. Tracking suitable habitat for tree populations under climate change in western North America. *Climatic Change*, 117(1): 289-303.
DOI:10.1007/s10584-012-0548-8
- Hungerford RD, Nemani RR, Running SW, Coughlan JC, 1989. *MTCLIM: a mountain microclimate simulation model*, USDA Forest Service Research Paper, Doc No INT-414. 0146-3551.
- Huntington JL, Niswonger RG, 2012. Role of surface-water and groundwater interactions on projected summertime streamflow in snow dominated regions: An integrated modeling approach. *Water Resources Research*, 48(11): W.11524.
DOI:10.1029/2012WR012319
- Intergovernmental Panel on Climate C, 2013. Long-term climate change: Projections, commitments and irreversibility Pages 1029 to 1076, *Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 1029-1136. DOI:10.1017/CBO9781107415324.024
- Jacques J-MS, Huang YA, Zhao Y, Lapp SL, Sauchyn DJ, 2011. The effects of atmosphere-ocean climate oscillations on and trends in Saskatchewan River discharges. Prepared for the Saskatchewan Watershed Authority: Moose Jaw, SK, pp. 40.
- Knutti R, Sedláček J, 2013. Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, 3(4): 369-373.
DOI:10.1038/nclimate1716
- Kouwen N, Mousavi S, Singh V, Frevert D, 2002. *WATFLOOD/SPL9 hydrological model & flood forecasting system*. *Mathematical models of large watershed hydrology*: 649-685.

- Kulkarni A, von Storch H, 1995. Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend. *Meteorologische Zeitschrift*, 4(2): 82-85.
- Lapp S, Byrne J, Townshend I, Kienzle S, 2005. Climate warming impacts on snowpack accumulation in an alpine watershed. *International Journal of Climatology*, 25(4): 521-536. DOI:10.1002/joc.1140
- Lapp S, Sauchyn D, Toth B, 2009. Constructing scenarios of future climate and water supply for the SSRB: use and limitations for vulnerability assessment. *Prairie Forum*, 34(1): 153-180.
- Mantua NJ, Hare SR, 2002. The Pacific decadal oscillation. *Journal of oceanography*, 58(1): 35-44. DOI:10.1023/A:1015820616384
- Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC, 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, 78(6): 1069-1079. DOI:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2
- McCuen RH, 2003. *Modeling hydrologic change: statistical methods*. CRC Press, Boca Raton, FL.
- McGinn S, Toure A, Akinremi O, Major D, Barr A, 1999. Agroclimate and crop response to climate change in Alberta, Canada. *Outlook on Agriculture*, 28(1): 19-28.
- Mearns LO, Hulme M, Carter TR, Leemans R, Lal M, Whetton P, 2001. *Climate scenario development*, Cambridge.
- Mekis É, Vincent LA, 2011. An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. *Atmosphere-Ocean*, 49(2): 163-177.
- Millett B, Johnson WC, Guntenspergen G, 2009. Climate trends of the North American prairie pothole region 1906–2000. *Climatic Change*, 93(1): 243-267. DOI:10.1007/s10584-008-9543-5
- Mote PW, 2006. Climate-driven variability and trends in mountain snowpack in Western North America. *Journal of Climate*, 19(23): 6209-6220. DOI:10.1175/Jcli3971.1
- Mote PW, Hamlet AF, Clark MP, Lettenmaier DP, 2005. Declining mountain snowpack in western North America. *Bulletin of the American meteorological Society*, 86(1): 39-49. DOI:10.1175/BAMS-86-1-39
- Nakicenovic N, Swart R, 2000. *Special report on emissions scenarios*. Special Report on Emissions Scenarios, Edited by Nebojsa Nakicenovic and Robert Swart, pp. 612. ISBN 0521804930. Cambridge, UK: Cambridge University Press, July 2000., 1.

- Nogués-Bravo D, Araújo MB, Errea MP, Martínez-Rica JP, 2007. Exposure of global mountain systems to climate warming during the 21st Century. *Global Environmental Change*, 17(3–4): 420-428. DOI:10.1016/j.gloenvcha.2006.11.007
- Pietroniro A, Leconte R, Toth B, Peters DL, Kouwen N, Conly FM, Prowse T, 2006. Modelling climate change impacts in the Peace and Athabasca catchment and delta: III—integrated model assessment. *Hydrological Processes*, 20(19): 4231-4245. DOI:10.1002/hyp.6428
- Pipes A, Quick MC, 1977. UBC watershed model users guide. Department of Civil Engineering, University of British Columbia.
- Rood SB, Ball DJ, Gill KM, Kaluthota S, Letts MG, Pearce DW, 2013. Hydrologic linkages between a climate oscillation, river flows, growth, and wood $\Delta^{13}C$ of male and female cottonwood trees. *Plant, cell & environment*, 36(5): 984-993.
- Rood SB, Foster SG, Hillman EJ, Luek A, Zanewich KP, 2016. Flood moderation: Declining peak flows along some Rocky Mountain rivers and the underlying mechanism. *Journal of Hydrology*. DOI:10.1016/j.jhydrol.2016.02.043
- Rood SB, Pan J, Gill KM, Franks CG, Samuelson GM, Shepherd A, 2008. Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, 349(3–4): 397-410. DOI:10.1016/j.jhydrol.2007.11.012
- Rood SB, Samuelson GM, Weber JK, Wywrot KA, 2005. Twentieth-century decline in streamflows from the hydrographic apex of North America. *Journal of Hydrology*, 306(1): 215-233. DOI:10.1016/j.jhydrol.2004.09.010
- Rood SB, Stupple GW, Gill KM, 2015. Century-long records reveal slight, ecoregion-localized changes in Athabasca River flows. *Hydrological Processes*, 29(5): 805-816. DOI:10.1002/hyp.10194
- Sen PK, 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324): 1379-1389.
- Shepherd A, Gill KM, Rood SB, 2010. Climate change and future flows of Rocky Mountain rivers: converging forecasts from empirical trend projection and downscaled global circulation modelling. *Hydrological Processes*, 24(26): 3864-3877.
- Shepherd A, McGinn SM, 2003. Assessment of climate change on the Canadian prairies from downscaled GCM data. *Atmosphere-Ocean*, 41(4): 301-316. DOI:10.3137/ao.410404
- St. Jacques J-M, Lapp SL, Zhao Y, Barrow EM, Sauchyn DJ, 2013. Twenty-first century central Rocky Mountain river discharge scenarios under greenhouse forcing. *Quaternary International*, 310: 34-46. DOI:10.1016/j.quaint.2012.06.023

- St. Jacques J-M, Sauchyn DJ, Zhao Y, 2010. Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability? *Geophysical Research Letters*, 37(6). DOI:10.1029/2009GL042045
- Stephens GL, L'Ecuyer T, Forbes R, Gettleman A, Golaz JC, Bodas-Salcedo A, Suzuki K, Gabriel P, Haynes J, 2010. Dreary state of precipitation in global models. *Journal of Geophysical Research: Atmospheres*, 115(D24). DOI:10.1029/2010JD014532
- Stevens B, Bony S, 2013. What are climate models missing? *Science*, 340(6136): 1053-1054. DOI:10.1126/science.1237554
- Tanzeeba S, Gan TY, 2012. Potential impact of climate change on the water availability of South Saskatchewan River Basin. *Climatic change*, 112(2): 355-386. DOI:10.1007/s10584-011-0221-7
- Vincent LA, Wang XL, Milewska EJ, Wan H, Yang F, Swail V, 2012. A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. *Journal of Geophysical Research: Atmospheres*, 117(D18). DOI:10.1029/2012jd017859
- WaterSMART, 2015. Climate vulnerability and sustainable water management in the SSRB project: Red Deer River Basin modelling, final report.
- Whited DC, Lorang MS, Harner MJ, Hauer FR, Kimball JS, Stanford JA, 2007. Climate, hydrologic disturbance, and succession: drivers of floodplain pattern. *Ecology*, 88(4): 940-953. DOI:10.1890/05-1149
- Wilby RL, Wigley T, 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography*, 21(4): 530-548. DOI:10.1177/030913339702100403
- Wuebbles D et al., 2014. CMIP5 climate model analyses: Climate extremes in the United States. *Bulletin of the American Meteorological Society*, 95(4): 571-583. DOI:10.1175/BAMS-D-12-00172.1
- WWF-Canada, 2009. Canada's rivers at risk: Environmental flows and Canada's freshwater future, World Wildlife Fund Canada.
- Wyman RR, 1995. Modeling snowpack accumulation and depletion, Mountain Hydrology Peaks and Valleys in Research and Applications Conference Proceedings.
- Yue S, Pilon P, Phinney B, Cavadias G, 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes*, 16(9): 1807-1829. DOI:10.1002/hyp.1095

- Yue S, Wang C, 2004. The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management*, 18(3): 201-218. DOI:Doi 10.1023/B:Warm.0000043140.61082.60
- Yue S, Wang CY, 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. *Water Resources Research*, 38(6). DOI:10.1029/2001WR000861

CHAPTER 3: COTTONWOOD RECRUITMENT AND STREAMFLOW MANAGEMENT ALONG THE LOWER RED DEER RIVER

3.1 Introduction

Natural floodplains are among the most dynamic and biologically productive ecosystems in the world (Tockner and Stanford, 2002). In the semi-arid prairies of western North America, riparian areas are a haven for a diversity of plant and animal species not found elsewhere in the prairie landscape (Finch and Ruggiero, 1993; Knopf et al., 1988; Sabo et al., 2005). Cottonwood trees are often the dominant and keystone species found in these areas, forming the foundation of the riparian woodland ecosystem (Braatne et al., 1996). This makes them highly valued, not only for their ecological services and high productivity, but also for their recreational and aesthetic value.

Significant declines in the abundance and health of cottonwood woodlands have been reported downstream of dams and diversions along many rivers within the South Saskatchewan River Basin (SSRB) in southern Alberta, including the Waterton, St. Mary, Oldman, and Bow Rivers (Rood and Bradley, 1993; Rood and Heinze-Milne, 1989; Rood et al., 2005; Rood et al., 1999). These losses are the result of many interacting factors, most of which can be attributed to water management and the alteration of the natural streamflow pattern (Poff et al., 1997; Rood and Mahoney, 1990).

Fortunately, recent efforts to restore seasonal flow regimes and facilitate natural fluvial and geomorphic processes downstream of dams have been largely successful in the recovery of cottonwood populations (Rood et al., 2005). In Alberta, these efforts have been mainly restricted to the southernmost tributaries of the South Saskatchewan River.

The impact of water management on the recruitment of cottonwoods along the most northern tributary, the Red Deer River, remains largely unknown and operation of the Dickson Dam, the only dam along this river, have continued mostly unchanged since its construction in 1983.

The Dickson Dam is unique in southern Alberta as it is not managed primarily for either agricultural purposes or power generation, but rather functions to augment winter flows in order to maintain dissolved oxygen levels (Baker and Telang, 1985). This difference in management may have different implications for the reproduction and survival of cottonwoods in this system.

The Red Deer River is the least regulated and least allocated river system within the SSRB and has been considered, ecologically, one of the healthiest rivers in western North America (Cordes et al., 1997). However, past studies have found that the riparian cottonwood populations along the Red Deer River may be at risk. Marken (1993) reported that the Red Deer River tended to be dominated by mature and aging cottonwoods and since 1950 there have been few opportunities for cottonwood seedling establishment due to a lack of large floods and negligible channel migration. Marken (1993) also noted that in addition to streamflow modifications, other activities, livestock grazing in particular, have had a moderate to severe impact on cottonwood survival. Cordes et al. (1997) reported that the construction of the Dickson Dam has led to a significant attenuation of floods and, consequently, reduced the likelihood of extensive poplar regeneration occurring again. Clipperton et al. (2003) indicated that the operations of the Dickson Dam may be exacerbating an already declining situation for cottonwoods by eliminating the few opportunities for cottonwood recruitment. While this suggests that the current

cottonwood populations along the Red Deer River are not likely to be sustained, historical aerial photograph comparisons of cottonwood woodland extent by Bradley et al. (1991) and by Clipperton et al. (2003) have revealed little to no change in overall riparian woodland abundance along the Red Deer River. These analyses, however, did not include ground-truthing or field studies and while cottonwood populations appear healthy, there may be a deficiency in cottonwood recruitment.

Deficiencies in seedling recruitment is the predominant factor impacting riparian cottonwood forests (Braatne et al., 2007; Polzin and Rood, 2000; Rood and Mahoney, 1990). Cottonwood trees are relatively short lived and ongoing replenishment is essential for the maintenance of healthy populations. Dams and water management can disrupt the establishment and survival of cottonwood seedlings which can lead to the progressive decline in cottonwood populations (Polzin and Rood, 2000).

In this study, we analyze the hydrology along a lower reach of the Red Deer River and employ a variety of techniques, including a GIS based analysis of aerial photography, dendrochronology, and field surveys to evaluate historical cottonwood recruitment. With 34 years passing since the construction of the Dickson Dam an accurate assessment of cottonwood recruitment following damming is now possible. Within this time frame, there have been two substantial floods in 2005 and 2013 and a period of drought in 2001 and 2002. In this analysis, we aim to identify the effects water management and other human activities have on the recruitment and health of cottonwood woodlands along the lower Red Deer River, as well as identify opportunities for the application of better management practices.

3.1.1 Study location

This study is focused primarily on a section of the Red Deer River flowing through Dinosaur Provincial Park (Figure 3-1), a region noted for its large, relatively undisturbed floodplains and diverse mosaic of cottonwood stands (Bradley et al., 1991). Dinosaur Provincial Park provides an ideal location to assess cottonwood recruitment along the Red Deer River as it includes the only protected floodplains along the lower river and, while there is some grazing, most of these floodplains are free of any major human activities. The river fringed by badlands topography and is characterized by large floodplains and a confined meander with adequate island building to be classified as a braided stream (McPherson, 1967). Floodplains within Dinosaur Provincial Park contain some of the densest cottonwood woodlands along the entire length of the Red Deer River (Figure 3-2) (Bradley et al., 1991). Woodlands are largely dominated by pure stands of plains cottonwood (*Populus deltoides* Bartr. ex Marsh), however, some mature *P. deltoides*, *P. balsamifera* L. hybrids (*P. jackii* Sarg.) have been observed within the park.

Riparian cottonwoods along the lower Red Deer River may be particularly sensitive to flow management. The Red Deer River marks the most northern and westerly extension of plains cottonwood in North America (Brayshaw, 1965). Populations at the periphery of their range are generally less prolific, have more variable densities, and exhibit lower genetic diversity as they tend to occur in less favorable habitats and are subject to more stressful conditions. Consequently, these populations are typically more sensitive to environmental changes (Hampe and Petit, 2005; Lawton, 1993; Lesica and Allendorf, 1995; Parsons, 1990).

Compared to the upper river, the lower Red Deer River is very dry and experiences some of lowest annual precipitations in Alberta, often less than 350 mm a year (Bryan and Campbell, 1980). The lack of precipitation makes cottonwoods primarily dependent on river flows for survival. In addition to this, plains cottonwood rarely reproduce asexually and sexual reproduction is highly dependent on natural flow processes, thus the alteration of the natural flow regime can be detrimental to reproduction (Rood et al., 1994).

While the Dickson Dam is located over 300 km upstream of Dinosaur Provincial Park, the area upstream of the dam contributes over 80% of the annual average discharge and it is likely that flow alterations originating from the Dickson Dam directly impact riparian cottonwoods along the lower Red Deer River.

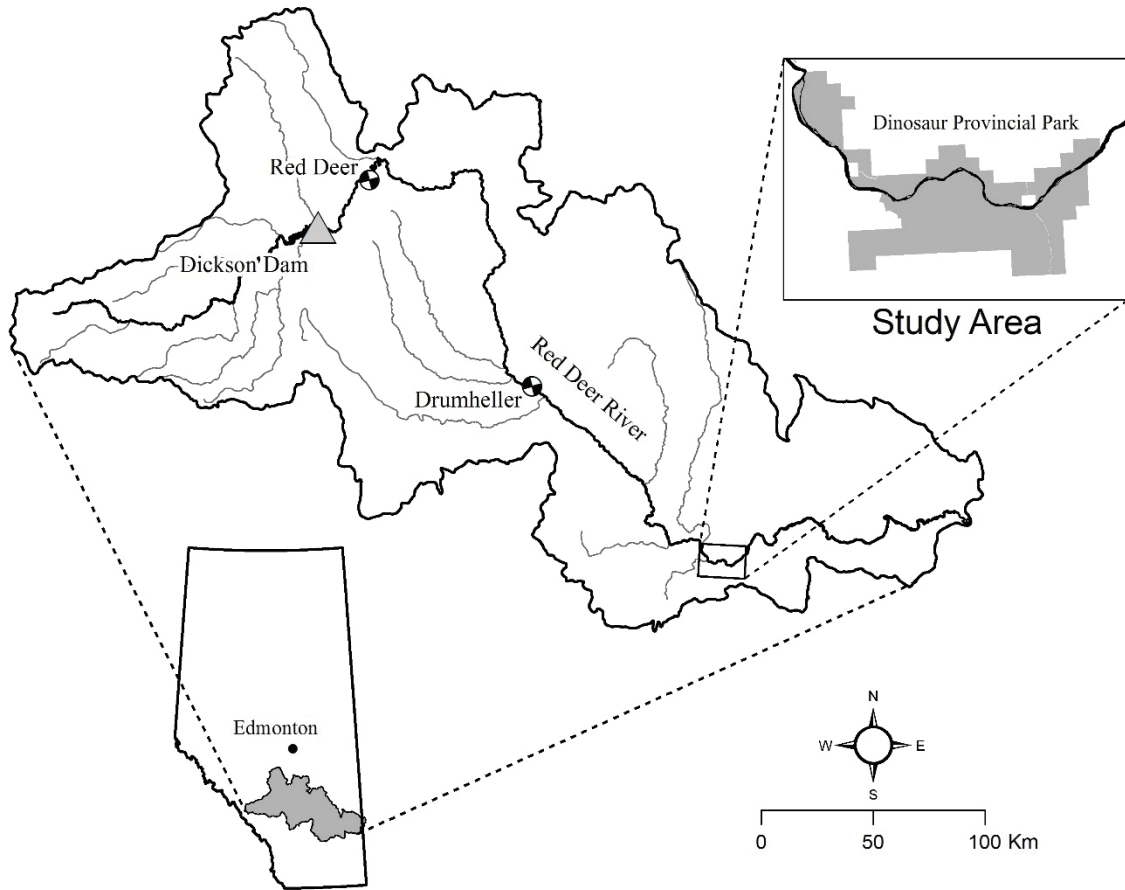


Figure 3-1: Location of Dinosaur Provincial Park, the study area for this study, within the Red Deer River Basin (middle) and within Alberta (bottom-left).



Figure 3-2: Typical woodland and river reach through Dinosaur Provincial Park, summer 2016. Note the arcuate banding of cottonwoods indicating sequential recruitment with channel migration. (Photo: L. Philipsen)

3.2 Methods

3.2.1 Aerial photograph analysis

To compare changes in woodland abundance on a decadal basis, digital aerial photographs (scans of contact prints, 1200 dots-per-inch) of the Red Deer River through Dinosaur Provincial Park were obtained from Alberta Environment and Parks Air Photo Distribution for 1950, 1962, 1974, 1985, 1991, 2001 and 2012 (Table 3-1). Photos were imported into ESRI ArcGIS 10.0 software (Redlands, CA) and georectified using a 1999 orthophoto as a common base layer. A minimum of 30 ground control points (GCPs) were used for each aerial photograph. GCPs were distributed as evenly as possible, but were limited to floodplains within the river valley as this was the primary area of interest. This allowed for a denser array of GCPs and overall produced greater accuracy. The higher elevation areas outside of the river valley were later clipped out. Where possible, hard-edged GCPs (e.g. building corners) were applied to each photograph, but the majority of GCPs consisted of soft edge points such as the base of trees. The use of soft edge points typically does not add significant error (Hughes et al., 2006). Images were transformed using a second order polynomial transformation. Spatial error was equal to or less than 1.7 metres for all photos with root mean square error (RMSE) ranging from 1.7 for the 1950 photos to 0.6 for the 2012 photos. Aerial images for each year were resampled using nearest neighbor resampling, cropped to minimize overlap and mosaicked, creating continuous images of a common reach for comparison. Woodland areal extent and channel boundaries were then digitized for each decade.

Table 3-1: Aerial photography used for the Red Deer River through Dinosaur Provincial Park for georeferencing and analysis.

Year	Scale	Type	Date acquired (day/month)	Number of photos
1950	1:40,000	B/W	12/05	3
1962	1:31,680	B/W	08/07, 30/09	5
1974	1:31,680	B/W	30/7	5
1985	1:25,000	B/W	27/06	5
1991	1:30,000	B/W	25/07	4
2001	1:30,000	B/W	08/07	3
2012	1:30,000	RGB	07/06	3

Previous studies have classified digitized woodland polygons by density (Bradley et al., 1991; Clipperton et al., 2003). This method was found to be subjective and challenging given the variability in the quality of air photos. Bradley *et al.* (1991) found that density classification was particularly difficult in older photographs. Rather than classifying by density, more time was invested in generating precise polygons for the areal extent of trees. For example, where woodlands were sparse, individual tree canopies were digitized. Woodland areal extent was first digitized for the 2012 aerial photograph mosaic. This area was then overlaid on the previous period and the areal extent was altered to account for additions or losses in woodland area. This process was repeated for all the photographs.

In some cases, typically in older photographs that were over- or under-exposed, other vegetation such as water birch (*Betula occidentalis* Hook.), thorny buffaloberry (*Shepherdia argentea* Nutt.), saskatoon-berry (*Amelanchier alnifolia* (Nutt.) Nutt.), Bebb willow (*Salix bebbiana* Sarg.) and sandbar willow (*Salix exigua* Nutt.) amongst other species, were indistinguishable from cottonwoods. To ensure these were not included in the cottonwood areal extent, reference was made to high quality oblique aerial imagery obtained 2014. Only mature trees are included in the analysis as younger age classes could not be differentiated from shrubs. One other tall species, peachleaf willow (*Salix amygdaloides* Anderss.), was also occasionally found within woodlands and was indistinguishable from cottonwood trees in both the vertical and oblique imagery and was included in the areal extent.

Channel boundaries were typically clearly defined along cut banks, but were less evident along floodplains, particularly along downstream portions where floodplains were

actively building. When the channel boundary was not clear, the limit of vegetation was digitized to denote channel boundaries (Richard et al., 2005; Winterbottom, 2000). This non-vegetated area represents the active channel width or the bankfull channel (Nicoll and Hickin, 2010; Richard et al., 2005). Vegetated islands were also digitized. In addition to the aerial photographs, a historical topographic map was georeferenced allowing channel boundaries to be digitized for 1935 (Geological Mapping Division, 1950). Digitized channel boundaries were then used to calculate channel migration rates and average channel widths.

Reduced cottonwood recruitment can be associated with reduced levels of channel migration (Bradley and Smith, 1986; Everitt, 1968). Channel migration rates were calculated by digitizing an approximate centreline for each photo mosaic and for the topographic map, and then generating perpendicular lines to each centreline between the outer channel banks at 5 m spacing. Points central to these lines were then generated and subsequently connected to form true centrelines (Figure 3-3a). Migration, in metres, for each period was calculated by dividing migration area — the area enclosed by two successive channel lines — by the length of the earlier centre line (Figure 3-3b) (Giardino and Lee, 2011; Shields Jr et al., 2000). Total migration was then divided by the number of years between sequential channel centrelines to calculate the average channel migration rate per year.

To calculate channel widths, perpendicular lines were created on either side of the previously generated channel centerlines between the outer banks at 25 m spacing. If lines crossed an island, this area was removed. The length of each line was then calculated and

averaged for the entire reach and for each time period to generate average active channel widths.

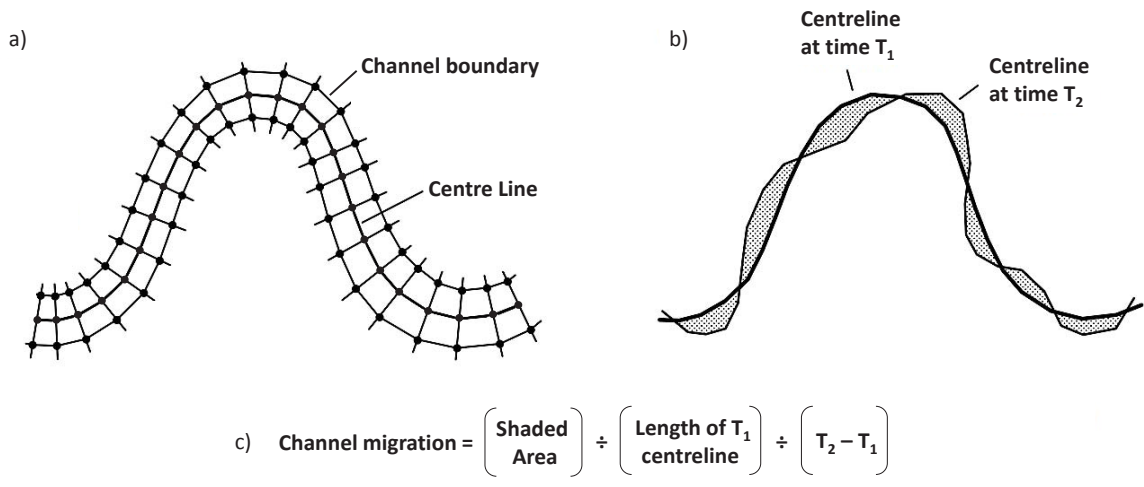


Figure 3-3: Methods for calculation of channel migration: (a) generating channel centreline, (b) migration area (shaded area) and (c) channel migration equation. Figure adapted from Shields *et al.* (2000).

3.2.2 Dendrochronology

To analyze cottonwood recruitment preceding the availability of aerial photography, 45 cottonwood trees were aged throughout one particularly densely populated floodplain during field visits in 2014 and 2015. Trees composed of a single main trunk and appeared to be representative of trees within a distinct arcuate band were selected. Arcuate bands of cottonwoods indicate sequential recruitment events (Figure 3-2) (Rood et al., 1998).

For each sampled tree, the base diameter was recorded and a core was extracted from the south side of the tree using a 5.15 mm diameter Swedish increment borer. Cores were extracted at approximately 30 cm above the ground surface, the lowest possible height while allowing for sufficient room for the rotation of the increment borer. Cores were cut laterally using a razor blade and tree rings were counted using a stereo-microscope to determine the age of each tree.

In some cases, the pith — the centre of the stem — was missed when obtaining trees cores or was not present due to heart rot. To account for these missing rings, a concentric circle ruler printed on a transparency was overlaid on the core and the distance between the last visible ring and centre was calculated. This distance was then divided by the average ring width of the last two or three visible rings to estimate the number of missing rings.

An intricacy in aging cottonwoods is that often the base of trees can be deeply buried in alluvium. In these cases, the actual establishment date can be much earlier than that calculated using tree ring aging (Gonzalez, 2001). Along the Red Deer River Marken (1993), found that young saplings 1.0 to 1.5 m above base stage had an average of six

years buried by a metre of sediment. While this is likely highly variable between locations, to account for vertical accretion of sediments burying early growth years, a correction of factor of six years was added to the age each of our cored trees. In addition to the six-year correction factor, Marken (1993) also allocated additional years to mature trees based on their elevation. We, however, did not have elevations above base stage for most our trees and assumed that mature trees were at an adequate elevation that the majority of flooding and deposition events would not impact them and thus, additional growth years being buried would be minimal.

For 13 trees, cores were not obtained or determined not to be of adequate quality for aging. In these cases, ages were instead extrapolated using the statistical relationship between diameter and age. Base diameter of trees aged throughout Dinosaur Provincial Park were plotted with their respective ages and fitted with a second order polynomial regression line (Figure 3-4). Trees with a diameter of 10 cm or less were aged using cross sectional discs. All other trees were aged using tree cores. The resulting equation from regression analysis was applied to the diameter of trees without cores to estimate age. To prevent any unrealistic age extrapolations, diameters that resulted in ages greater than 200 years were simply classified as greater than 200. In addition to diameter, heights of some trees were also sampled, but were found to be highly variable and the relationship between height and age was determined not to be adequate enough to make any accurate extrapolations (Figure 3-5).

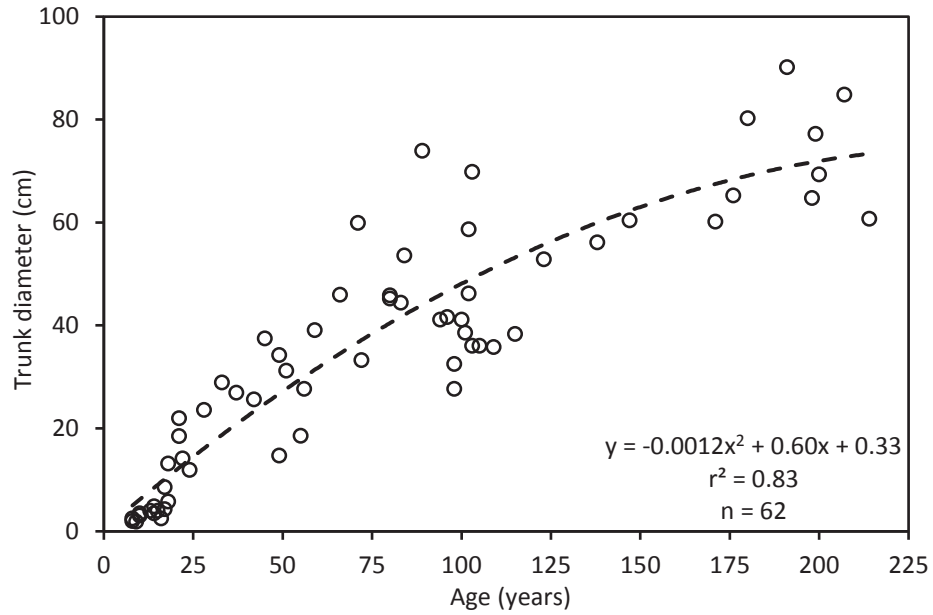


Figure 3-4: Regression analysis of age and diameter of *P. deltoides* along the Red Deer River through Dinosaur Provincial Park.

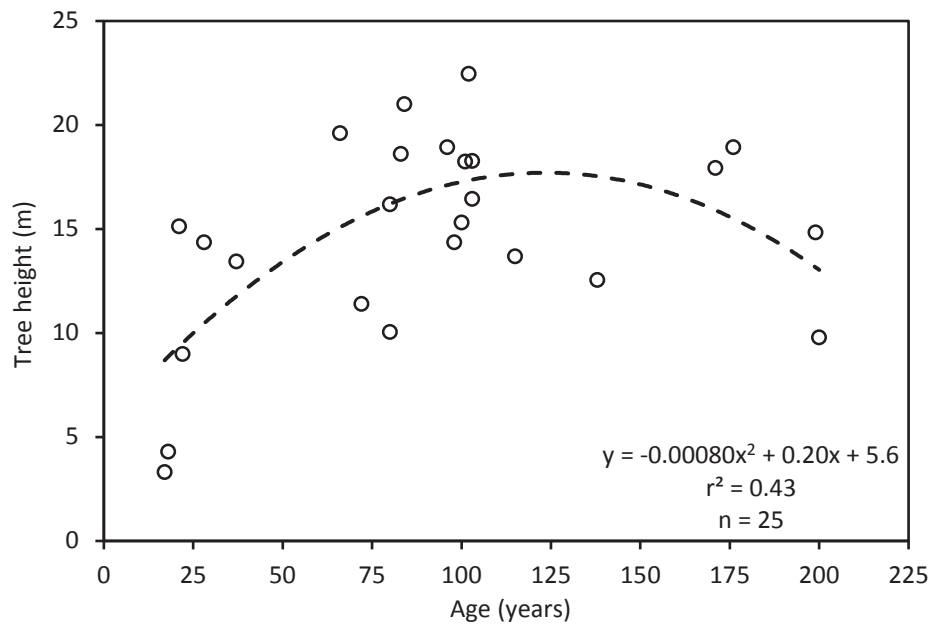


Figure 3-5: Regression analysis of age and height of *P. deltoides* along the Red Deer River through Dinosaur Provincial Park.

3.2.3 Field survey

To analyze recent recruitment not visible in the aerial photography, 9 transects were established at sites within seven different floodplains within Dinosaur Provincial Park (Appendix D). This encompassed all floodplains within the park that were along a sinuous river reach, morphologically active and contained abundant cottonwood populations that displayed distinct arcuate bands of recruitment. Of the seven floodplains, four were actively grazed by cattle. Sites were accessed either by foot or by canoe during base flow (low flow) conditions in late summer and fall 2014 and 2015.

At each site, banks were surveyed and transects were established perpendicular to the water edge where the most seedlings and saplings were observed, or at locations that appeared to have the appropriate conditions for cottonwood establishment such as bare sediments and a lower or sloped bank. These areas varied greatly between sites, but were typically located on the downstream portion of the floodplain where the floodplain was actively building. Transects commenced from the water edge to the nearest band of mature cottonwoods and ranged from 50 to 145 m. Elevations above water level were measured to the nearest cm along each transect using a staff gauge and auto-level at 4 m intervals for gradual slopes and at 1 m spacing for steep slopes. In order to sample cottonwood densities, a belt transect method was used with variable sized quadrats. This was done to account for decreasing densities with age due to self-thinning. Quadrats with dimensions of 1 x 1, 2 x 4 and 5 x 10 m were used to sample seedlings, saplings and trees, respectively. Seedlings were defined as having a height less than 0.5 m, saplings a height from 0.5 to 2 m, and trees a height greater than 2 m.

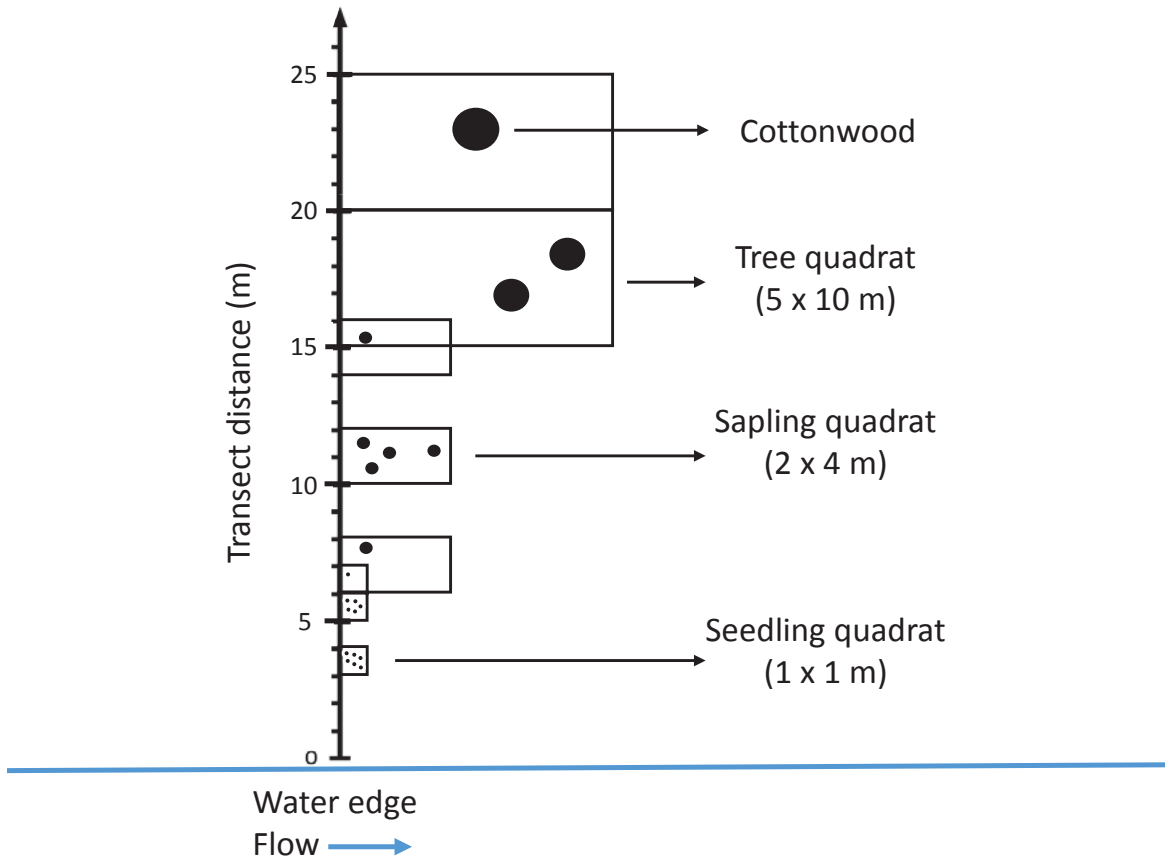


Figure 3-6: Typical belt transect sampling. Seedling, sapling and tree quadrats were placed along the transect when cottonwoods within their respective height category were observed.

Within each quadrat the height and diameter was measured for a sample of cottonwoods that were representative of the entire quadrat. For small stems, diameters were measured using calipers and heights were measured using a staff gauge. For larger trees, a diameter tape was used to measure base diameter and an inclinometer and measuring tape were used to triangulate tree height.

For each transect, a sample of seedlings, saplings and trees that represented distinct bands were selected and aged. Where possible, seedlings and saplings were aged visually by counting the annular rings of terminal bud scars. For some saplings and trees, with a diameter less than 10 cm, cross sections were obtained for aging. Trees greater than 10 cm in diameter were aged using the technique described in the dendrochronology section. This data allowed for age extrapolations of cottonwoods of similar size along the transect and was also used to develop Figure 3-4 and Figure 3-5. Trees that were beaver browsed were recorded as such and were not included in age calculations.

3.2.4 Hydrology

Changes in woodland extent and channel migration were compared to average annual discharges and max daily discharges for the Red Deer River at Red Deer (05CC002) obtained from the Water Survey of Canada's Hydrological Database (HYDAT) (<http://wateroffice.ec.gc.ca/>).

Inflows and outflows from the Dickson Dam/Gleniffer Reservoir were compared to determine how management alters natural hydrologic processes necessary for cottonwood recruitment. Inflow and outflow data for the Dickson Dam/Gleniffer Reservoir was obtained from Alberta Environment and inflow and outflow annual max daily discharges,

median monthly discharges, monthly minimum discharges and monthly maximum discharges were calculated and compared. Differences in median inflow and outflow discharges were tested using the Wilcoxon Signed Rank Test. All statistical analyses were performed using SPSS v.19 (IBM, Armonk NY).

Rate of river stage decline, or ramping, following floods is an important component of successful seedling recruitment. Ramping was analyzed for three post-dam floods in 1990, 2005 and 2013. Using stage measurements obtained from Alberta Environment, the rate of river stage decline at Drumheller (05CE001) was compared to the optimal rate of stage decline of 4 cm/day and deviations were noted (Mahoney and Rood, 1998). For each violation, inflows and outflows from the Dickson Dam/Gleniffer Reservoir were analyzed, to determine if management accelerated stage decline.

Ramping was analysed using data collected from the Drumheller gauging station as it was the closest upstream gauging station to the study area. Ramping analysis was limited to June and July as this is the period of seed dispersal for *P. deltoides* at high latitudes (VanHaverbeke, 1990).

3.3 Results

3.3.1 Aerial photograph analysis

Analysis of aerial photographs revealed the most recruitment of cottonwoods occurred from 1950 to 1962 with a 19% increase in total woodland area. Slight increases in woodland area were calculated from 1962 to 1974 and 1974 to 1985 of 0.76% and 0.25%, respectively. For the photograph intervals of 1985 to 1991, 1991 to 2001 and 2001 to 2012, losses were greater than recruitment, and total woodland areal extent slightly

decreased (Figure 3-7). Forest losses were relatively consistent between photograph intervals, averaging 0.37 ha/year, with the greatest losses occurring from 1985 to 1991. Losses from 1985 to 1991 resulted primarily from a fire within one floodplain. From 1950 to 2012, 54 ha of cottonwoods were recruited and 23 ha were lost resulting in a net gain of 40 ha or 17% (Figure 3-8). Losses were the result of a variety of different factors including human activity, beaver browsing, fire, erosion and natural mortality.

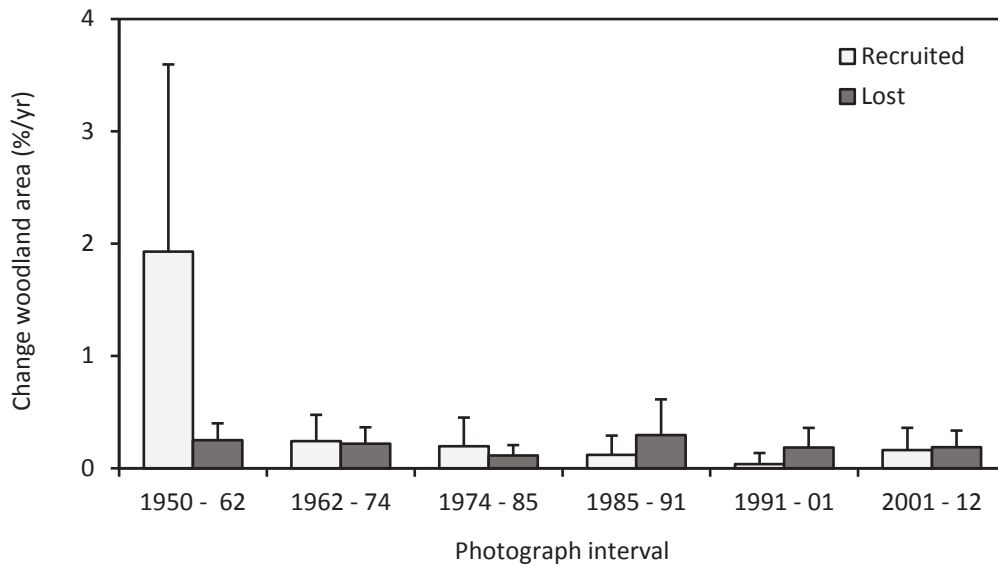


Figure 3-7: Average cottonwood woodland area recruited and lost for 8 floodplains between aerial photograph intervals in Dinosaur Provincial Park (+1 SD, n = 8). As time between photograph intervals is not equal, cottonwood area recruited or lost is reported in percent change per year, however, it is unlikely cottonwoods are recruited every year.

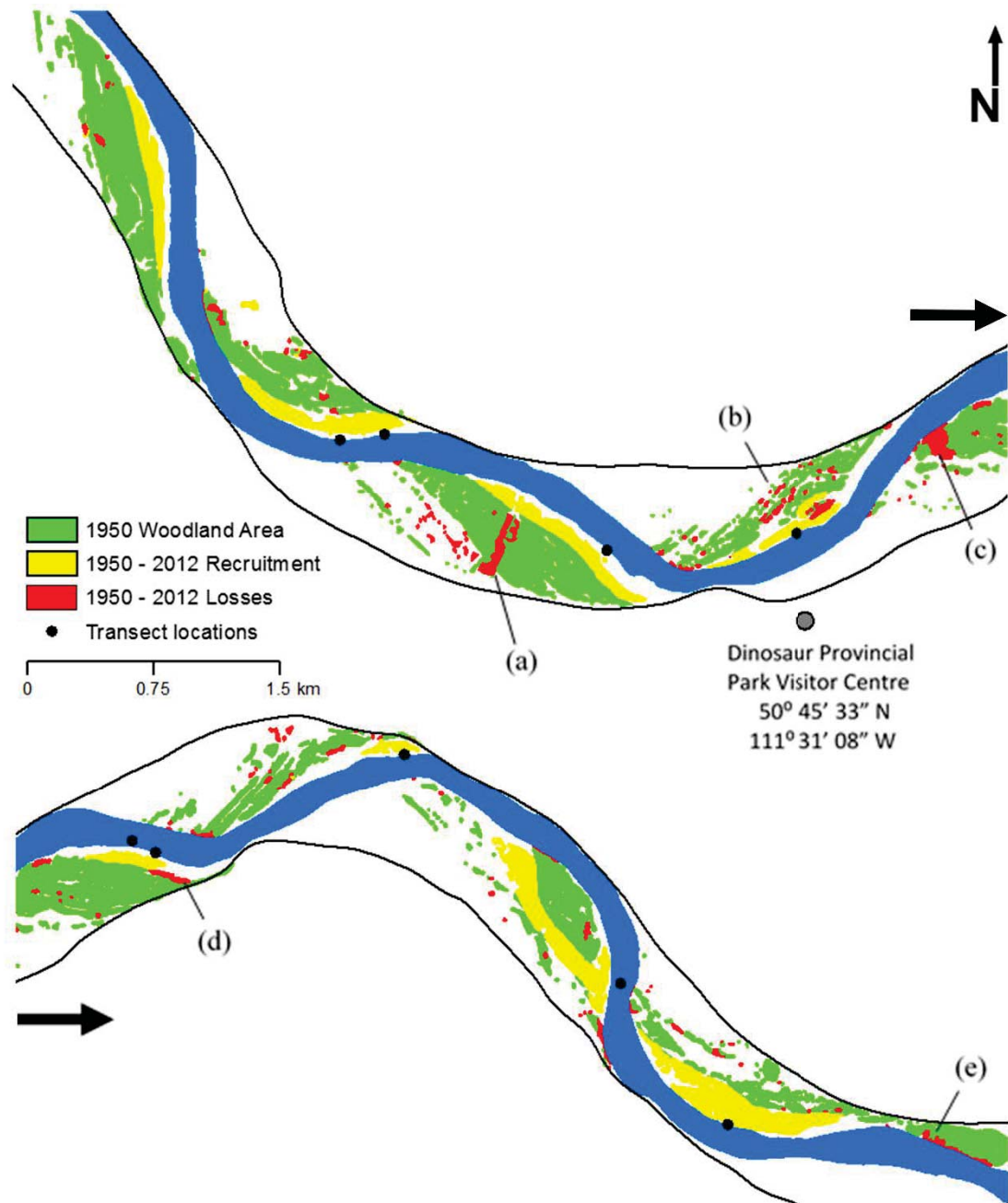


Figure 3-8: Map of the Red Deer River (blue) showing recruitment (yellow) and losses (red) in cottonwood areal extent from 1950 to 2012. Examples of losses resulting from different factors are indicated; (a) human activity, (b) natural mortality, (c) fire, (d) beaver browsing, and (e) erosion. The bottom figure is a continuation of the top. River flow direction is from left to right in both panels. Transect locations are indicated (black dots).

Channel centre line migration was greatest from 1950 to 1962 at a rate of 2.2 m per year followed by 1935 to 1950, with a migration rate of 1.2 m per year (Figure 3-9). Channel migration from 1950 to 1962 is primarily the result of accretion. A substantial proportion of this accretion is the result of the abandonment of two channels.

The lowest migration rates were 1991 to 2001 and 2001 to 2012, with rates of 0.42 and 0.39 m per year respectively. These periods had the lowest accretion rates, with erosion exceeding accretion. Erosion was greatest from 1935 to 1950, with a rate of 3.0 ha per year followed by 1962 to 1974, with a rate of 1.9 ha per year.

Active channel width was greatest in 1935 and 1950 and declined from 1950 to 1962. The active channel width stayed relatively constant from 1962 to 2012 with a small increase in 1974 before declining again in 1985 (Figure 3-10). Overall, from 1935 to 2012 the active channel width has significantly decreased ($r^2 = -0.66$, $p = 0.014$).

The average of annual average discharges for each photograph interval was greatest from 1950 to 1962, with an average discharge of 49 m³/s, and was lowest from 1974 to 1985, with an average discharge of 36 m³/s (Figure 3-11a). The lowest annual flow occurred in 1949 and the highest flow in 1954.

The greatest max daily discharge from 1930 to 2012 occurred in 1954 with a discharge of 1210 m³/s, followed by 2005 with a discharge of 1180 m³/s and 1952 with a discharge of 1070 m³/s (Figure 3-11b). Recurrence analysis using a log-normal distribution determined the 1954 event to be a 1-in-36 year flood and the 2005 and 1952 floods to be 1-in-33 year and 1-in-25 year events respectively (Appendix E). Smaller flood events occurred in 1990 and 1970 with both max daily discharges being approximately 1-in-13 year events.

Average maximum daily discharges were lowest from 1974 to 1985 and highest from 1950 to 1962.

Recruitment was positively correlated with both the rate of river migration and accretion (Table 3-2). River migration rate was correlated with accretion but not erosion. Annual average discharges (Q_{ave}) for each photograph interval and average max daily discharges (Q_{max}) were not correlated with changes in river morphology or cottonwood abundance.

3.3.2 Dendrochronology

Dendrochronological analysis of one floodplain revealed that the greatest cottonwood recruitment occurred 50 to 100 years prior to 2015 with most cottonwoods in this area being 80 to 100 years of age (Figures 3-12 and 3-13). The least recruitment in 200 years occurred in the previous 50 years. Overall the floodplain is dominated by mature trees with 65% of the total area being represented by trees greater than 100 years of age.

While recruitment typically occurs in sequential linear bands along the downstream portion of the floodplain, recruitment resulting from the incorporation of islands into the floodplain and recruitment within abandoned channels appears to be common.

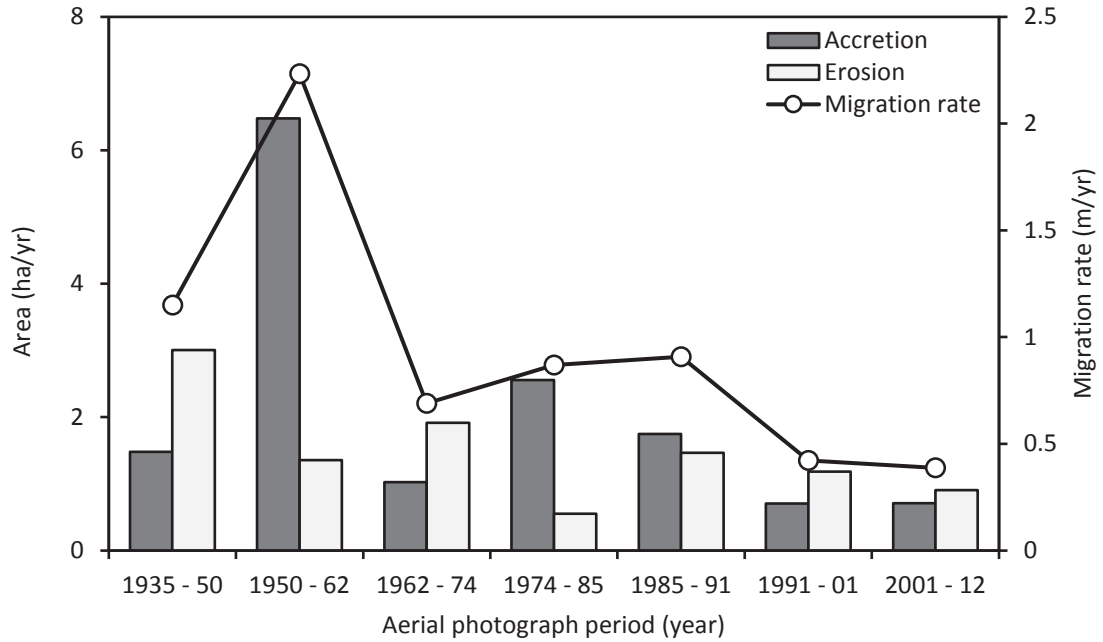


Figure 3-9: Average migration, erosion and accretion rates of the Red Deer River, AB, as determined by aerial photograph analysis.

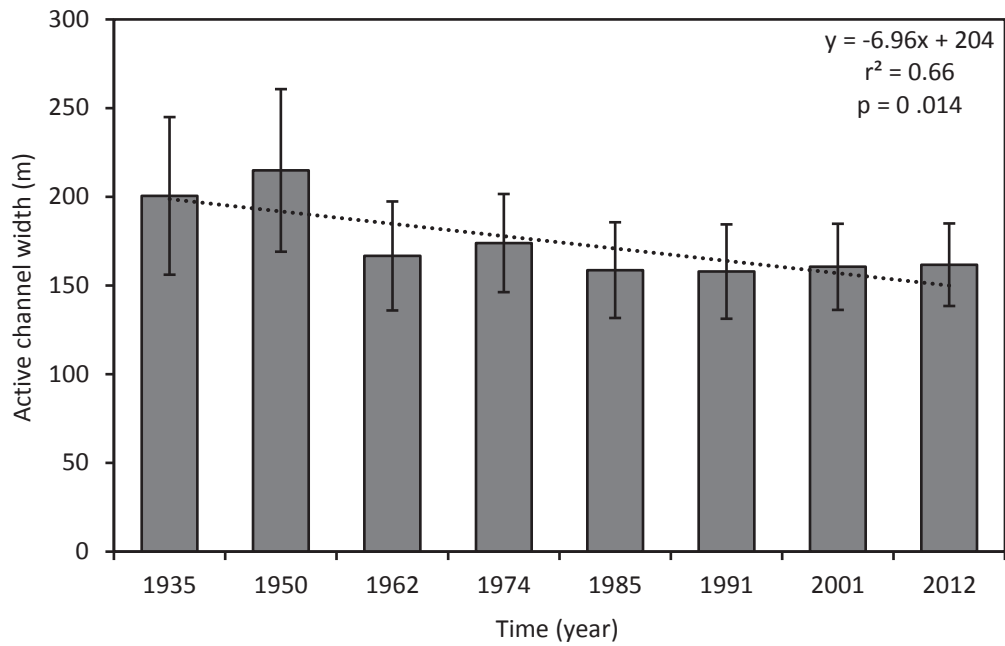


Figure 3-10: Average active channel widths for photo mosaics and 1935 topographic map of the Red Deer River, AB (± 1 SD, $n = 581$).

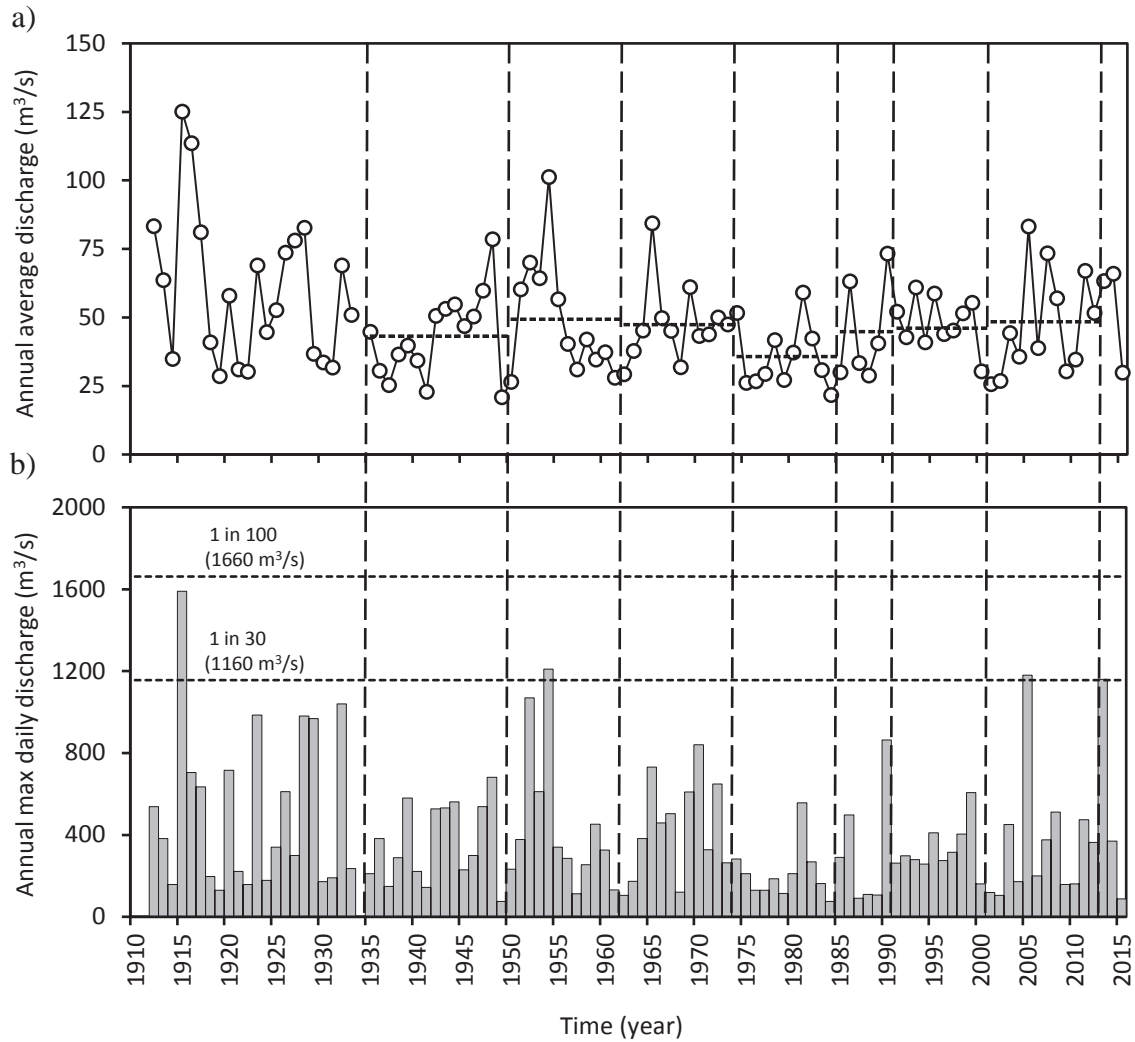


Figure 3-11: (a) Annual average discharges and (b) annual max daily discharges of the Red Deer River at Red Deer from 1935 to 2015. Vertical dashed lines represent the year of each aerial photograph mosaic and the topographic map. Horizontal dashed lines in figure (a) represent the average annual average discharge for each photograph interval. Horizontal dashed line in figure (b) represents 1-in-30 and 1-in-100 year flood recurrence discharges. No discharge data were available for 1934.

Table 3-2: Bivariate correlation analyses for changes in hydrology, river morphology and cottonwood abundance between photograph intervals. Values represent Pearson r^2 coefficients. Significant statistical associations are in bold and distinguished using two levels of confidence: * = $p < 0.05$, ** = $p < 0.01$ ($n = 6$).

	Q_{\max}	Recruitment	Losses	Migration	Erosion	Accretion
Q_{ave}	0.824*	0.161	0.132	0.036	0.381	0.011
Q_{\max}		0.343	0.165	0.154	0.469	0.090
Recruitment			0.050	0.895**	0.031	0.882**
Losses				0.139	0.429	0.053
Migration					0.022	0.972**
Erosion						< 0.001

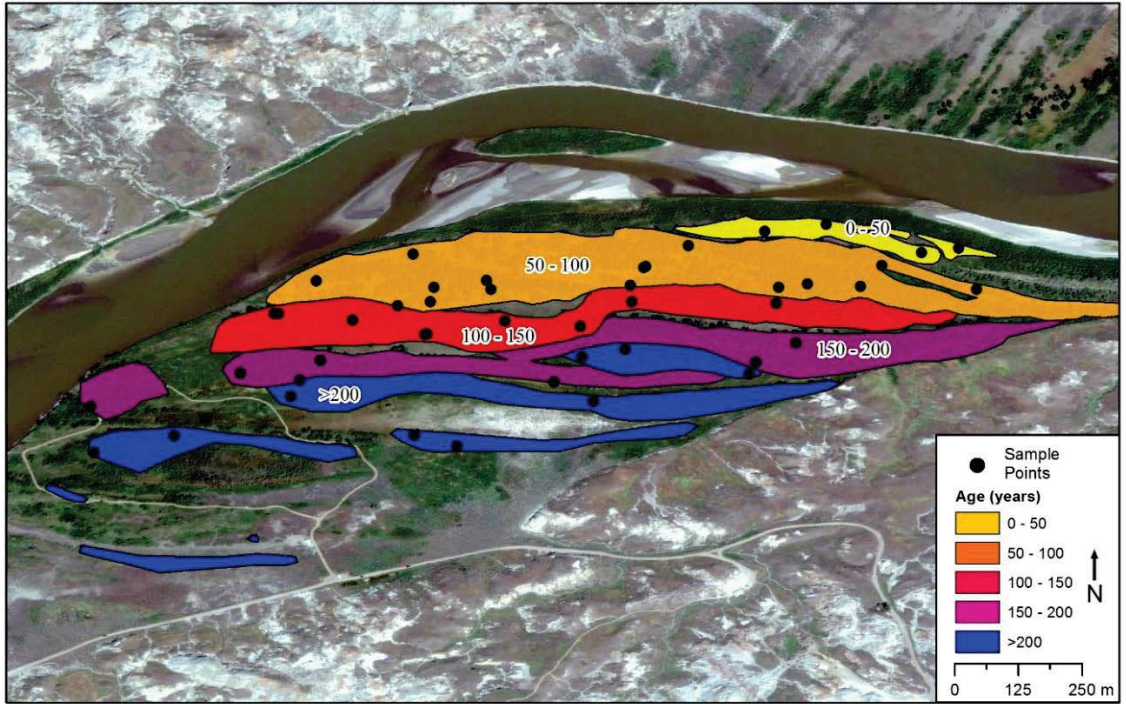


Figure 3-12: Map showing age and distribution of cottonwoods within one floodplain at the study reach along the Red Deer River. Sample points represent locations where trees were aged using dendrochronology. Ages are relative to 2015.

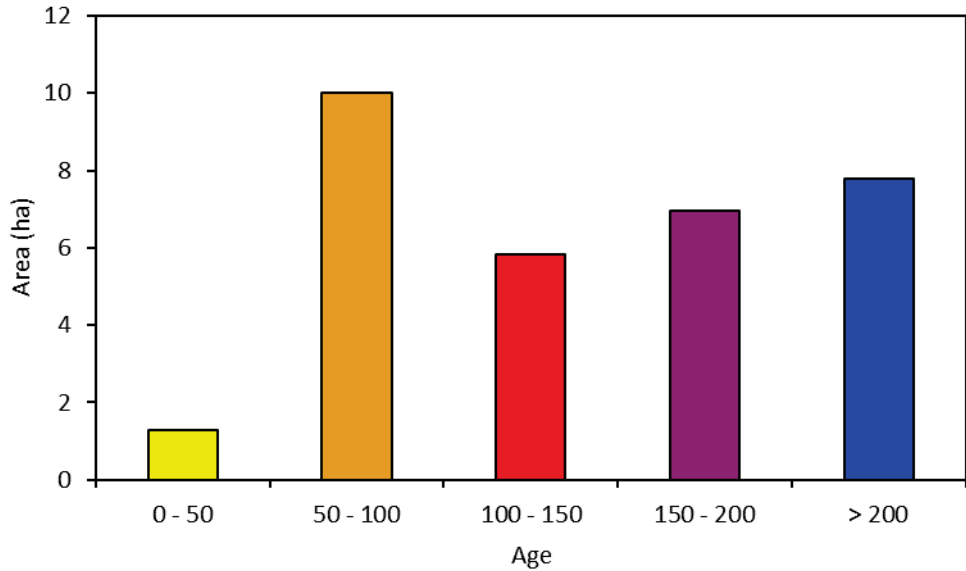


Figure 3-13: Relative areas of each age group for cottonwoods along the Red Deer River study reach presented in figure 3-12. Ages are relative to 2015. Note that tree densities decline with age.

3.3.3 Field survey

Field surveys revealed that overall young cottonwoods typically survived within sandbar willow communities adjacent to the stream. Willows trap coarse sediments during floods thereby creating ideal microsites for cottonwood establishment (Cordes et al., 1993).

Populations of cottonwood seedlings originating from high flows in 2013 were found along many transects at an elevation of 0.5 to 2.0 metres above base flow (Figure 3-14a, Figure 3-15). These cottonwoods are likely to persist and are established at a similar elevation to other successful recruitment bands along other rivers (Mahoney and Rood, 1998). Large bands of cottonwoods originating from high flows in 2005 were also observed and were typically at an elevation of 2 metres above base flow (Figure 3-14b). Three transects revealed little to no seedlings or saplings are not presented.

Seedlings established in 2014 were also found to be abundant along many floodplains. These seedlings are, however, established at a low elevation above base flow and will likely be scoured away by high flows or by ice (Figure 3-14c).

Aging young cottonwoods was difficult. In many cases, young cottonwoods were buried in varying levels of sediments making counting terminal bud scars difficult. This also made for highly variably height and diameter measurements. Many cottonwoods were also beaver browsed. At four transects beaver activity was particularly intensive, with 19%, 35%, 52% and 100% of cottonwoods being browsed, with some cottonwoods being browsed several times. While many cottonwoods survived being browsed and displayed vigorous coppice growth, many dead stumps were also observed along transects.

Browsing appeared to be restricted primarily to saplings and trees, however, it is possible that seedlings were also being browsed but this was more difficult to distinguish.

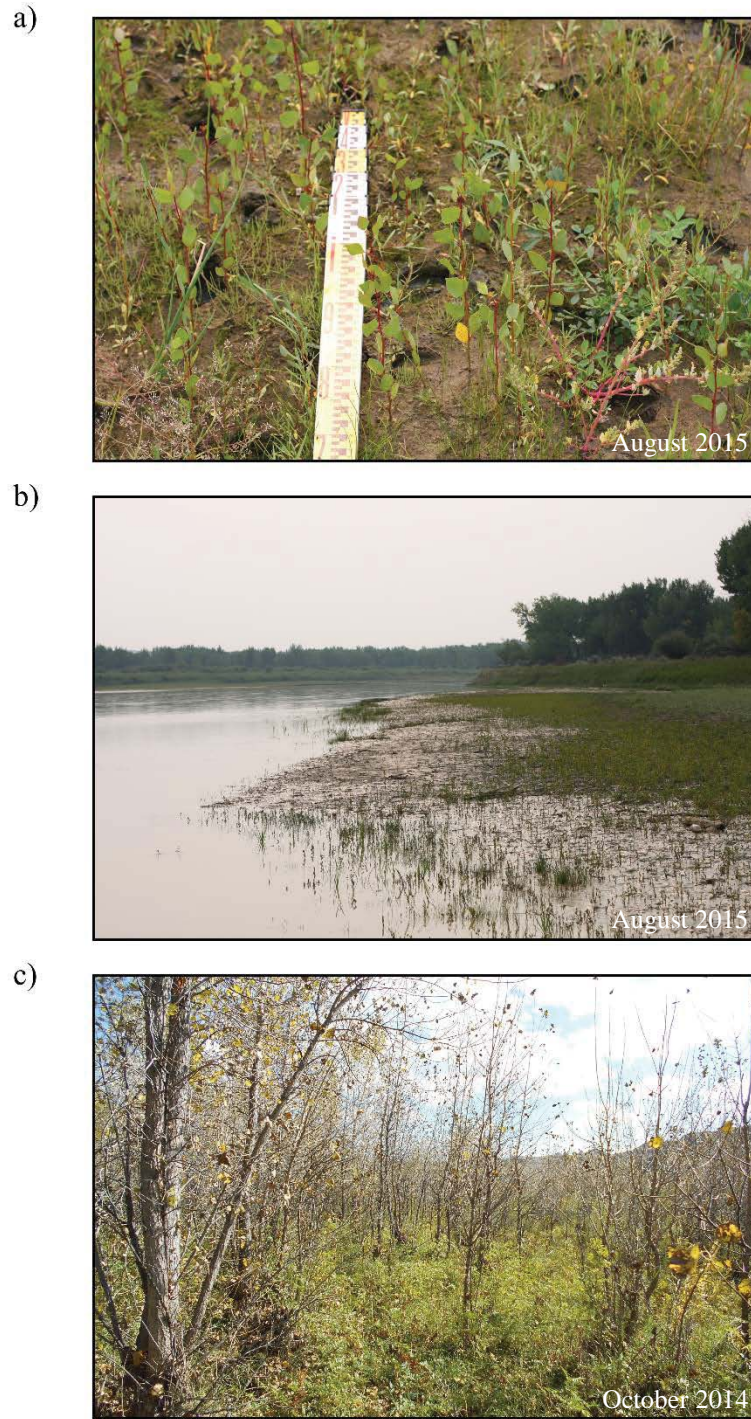


Figure 3-14: Cottonwoods in Dinosaur Provincial Park, AB, established in (a) 2013, (b) 2014 and (c) 2005. Photo dates are indicated (Photos: L. Philipsen).

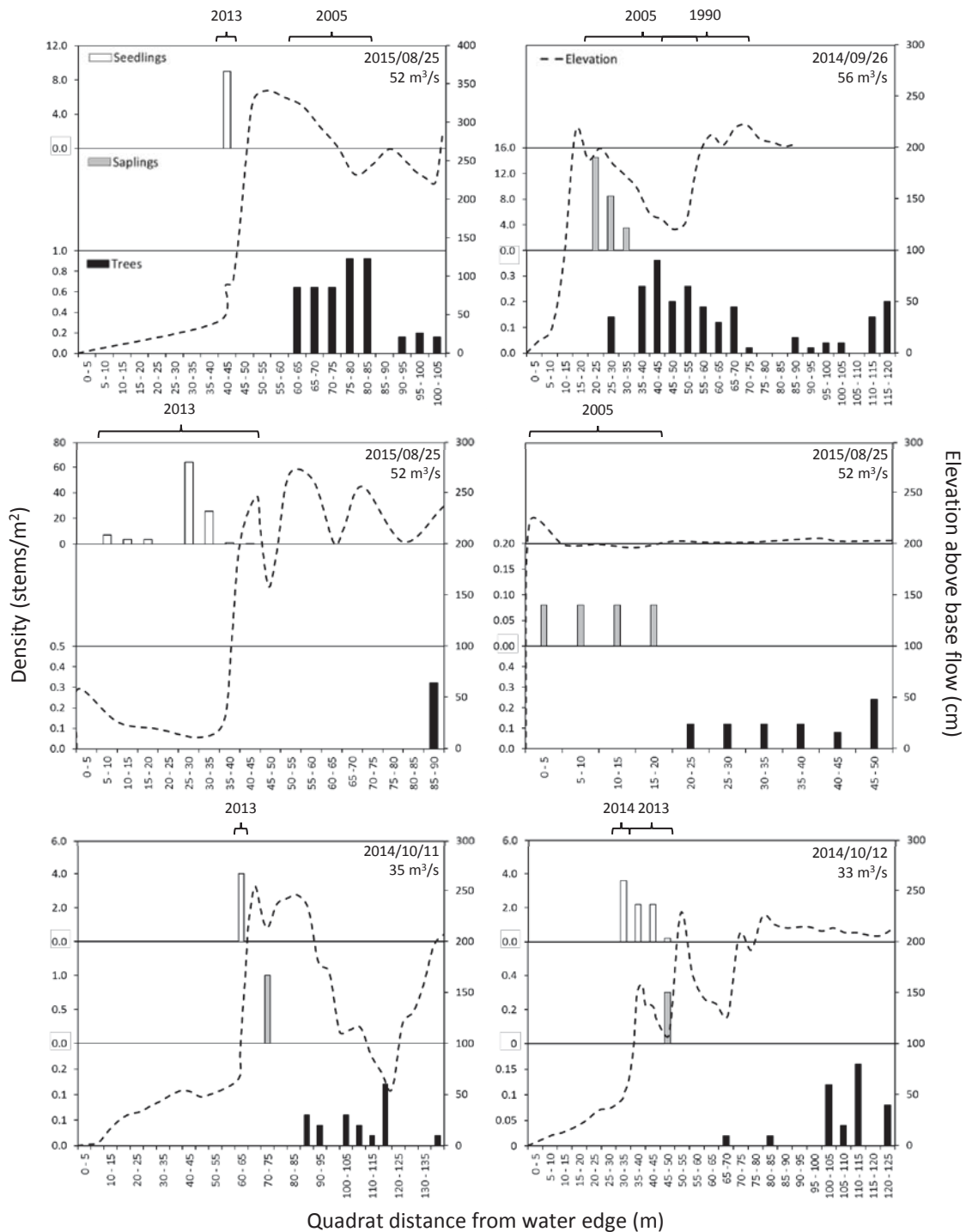


Figure 3-15: Density and elevation of cottonwood seedlings, saplings, and trees along transects in Dinosaur Provincial Park. Where possible, the year of establishment is indicated. The date and corresponding discharge, as recorded at Drumheller, of each transect is shown. Note that density scale on primary axis is variable between transects.

3.3.4 Hydrology

Analysis of inflows and outflows revealed that, except for a few months in the spring and fall, inflow and outflow median discharges, median minimum discharges and median maximum discharges were significantly different for most months (Table 3-3). Median inflows were most different from outflows in May and June, and in the winter months from November to March. Inflows exceeded outflows in May and June, and outflows exceeded inflows in the winter (Figure 3-16a). This pattern is also seen in median monthly minimum discharges with minimum outflows being significantly lower than inflows in June and July and greater in November, December, February and March (Figure 3-16b).

Late summer inflow and outflow median discharges and median minimum discharges, while statistically different, are similar with median outflow discharges being only 2 to 5 m^3/s different from inflows.

Inflow and outflow median monthly maximum discharges were most different in June and July (Figure 3-16c). On average, from 1984 to 2013, the Dickson Dam has attenuated annual maximum daily discharges by 33%. For large floods in particular, inflow and outflow discharges can be very different (Figure 3-17). For example, during peak flows in 2005, 2370 m^3/s was recorded entering Gleniffer Reservoir with 1570 m^3/s being discharged downstream. During peak flows in 2013, 1620 m^3/s was recorded entering Gleniffer Reservoir and 1201 m^3/s was discharged.

Following floods in 1990, 2005 and 2013, there were multiple occasions where the observed rate of stage decline exceeded the ideal rate for two or more consecutive days (Figure 3-18). In 2005, commencing in early July, the average rate of stage decline over

five consecutive was over four times the optimal rate. In 2013, also commencing in early July, the average rate of stage decline was over six times the optimal rate for three consecutive days. In both cases, the sharp decrease in river stage appears to be partly the result of a reduction in discharge leaving the Dickson Dam. While inflows decline at a relatively consistent rate, outflows decline at an accelerated rate. It is likely that, without management, the natural stage decline would have been closer to the optimal rate.

In 2013, another period of accelerated stage decline can be observed between July 13 and July 16. This also appears to be the result of management, with outflows declining at an accelerated rate compared to inflows.

Discharges during the period of cottonwood seed release were significantly different in 1990 compared to 2013 and 2005 as there was three peak discharges. The impact of management on river stage at Drumheller is still, however, observable. Between June 11 and July 1, inflows decline at a relatively consistent rate, but outflows show two sharp consecutive declines, accelerating the rate of river stage decline in Drumheller.

While the Dickson Dam is far upstream from Drumheller and the study area in Dinosaur Provincial Park, the impacts of management are still observable in these lower reaches.

Table 3-3: Comparison of Dickson Dam/Gleniffer Reservoir inflow and outflow monthly average discharges, monthly minimum discharges and max daily discharges from 1984 to 2013 using the Wilcoxon signed rank test. Z values are presented. Significant differences are indicated (** = $p < 0.01$). Negative values indicate a greater inflow than outflow.

	Average Q	Minimum daily Q	Max daily Q
January	4.784**	4.784**	4.762**
February	4.783**	4.783**	4.435**
March	4.130**	4.784**	-2.417**
April	-0.278	3.918**	-2.859**
May	-3.528**	1.378**	-4.309
June	-4.721**	-4.576**	-4.083**
July	-4.618**	-4.021**	-2.498**
August	-4.639**	-3.861**	-3.514**
September	-2.834**	-2.845	-0.749**
October	0.878	2.984	0.180**
November	4.704**	4.763**	1.766**
December	4.783**	4.783**	4.538**

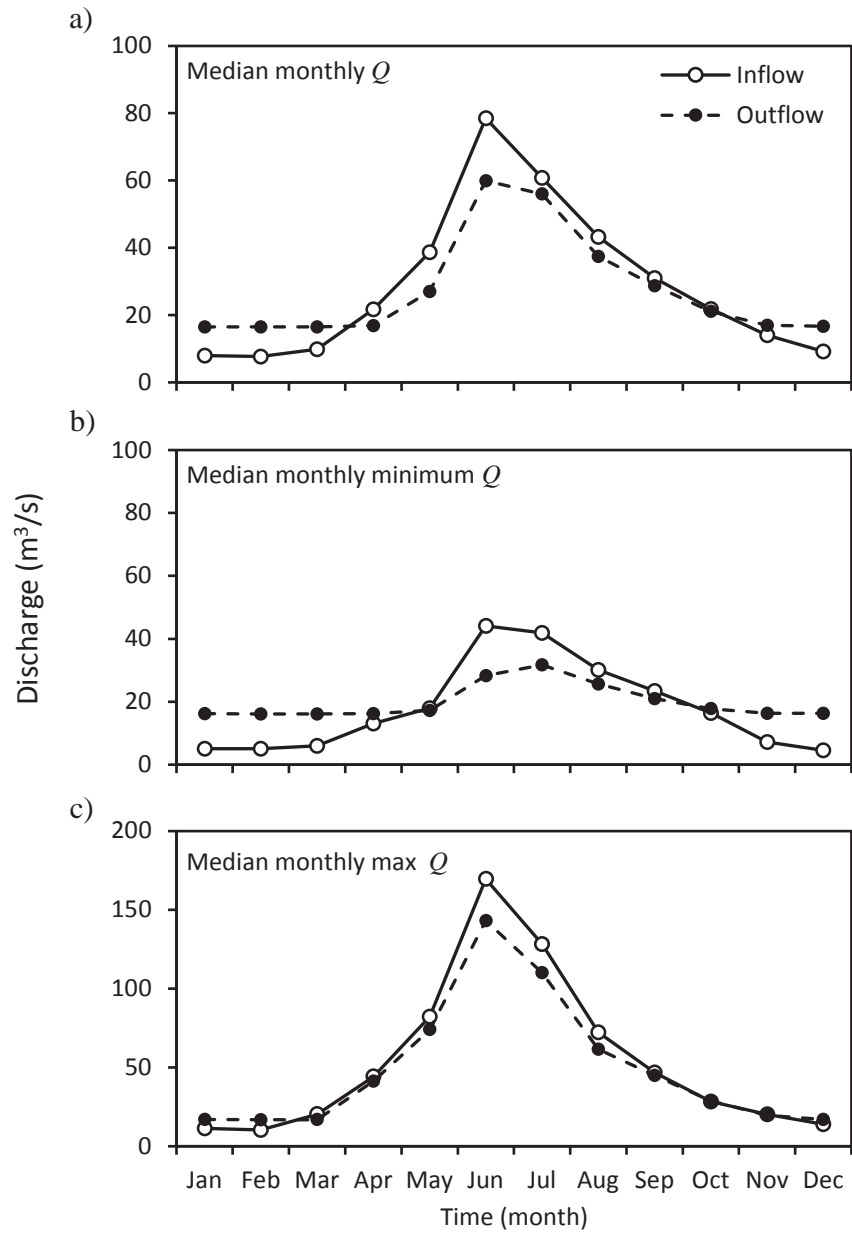


Figure 3-16: Comparison of inflow and outflow (a) median monthly discharges, (b) median monthly minimum discharges and (c) median monthly max discharges for the Dickson Dam/Gleniffer Reservoir from 1984 to 2013.

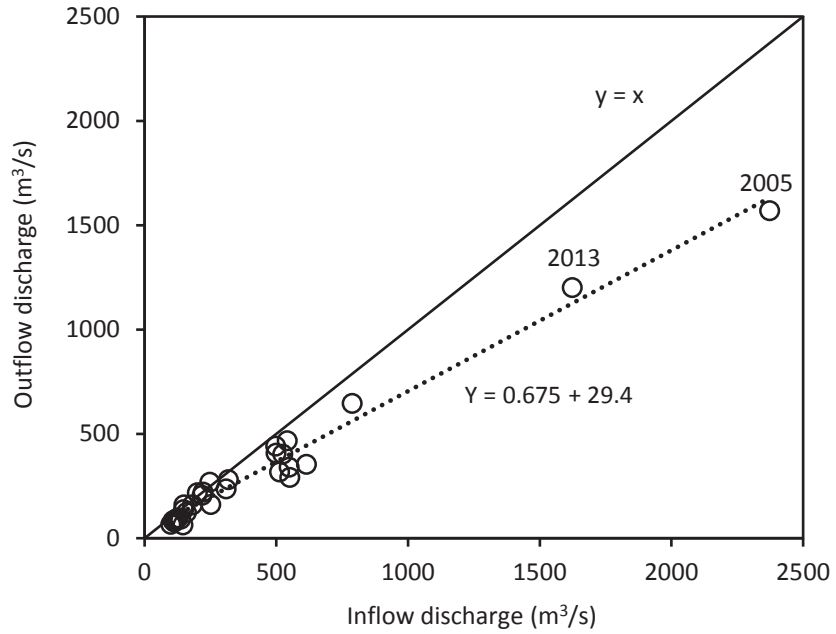


Figure 3-17: Comparison of inflow and outflow annual max daily discharges for the Dickson Dam/Gleniffer Reservoir from 1984 to 2013.

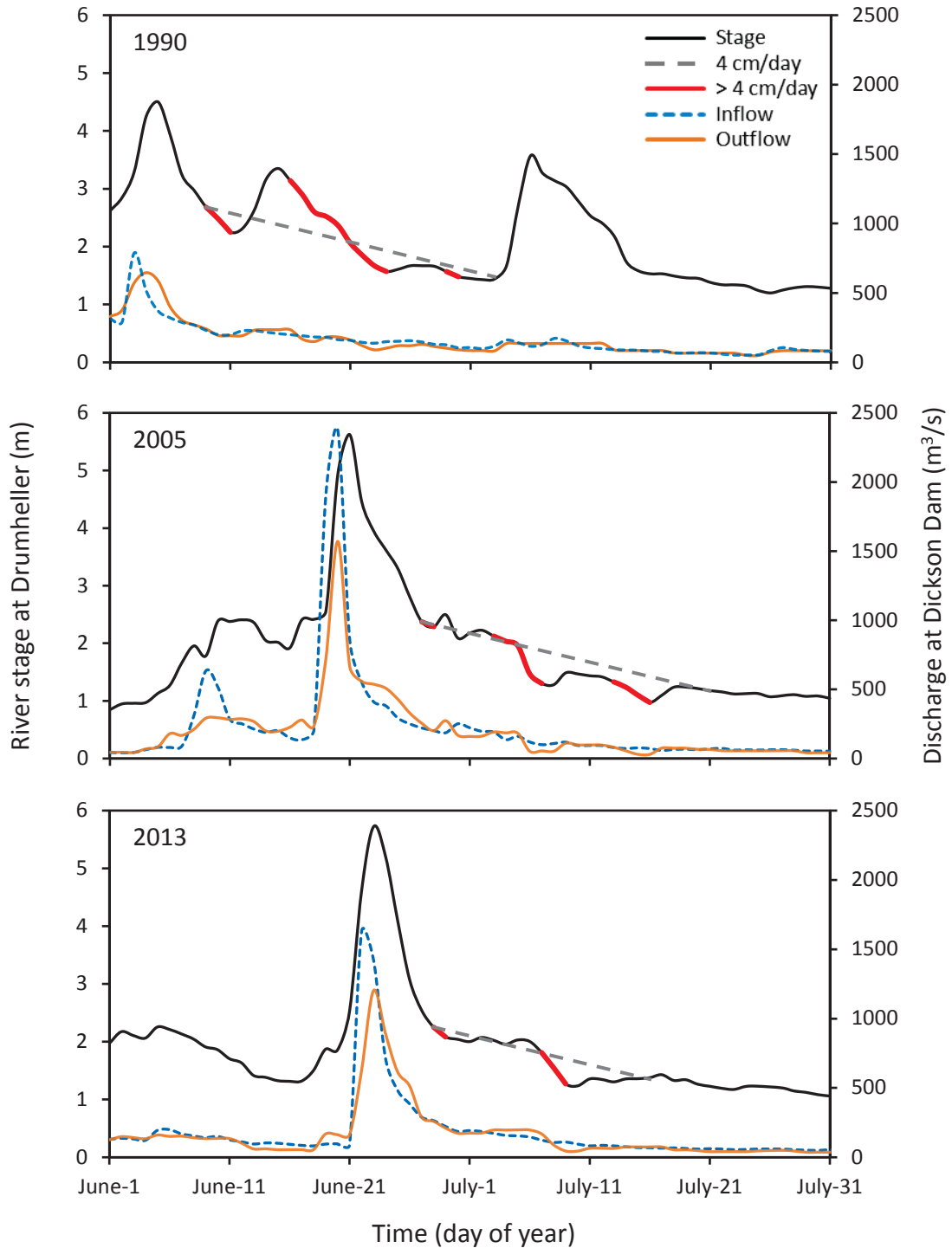


Figure 3-18: Ramping analysis of the 2013, 2005 and 1990 floods. The solid orange line and dashed blue lines indicate Dickson Dam/Gleniffer Reservoir outflow and inflow discharges, respectively. Red Deer River stage at Drumheller is represented by the solid black line with red sections indicating a post-peak stage decline rate of greater than 4 cm/day for two or more consecutive days. The optimal rate of stage decline (4cm/day) for seedling survival is indicated by the dashed grey line.

3.4 Discussion

In this study, we analysed the hydrology and recruitment of cottonwoods along the lower Red Deer River, with the intention of evaluating the current status of cottonwood populations, identifying any areas of concern and suggest management opportunities.

Analysis of aerial photographs revealed extensive cottonwood recruitment from 1950 to 1962. Recruitment during this period appears to be the result of a combination of both lows flow and high flows. The lowest average flow on record for the Red Deer River occurred in 1949. This was followed by another below average flow in 1950. These low flows resulted in the abandoning of channels and were the main cause of substantial accretion, channel migration and a reduction in the active channel width. The four years following 1950 were above average and included two floods in 1952 and 1954. These floods would have likely inundated the banks and channels abandoned by the previous low flows and created ideal conditions for cottonwood recruitment and survival.

Recruitment in these areas can be observed in subsequent aerial photographs. Flows in 1952 in particular, produced an optimal hydrograph and provide a target for artificial flow patterns (Rood, 1997) (Figure 3-19).

Cottonwood seeds, while prolific, are viable for only a short period of time and are easily outcompeted, making successful establishment highly dependent on the availability of ideal nursery sites (Braatne et al., 1996). Floods provide the geomorphic disturbances necessary to produce these nursery sites (Polzin and Rood, 2006; Scott et al., 1996).

Consequently, seedling establishment is typically correlated with periodic spring flooding that mobilizes and deposits moist sediments for seedling germination (Auble et al., 1997; Bradley and Smith, 1986; Rood et al., 1998; Rood et al., 1999). Along the Red Deer

River, following the floods in 1952 and 1954, no substantial floods were observed for 50 years. Thus, little channel migration and cottonwood recruitment is observed and overall cottonwood areal extent slightly declines.

The Dickson Dam, while being relatively small, appears to have a substantial capacity to attenuate floods. Because the Dickson Dam is not primarily managed for irrigation and rather functions to augment winter discharges, compared to other dams, the reservoir is at a lower elevation during peak flows in June, enhancing the Dickson Dam/Gleniffer Reservoirs capacity to attenuate floods (Figure 3-20).

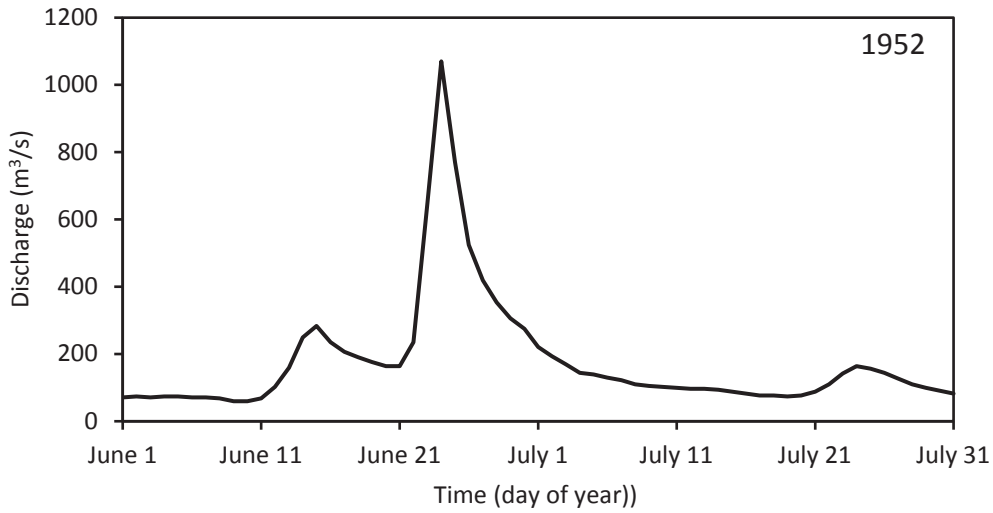


Figure 3-19: Hydrograph for the Red Deer River at Red Deer in 1952.

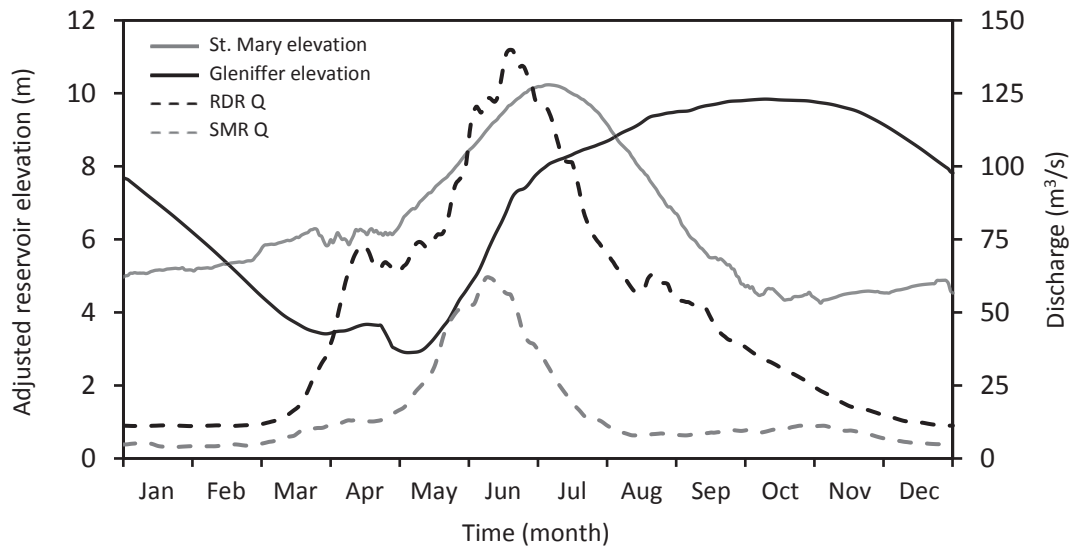


Figure 3-20: Comparison of average daily discharge (Q) of the Red Deer River at Red Deer (RDR) and the St. Mary River near Lethbridge (SMR) and the corresponding reservoir elevation for the Gleniffer Reservoir and St. Mary Reservoir. The St. Mary Reservoir is managed primarily for irrigation. Values represent 5 day moving averages. Reservoir elevations are adjusted to be metres above 938 m for the Gleniffer Reservoir and above 1092 m for the St. Mary Reservoir.

In their analysis, Cordes et al. (1997) reported that the attenuation of floods by the Dickson Dam would reduce the likelihood of “general” recruitment events occurring along the Red Deer River. These events occur when flood flows overtop and saturate floodplains and the subsequent scouring and deposition of sediments results in extensive seedling establishment at locations even distant from the stream channel (Rood et al., 2007; Rood et al., 1998). Smaller floods result in less geomorphic activity and typically result in less recruitment that is limited to areas immediately adjacent to the river. This type of recruitment is called “fringe” recruitment (Cordes et al., 1997).

Peak discharges on the Red Deer River were substantially attenuated in 2005 and 2013. Maximum daily discharges in 2013 and 2005 were both calculated to be roughly 1-in-30 year events. Without attenuation, the 2013 flood would have likely been approaching a 1-in-80 year event and the 2005 flood an over a 1-in-100 year event. It is difficult to determine how these differences in magnitude would impact recruitment. However, both floods, while being attenuated, still provided adequate discharge to produce extensive overbank flooding and resulted in considerable cottonwood seedling colonization.

Previous studies have shown that the overall streamflow pattern is more crucial to cottonwood recruitment than the magnitude of flood events (Mahoney and Rood, 1998; Rood, 1997; Scott et al., 1996). Following a flood, the rate of river stage decline can be a determining factor in the extent of successful seedling recruitment. To avoid drought stress and mortality following establishment, seedling root growth must be adequate enough to maintain contact with receding soil moisture, which is closely related with declining river stage (Mahoney and Rood, 1998). Studies have demonstrated that many seedlings can survive water-table declines up to 4 cm per day (Mahoney and Rood, 1991;

Segelquist et al., 1993). An accelerated rate will increase drought-induced seedling mortality.

Along the Red Deer River, stage decline at Drumheller exceeded 4 cm per day for multiple days following peak discharges in 1990, 2005 and 2013. In many cases, this appears to be the result of management, with the Dickson Dam accelerating the natural rate of stage decline. While exceeding the optimal rate, the rate of stage decline following these floods was not detrimental to seedling recruitment with bands of cottonwoods associated with each flood still being observed in Dinosaur Provincial Park. This may be partly due to the channel at Dinosaur Provincial Park being less constrained compared to that at Drumheller. This combined with Dinosaur Provincial Park being further downstream, would result in a slower lowering of stage with discharge. Floodplains along the lower Red Deer River are also primarily composed of fine sediments. Survivable rates of water decline are strongly related to substrate texture (Kranjcec et al., 1998). Finer textured soils have greater capacity to retain moisture, thus allowing soils to remain saturated for longer as the water table recedes (Mahoney and Rood, 1991). This would likely allow seedlings to survive a faster rate of stage decline.

Late summer streamflow is another important component for the maintenance of cottonwood health. Dams can reduce summer flows which, combined with hot and dry weather, can induce drought stress in all age-classes of cottonwoods (Braatne et al., 1996; Rood et al., 2003; Rood and Mahoney, 1995). For mature trees, low summer flows can result in reduced radial growth, declines in crown volume resulting from branch sacrifice and, in extreme occasions, mortality (Rood et al., 2000; Scott et al., 1999; Stromberg and Patten, 1996). Old trees in particular are susceptible to stress-induced mortality

(Albertson and Weaver, 1945). Along the Red Deer River, the Dickson Dam has only a minor impact on average and minimum summer flows. Thus, it is probable that management has little impact on mature trees and existing cottonwood populations do not appear to be stressed. This is explored further in chapter 4.

Harvesting of cottonwoods by beavers was extensive within some woodlands (Figure 3-21a). Beavers selectively browse cottonwoods over other plants and along one transect 100% of young cottonwoods had been browsed to varying extents (Crouch, 1979).

Overall, cottonwoods are robust to the impacts of browsing, responding with vigorous coppice growth. Some browsing can even be healthy for riparian woodlands, providing a form of rejuvenation as coppice regrowth is often considerably more rapid than initial shoot growth of seedlings (Dickmann and Stuart, 1983; Herbison and Rood, 2015).

Excessive beaver browsing, however, can lead to mortality and along transects many dead stumps were observed. This can lead to the thinning of woodlands and provide additional stress on declining populations (Andersen and Cooper, 2000).

Cattle grazing was also present along most floodplains. Light grazing is typically not detrimental to poplar forests, but heavy grazing can lead to the degradation of riparian areas (Braatne et al., 1996; Bradley et al., 1991; Samuelson and Rood, 2004). Browsing and pugging — the perforation of moist substrates by animals hooves — can have a substantial impact on the establishment of seedlings, especially in the first few years of growth (Kalischuk et al., 2001). Cattle grazing within Dinosaur Provincial Park, for the most part, is not intensive, but pugging and browsing was still observed at most sites. Limiting cattle grazing during recruitment years would likely be beneficial for seedling establishment.

Recruitment years typically coincide with years of greater precipitation, which results in greater productivity in the surrounding grasslands. This increased productivity should limit the need for grazing in riparian areas. It was observed by a local rancher that, following floods, cattle typically avoided the river valley, preferring the upper grasslands because of both higher productivity and lower mosquito populations, which can be tremendous in the river valley in wet years (L. Lucas, personal communication, September 9, 2014). This interaction provides a natural feedback beneficial to seedling survival, provided cattle are not confined to the floodplain.

Fires pose another risk to woodlands along the lower Red Deer River. Compared to other cottonwood species and hybrids, plains cottonwood respond poorly to fire and other disturbances as they are not replaced via suckering is rare (Gom and Rood, 2000; Rood et al., 2007). In 1989, a fire in Dinosaur Provincial Park consumed a portion of a riparian woodland. Following the fire there was limited regrowth of cottonwoods resulting in an area of the floodplain transitioning from woodland, to an area dominated by grasses and shrubs (Figure 3-21b). Another fire upstream of Dinosaur Provincial Park near Emerson Bridge, resulted in the complete removal of woodlands along multiple floodplains, with only a few, likely hybrid, trees surviving. While large fires are rare, they can be potentially devastating to cottonwood populations, especially along the lower Red Deer River as populations are dominated plains cottonwood.

Woodlands along the lower Red Deer River are dominated by mature trees. Large floods in the late 1800s and the early 1900s (1902, 1915) combined with the virtual elimination of the bison by 1880 and the extirpation of beavers, created optimal conditions for cottonwood recruitment (Cordes et al., 1993). As a result, a substantial proportion of

cottonwoods along the lower Red Deer River are around 100 years of age, with the average woodland tree age being well over 100 years (Figure 3-22). In Alberta, the life-span of poplar trees is typically only about a century and as woodlands continue to age, the rate of natural mortality will likely accelerate (Shaw, 1976).

a)



b)



Figure 3-21: Cottonwood losses along the Red Deer River in Dinosaur Provincial Park resulting from (a) beaver browsing and (b) fire; summer 2016. (Photos: L. Philipsen)



Figure 3-22: Photograph comparison between 1912 and 2016 of a woodland at Steeveville, Alberta (50.837° , -111.596°). A substantial proportion of the 2016 woodland was formed prior to 1912. The top photo was captured 1912 (Glenbow archive NA-986-1) and the bottom 2016 (L. Philipsen). Photos are looking upstream of the Red Deer River.

Following construction of the Dickson Dam in 1983, cottonwood populations along the lower Red Deer River have retained their areal extent. This is contrary to other rivers in Southern Alberta, where damming and diversion have led to the collapse of cottonwood populations. The decline in poplar abundance within these other systems has been attributed to a deficiency in seedling recruitment resulting from the alteration of the natural flow patterns, including the attenuation of floods and accelerated rates of downstream stage decline following recruitment events (Rood and Mahoney, 1990).

Flood flows are typically synonymous with discharges at or above bankfull. Bankfull discharge is defined as the discharge at which the river channel is filled to the channel level (Andrews, 1980). These flows provide a threshold of flow magnitude that is conducive to cottonwood replenishment (Auble et al., 1997; Howe and Knopf, 1991; Rood et al., 1998). Bankfull events are rare and, consequently, so are recruitment events. Along the lower Red Deer River, bankfull discharges only occur every 12 to 28 years (McPherson, 1967; Neill, 1965; Smith, 1979). The Dickson Dam has a substantial capacity to attenuate these events. While this likely does not have a substantial impact on recruitment associated with large floods, it may have an impact on smaller, fringe recruitment events associated with lower discharges around bankfull.

Floods in 1990, 2005 and 2013 resulted in substantial cottonwood recruitment along the Red Deer River. During these years, however, dam management accelerated the recession in downstream stage which would have likely have increased drought stress on seedlings and resulted in greater seedling mortality. An artificially managed stage decline rate that followed the optimal rate would have likely enhanced cottonwood recruitment.

In floods years, water is abundant and demand is typically reduced. This combined with the under allocation of the Red Deer River provides an opportunity to manage flows for environmental purposes with limited risk to supply. As woodlands along the Red Deer River continue to age, the rate of natural mortality will also increase. To maintain the current abundance of cottonwoods and the ecosystem services they provide, it will be important to capitalize on the few floods events that occur. The implementation of strategies, such as the gradual ramping of flows following floods, will enhance cottonwood populations along the lower Red Deer River and will likely mitigate negative impacts of flow attenuation, beaver activity and grazing.

3.5 References

- Albertson FW, Weaver JE, 1945. Injury and death or recovery of trees in prairie climate. *Ecological Monographs*, 15(4): 393-433. DOI:Doi 10.2307/1948428
- Andersen DC, Cooper DJ, 2000. Plant-herbivore-hydroperiod interactions: Effects of native mammals on floodplain tree recruitment. *Ecological Applications*, 10(5): 1384-1399. DOI:10.2307/2641293
- Andrews ED, 1980. Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. *Journal of Hydrology*, 46(3-4): 311-330. DOI:10.1016/0022-1694(80)90084-0
- Auble GT, Scott ML, Friedman JM, Back J, Lee VJ, 1997. Constraints on establishment of plains cottonwood in an urban riparian preserve. *Wetlands*, 17(1): 138-148. DOI:10.1007/bf03160725
- Baker BL, Telang SA, 1985. Abundances of oxygen and organics in the Red Deer River: Comparison with Marmot Basin streams. *Canadian Water Resources Journal*, 10(2): 19-27. DOI:10.4296/cwrj1002019
- Braatne JH, Jamieson R, Gill KM, Rood SB, 2007. Instream flows and the decline of riparian cottonwoods along the Yakima River, Washington, USA. *River Research and Applications*, 23(3): 247-267. DOI:10.1002/rra.978
- Braatne JH, Rood SB, Heilman PE, 1996. Life history, ecology, and conservation of riparian cottonwoods in North America, *Biology of Populus and its implications for management and conservation*. NRC Research Press, Ottawa, ON, Canada, pp. 57-85.
- Bradley CE, Reintjes F, Mahoney JM, 1991. The biology and status of riparian poplars in southern Alberta. *Alberta Forestry, Lands and Wildlife*, 85 pp.
- Bradley CE, Smith DG, 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. *Canadian Journal of Botany*, 64(7): 1433-1442. DOI:10.1139/b86-195
- Brayshaw TC, 1965. Native poplars of southern Alberta and their hybrids. Canada, Department of Forestry, Petawawa Experiment Station, Ottawa, Publication 1109.
- Bryan RB, Campbell IA, 1980. Sediment entrainment and transport during local rainstorms in the Steeveville Badlands, Alberta. *CATENA*, 7(1): 51-65. DOI:10.1016/S0341-8162(80)80003-8
- Clipperton G, Koning C, Locke A, Mahoney J, Quazi B, 2003. Instream flow needs determinations in the South Saskatchewan River Basin, Alberta. *Alberta Environment and Sustainable Resource Development*, Pub No T/719, Calgary, Alberta, Canada: 271.

- Cordes LD, Getty MA, Hughes F, 1993. Red Deer River instream flow studies: riparian vegetation component, Alberta Environmental Protection, Edmonton, 125 pp.
- Cordes LD, Hughes FMR, Getty M, 1997. Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: The Red Deer River, Alberta, Canada. *Journal of Biogeography*, 24(5): 675-695.
DOI:10.1111/j.1365-2699.1997.tb00077.x
- Crouch GL, 1979. Long-term changes in cottonwoods on a grazed and an ungrazed plains bottomland in northeastern Colorado. Forest Service, U.S. Department of Agriculture. Research Note RM-370. US Dept. of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Dickmann DI, Stuart KW, 1983. The culture of poplars in eastern North America. Department of Forestry, Michigan State University, East Lansing, Michigan.
- Everitt BL, 1968. Use of the cottonwood in an investigation of the recent history of a flood plain. *American Journal of Science*, 266(6): 417-439.
DOI:10.2475/ajs.266.6.417
- Finch DM, Ruggiero LF, 1993. Wildlife habitats and biological diversity in the Rocky Mountains and northern Great Plains. *Nat Area J*, 13(3): 191-203.
- Geological Mapping Division, 1950. Map 969A Steveville. Department of Mines and Technical Surveys, Canada
- Giardino JR, Lee AA, 2011. Rates of channel migration on the Brazos River. Department of Geology & Geophysics, Texas A & M University, College Station, TX, 45 pp.
- Gom LA, Rood SB, 2000. Fire induces clonal sprouting of riparian cottonwoods. *Canadian Journal of Botany*, 77(11): 1604-1616. DOI:10.1139/b99-135
- Gonzalez MA, 2001. Recent formation of arroyos in the Little Missouri Badlands of southwestern North Dakota. *Geomorphology*, 38(1-2): 63-84.
DOI:10.1016/S0169-555X(00)00070-2
- Hampe A, Petit RJ, 2005. Conserving biodiversity under climate change: the rear edge matters. *Ecology Letters*, 8(5): 461-467. DOI:10.1111/j.1461-0248.2005.00739.x
- Herbison B, Rood SB, 2015. Compound influences of river damming and beavers on riparian cottonwoods: A comparative study along the Lardeau and Duncan Rivers, British Columbia, Canada. *Wetlands*, 35(5): 945-954. DOI:10.1007/s13157-015-0685-8
- Howe WH, Knopf FL, 1991. On the imminent decline of Rio Grande cottonwoods in central New Mexico. *The Southwestern Naturalist*: 218-224.
DOI:10.2307/3671924

- Hughes ML, McDowell PF, Marcus WA, 2006. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology*, 74(1–4): 1-16. DOI:10.1016/j.geomorph.2005.07.001
- Kalischuk AR, Rood SB, Mahoney JM, 2001. Environmental influences on seedling growth of cottonwood species following a major flood. *Forest Ecology and Management*, 144(1–3): 75-89. DOI:10.1016/S0378-1127(00)00359-5
- Knopf FL, Johnson RR, Rich T, Samson FB, Szaro RC, 1988. Conservation of riparian ecosystems in the United States. *The Wilson Bulletin*, 100(2): 272-284.
- Kranjcec J, Mahoney JM, Rood SB, 1998. The responses of three riparian cottonwood species to water table decline. *Forest Ecology and Management*, 110(1–3): 77-87. DOI:10.1016/S0378-1127(98)00276-X
- Lawton JH, 1993. Range, population abundance and conservation. *Trends in Ecology & Evolution*, 8(11): 409-413. DOI:10.1016/0169-5347(93)90043-O
- Lesica P, Allendorf FW, 1995. When Are Peripheral Populations Valuable for Conservation? *Conservation Biology*, 9(4): 753-760. DOI:10.1046/j.1523-1739.1995.09040753.x
- Mahoney JM, Rood SB, 1991. A device for studying the influence of declining water table on poplar growth and survival. *Tree Physiology*, 8(3): 305-314. DOI:10.1093/treephys/8.3.305
- Mahoney JM, Rood SB, 1998. Streamflow requirements for cottonwood seedling recruitment—An integrative model. *Wetlands*, 18(4): 634-645. DOI:10.1007/bf03161678
- Marken S, 1993. Plains cottonwoods and riparian plant communities on the lower Red Deer River, Department of Geography, University of Calgary, Calgary, Alberta.
- McPherson H, 1967. Morphology and fluvial processes of the lower Red Deer River Valley, Alberta, McGill University, Montreal, Quebec.
- Neill CR, 1965. Channel regime of the lower Red Deer River, Alberta Research Council open file report 1965-6, Edmonton, Alberta.
- Nicoll TJ, Hickin EJ, 2010. Planform geometry and channel migration of confined meandering rivers on the Canadian prairies. *Geomorphology*, 116(1–2): 37-47. DOI:10.1016/j.geomorph.2009.10.005
- Parsons PA, 1990. The metabolic cost of multiple environmental stresses: Implications for climatic change and conservation. *Trends in Ecology & Evolution*, 5(9): 315-317. DOI:10.1016/0169-5347(90)90089-V

- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC, 1997. The natural flow regime. *BioScience*, 47(11): 769-784. DOI:10.2307/1313099
- Polzin ML, Rood S, 2000. Effects of damming and flow stabilization on riparian processes and black cottonwoods along the Kootenay River. *Rivers*, 7(3): 221-232.
- Polzin ML, Rood SB, 2006. Effective disturbance: seedling safe sites and patch recruitment of riparian cottonwoods after a major flood of a mountain river. *Wetlands*, 26(4): 965-980.
- Richard GA, Julien PY, Baird DC, 2005. Statistical analysis of lateral migration of the Rio Grande, New Mexico. *Geomorphology*, 71(1-2): 139-155. DOI:10.1016/j.geomorph.2004.07.013
- Rood SB, 1997. Instream flows and riparian cottonwoods along the Red Deer River, Alberta. Prepared by Chinook Environmental Resources for Alberta Environmental Protection, Calgary, Alberta.
- Rood SB, Braatne JH, Hughes FM, 2003. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology*, 23(16): 1113-1124. DOI:10.1093/treephys/23.16.1113
- Rood SB, Bradley CE, 1993. Assessment of riparian cottonwoods along the Bow River downstream from Calgary, Alberta. Final Report to Trout Unlimited Canada, University of Lethbridge, Calgary, Alberta.
- Rood SB, Goater LA, Mahoney JM, Pearce CM, Smith DG, 2007. Floods, fire, and ice: disturbance ecology of riparian cottonwoods. The review is one of a selection of papers published in the Special Issue on Poplar Research in Canada. *Canadian Journal of Botany*, 85(11): 1019-1032. DOI:10.1139/B07-073
- Rood SB, Heinze-Milne S, 1989. Abrupt downstream forest decline following river damming in southern Alberta. *Canadian Journal of Botany*, 67(6): 1744-1749. DOI:10.1139/b89-221
- Rood SB, Hillman C, Sanche T, Mahoney JM, 1994. Clonal reproduction of riparian cottonwoods in southern Alberta. *Canadian Journal of Botany*, 72(12): 1766-1774. DOI:10.1139/b94-217
- Rood SB, Kalischuk AR, Mahoney JM, 1998. Initial cottonwood seedling recruitment following the flood of the century of the Oldman River, Alberta, Canada. *Wetlands*, 18(4): 557-570. DOI:10.1007/bf03161672
- Rood SB, Mahoney JM, 1990. Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. *Environmental Management*, 14(4): 451-464. DOI:10.1007/BF02394134

- Rood SB, Mahoney JM, 1995. River damming and riparian cottonwoods along the Marias River, Montana. *Rivers*, 5(3): 195-207.
- Rood SB, Patiño S, Coombs K, Tyree MT, 2000. Branch sacrifice: cavitation-associated drought adaptation of riparian cottonwoods. *Trees*, 14(5): 248-257.
DOI:10.1007/s004680050010
- Rood SB, Samuelson GM, Braatne JH, Gourley CR, Hughes FM, Mahoney JM, 2005. Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment*, 3(4): 193-201. DOI:10.2307/3868463
- Rood SB, Taboulchanas K, Bradley CE, Kalischuk AR, 1999. Influence of flow regulation on channel dynamics and riparian cottonwoods along the Bow River, Alberta. *Rivers*, 7(1): 33-48.
- Sabo JL, Sponseller R, Dixon M, Gade K, Harms T, Heffernan J, Jani A, Katz G, Soykan C, Watts J, 2005. Riparian zones increase regional species richness by harboring different, not more, species. *Ecology*, 86(1): 56-62. DOI:10.1890/04-0668
- Samuelson GM, Rood SB, 2004. Differing influences of natural and artificial disturbances on riparian cottonwoods from prairie to mountain ecoregions in Alberta, Canada. *Journal of Biogeography*, 31(3): 435-450. DOI:10.1111/j.0305-0270.2003.01052.x
- Scott ML, Friedman JM, Auble GT, 1996. Fluvial process and the establishment of bottomland trees. *Geomorphology*, 14(4): 327-339. DOI:10.1016/0169-555X(95)00046-8
- Scott ML, Shafroth PB, Auble GT, 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management*, 23(3): 347-358.
DOI:10.1007/s002679900191
- Segelquist CA, Scott ML, Auble GT, 1993. Establishment of *Populus deltoides* under simulated alluvial groundwater declines. *American Midland Naturalist*: 274-285.
DOI:10.2307/2426127
- Shaw RK, 1976. A taxonomic and ecologic study of the riverbottom forests on St. Mary River, Lee Creek, and Belly River in southwestern Alberta, Canada. *The Great Basin Naturalist*, 36(3): 243-271.
- Shields Jr DF, Simon A, Steffen LJ, 2000. Reservoir effects on downstream river channel migration. *Environmental Conservation*, 27(01): 54-66.
DOI:10.1017/S0376892900000072
- Smith DG, 1979. Effects of channel enlargement by river ice processes on bankfull discharge in Alberta, Canada. *Water Resources Research*, 15(2): 469-475.
DOI:10.1029/WR015i002p00469

- Stromberg JC, Patten DT, 1996. Instream flow and cottonwood growth in the eastern Sierra Nevada of California, USA. *Regulated Rivers: Research & Management*, 12(1): 1-12. DOI:10.1002/(SICI)1099-1646(199601)12:1<1::AID-RRR347>3.0.CO;2-D
- Tockner K, Stanford JA, 2002. Riverine flood plains: Present state and future trends. *Environmental conservation*, 29(03): 308-330. DOI:10.1017/S037689290200022X
- VanHaverbeke D, 1990. *Populus deltoides* var. *occidentalis* Rydb.: Plains Cottonwood. In: Burns, R., Honkala, B. (Eds.), *Silvics of North America: Volume 2. Hardwoods*. United States Department of Agriculture (USDA), Forest Service, Agriculture Handbook 654, pp. 536-543.
- Winterbottom SJ, 2000. Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. *Geomorphology*, 34(3-4): 195-208. DOI:10.1016/S0169-555X(00)00007-6

CHAPTER 4: COTTONWOOD GROWTH, CLIMATE, AND STREAMFLOW MANAGEMENT ALONG THE LOWER RED DEER RIVER

4.1 Introduction

In the semi-arid prairies of southern Alberta, the limited availability of reliable water resources restricts the survival of most tree species. The exception to this is riparian or streamside cottonwoods. Cottonwoods provide a woodland ecosystem in an otherwise treeless environment and contain a level of biodiversity and productivity not found elsewhere in the prairie landscape (Finch and Ruggiero, 1993; Knopf et al., 1988; Sabo et al., 2005). The ability of cottonwoods to survive in riparian environments can be attributed to their ability to tap into alluvial water supplied by adjacent rivers (Rood et al., 2011). This dependence on alluvial aquifers makes cottonwoods particularly sensitive to both natural and anthropogenic changes in streamflow.

Declines in riparian ecosystems and cottonwood populations in western North America have been found to be due, in part, to the impoundment and diversion of streamflow (Patten, 1998; Rood and Heinze-Milne, 1989; Stromberg, 1993). Cottonwood recruitment and survival is adapted to natural streamflow patterns. Periodic floods mobilize and deposit sediments along rivers providing ideal sites for cottonwood seeds to germinate and grow with little competition (Auble et al., 1997; Braatne et al., 1996). Following floods, the natural slow recession of streamflow facilitates root growth and allows seedlings to remain in continual contact with saturated soil (Mahoney and Rood, 1993; Rood et al., 2003). The construction of dams and diversions along rivers can disrupt these vital processes, which can lead to deficiencies in seedling recruitment, a factor identified as predominant in the progressive decline of cottonwood populations (Braatne et al.,

2007; Bradley and Smith, 1986; Polzin and Rood, 2000). However, as trees mature they continue to depend on shallow alluvial water and, in addition to limiting recruitment, changes in streamflow can also have a substantial impact on the health and survival of established cottonwoods within woodlands (Amlin and Rood, 2003; Shafroth et al., 2000; Stromberg et al., 1996).

River de-watering for human uses can lead to prolonged stress and result in the reduction of tree growth, cause canopy dieback, and potentially lead to mortality (Reily and Johnson, 1982; Rood et al., 2000; Scott et al., 1999; Stromberg et al., 1996; Tyree et al., 1994). Older trees in particular, can be susceptible to drought-induced stress and mortality (Albertson and Weaver, 1945). Along the St. Mary River in southern Alberta, the construction of the St. Mary Dam in 1951 for the storage and diversion of water for irrigation lead to dramatically reduced summer flows and subsequently caused widespread drought-induced mortality of cottonwoods downstream (Rood et al., 1995). The St. Mary River represents a particularly extreme case where a narrow valley and coarse substrates combined with severe dewatering resulted in abrupt streamflow and water table reductions. In most cases streamflow modifications are less extreme. Along the Yakima River in Washington state, USA, regulated flow resulted in a substantial reduction in the recruitment of cottonwoods but did not hinder growth of established trees (Braatne et al., 2007). Foster (2016) found that the occurrence of drought and increased water demand for irrigation along the Waterton River in the 1980s resulted in substantially lower tree growth in cottonwoods downstream of the Waterton Dam compared to upstream. However, it was also found that following the implementation of environmental flows and an increase in minimum discharges, growth of upstream and

downstream trees was similar, even after a subsequent period of drought in the early 2000s (Foster, 2016). This variability demonstrates that it is not the mere presence of a dam that causes stress and mortality of riparian trees along regulated rivers but it is rather the pattern of streamflow management that results in these impacts (Braatne et al., 2007; Mahoney and Rood, 1998).

In this study, we employ dendrochronology to analyze the impact the construction of the Dickson Dam in 1983 has on streamflow and cottonwood growth along the lower Red Deer River through Dinosaur Provincial Park. The Red Deer River presents a unique case in southern Alberta. It is the only major river that is not fully allocated and, unlike most dams in southern Alberta, the Dickson Dam is not primarily operated for hydro power or for agricultural purposes, namely irrigation. The Dickson Dam rather functions to capture and store water during the spring and summer for release during the winter. In doing so, the Dickson Dam restricts streamflow during the growing season. The impact this has on the growth of these downstream cottonwoods is currently unknown.

Dendrochronological studies along the Red Deer River are limited. Marken (1993) and Cordes et al. (1993, 1997) employed dendrochronology to age cottonwoods and identify historic cottonwood recruitment events along different sections of the Red Deer River. In another study, Smith and Reynolds (1983) used tree cores, wedges, and cross sections of cottonwoods collected along the Red Deer River near Red Deer to assess the stage and frequency of ice drives. These studies, however, did not consider growth of cottonwoods and the relationship between tree growth, streamflow and climate. Natural variability in tree growth with climatic cycles, such as the Pacific Decadal Oscillation (PDO), can be substantial (Rood et al., 2013; Whitfield et al., 2010). Understanding the potential impacts

of management on riparian ecosystem requires and integrated understanding of these relationships.

4.1.1 Study site

The lower Red Deer River flows through the semiarid shortgrass prairie of southern Alberta. This region receives little precipitation, less than 350 mm a year, much of which is sourced from short, moderately intense, convectional rainstorms (Bryan and Campbell, 1980). Summers temperatures can be very warm with an average maximum temperature of 25°C in June, July and August. The combination of a warm summer climate and lack of reliable precipitation makes cottonwood growth and survival highly dependent on water sourced from adjacent streamflow of the Red Deer River.

Floodplains within Dinosaur Provincial Park contain some of the largest and least disturbed cottonwood populations in southern Alberta and are a contributing factor in the parks designation as a UNESCO World Heritage Site (Bradley et al., 1991). The woodlands are primarily composed of pure stands of plains cottonwood (*Populus deltoides*), some of which are well over 200 years of age (Figure: 4-1). *P. deltoides* are particularly sensitive to groundwater recession and are consequently likely to be very sensitive to streamflow alterations (Cleverly et al., 2006; Cooper et al., 2003; Stromberg and Patten, 1996). Additionally, the lower Red Deer Rive represent the most northern and westerly extension of plains cottonwood in North America (Brayshaw, 1965). Growth of floodplain trees at the edge of their geographic distribution is likely to be particularly sensitive to alterations in streamflow (Johnson et al., 1976).



Figure 4-1: Plains cottonwood along the Red Deer River within Dinosaur Provincial Park, Autumn 2015. (Photos: N. Philipsen)

The Dickson Dam is a low capacity dam forming the Gleniffer Reservoir. It is situated about midway between Sundre and Red Deer, approximately 300 km upstream of Dinosaur Provincial Park, and is the only dam along the Red Deer River. Prior to the construction of the Dickson Dam, dissolved oxygen levels in the river would occasionally fall dangerously low during the winter months due to heavy loading of organic substances, particularly during ice cover (Baker and Telang, 1985). The operations of the Dickson Dam were designed to address this issue by sustaining winter flows at 16 m³/s (Clipperton et al., 2003).

The majority of streamflow in the Red Deer River originates from the Rocky Mountains and, while Dinosaur Provincial Park is located far downstream of the Dickson Dam, over 80% of the annual average discharge at the park is sourced upstream of the dam. Consequently, management at the Dickson Dam has direct impact on streamflow and, consequently, the woodlands within Dinosaur Provincial Park.

4.2 Methods

4.2.1 Cottonwood core collection and processing

During the summers of 2014 and 2015 trees varying in size and location were cored throughout floodplains in Dinosaur Provincial Park. Trees composed of a single main trunk and appeared to be representative of trees within a distinct arcuate band were selected for coring. Arcuate bands of cottonwoods indicate sequential recruitment events (Rood et al., 1998). A single core was extracted from the south side of each tree using a 5.15 mm diameter Swedish increment borer at approximately 30 cm above the ground surface, the lowest possible height while allowing for sufficient room for the rotation of

the increment borer. Core extraction near the base allows for the inclusion of the earliest rings and a better estimation of the year of establishment. While trees with extensive heart rot were excluded from analysis, trees with rot in only a few of the innermost rings were kept for analysis.

Cores were cut laterally using a razor blade and radial growth increments (RI) were measured using a dissecting microscope (10-40x), Velmex stage, Acu-Rite encoder (0.002 mm precision) and MeasureJ2X version 5.0 software (VoorTech Consulting, Holderness, New Hampshire). As trees do not grow radially symmetrically, the pith in some cores was missed during the coring process or was not present due to heart rot. In these cases, a concentric circle ruler printed on a transparency was used to estimate the missing distance and rings from the pith (Applequist, 1958).

To determine the age of each tree, the number of rings were summed and six additional years were added to account for the 30 cm extraction height and for the burial of growth years by sediment deposition (Marken, 1993).

For analysis, in addition to RI, basal area increment (BAI) in $\text{mm}^2\text{year}^{-1}$ was calculated. RI — a linear measurement — does not account for the ever-increasing diameter of trees, consequently, BAI is often used in forest growth analyses as it provides an approximation of total annual wood production (Biondi and Qeadan, 2008; Hornbeck and Smith, 1985; West, 1980).

In dendrochronology, the ‘juvenile effect’ — the rapid growth of young trees — can impact variation in chronologies, causing increases in growth that are not related to environmental factors (Fritts, 1976). Sampling strategies are often designed to minimize

this effect (Monserud and Marshall, 2001). In young trees, the period of accelerated growth can vary between species, individuals and locations. For plains cottonwood in Dinosaur Provincial Park, we found that, on average, growth started to plateau around 40 years of age. To minimize the juvenile effect on chronologies, we limited our analyses to tree growth that occurred when trees were 40 years of age or greater.

Autocorrelation is common in tree ring series (Fritts, 1976). Growth processes such as bud formation, production of growth hormones and storage of photosynthates can have a significant impact on the growth of subsequent years (D'arrigo and Jacoby, 1992).

Consequently, a year with poor climatic conditions for growth can display average, if not above average, growth if previous years' conditions were optimal. Accounting for autocorrelation or, in this case, biologically related persistence, is necessary for most statistical analyses (Monserud, 1986). For our analyses, we “post-whitened” our data, whereby average annual BAI values were calculated first before being subsequently adjusted to account for autocorrelation. While pre-whitening — the application of models to individual tree ring series before computing the mean — is preferred as it dampens the influence of individual trees on the master chronology, post-whitening is not an uncommon technique and appeared to work for this analyses (Monserud, 1986).

Adjusting for autocorrelation first involved detrending the series using linear regression and then fitting the series with a first order autoregressive model (AR(1)) (Riitters, 1990). The detrended series was then subtracted from the values forecasted by the AR(1) model to produce a residual chronology for analyses. Different autoregressive moving average models (ARMA) (Box and Jenkins, 1970) were explored, but the AR(1) model was determined to provide the best results.

4.2.2 Hydrology and climate

The association of tree growth with streamflow and various climatic factors, including evapotranspiration, precipitation and the PDO was explored using Pearson Product Moment correlations. Streamflow and most climatic data was available from 1912 to 2013 and correlations were limited to this period. Streamflow data for the Red Deer River at Red Deer (05CC002) was obtained from HYDAT, the Water Survey of Canada's Hydrological Database (<http://wateroffice.ec.gc.ca/>). Approximate evapotranspiration (ETP) during the summer (June, July, August) was calculated using the Hargreaves equation (Hargreaves and Samani, 1985). Average monthly minimum and maximum temperatures recorded at meteorological stations located at Brooks, Alberta (<http://climate.weather.gc.ca/>) were used in the computation. Annual precipitation (PPT) was also obtained using metrological station located at Brooks. PDO values were obtained from the PDO directory constructed by Mantua (2000) (<http://research.jisao.washington.edu/pdo/>). As the PDO is a long term cycle, with cycles persisting for 20–to–30 years, a five year moving average of PDO indices was used for analyses (Mantua et al., 1997).

Tree growth (BAI), annual discharges, minimum monthly discharges, ETP and the PDO were compared 30 years before (1953-1982) and after the construction of Dickson Dam (1984 to 2013). The year the dam was constructed, 1983, was not included in the analysis. Differences in means were tested using the Wilcoxon signed-rank test. All statistical analyses were preformed using SPSS v.19 (IBM, Armonk NY).

4.3 Results

4.3.1 Tree growth

Cottonwood growth varied substantially with age. On average, BAI appears to increase for the first 40 years of growth and then slowly decreases and plateaus thereafter before reaching approximately 100 years of age at which point there is another apparent increase in BAI (Figure 4-2). Consequently, basal area — the area occupied by the tree stem — rapidly increases during the first few growth years, plateaus as trees age, and at about 100 years of age, increases again (Figure 4-3). The apparent increase in BAI at approximately 100 years of age is also evident when the analysis is limited to trees with an age of greater than 150 years (Figure 4-4).

Average RI and BAI growth for mature trees greater than 40 years old was 1.78 mm and 11.6 cm², respectively. This is comparable to growth of cottonwoods along the Oldman River (Rood et al., 2013; Willms et al., 2006). Both RI and BAI were highly variable, showing periodic and cyclical patterns of faster and slower growth (Figure 4-5). Between 1842 and 2013, average RI growth stayed relatively consistent. This does not, however, translate into consistent total growth as RI does not account for the progressive expansion of trunk area. Consequently, while RI growth remains relatively steady, BAI growth increases between 1842 and 2013.

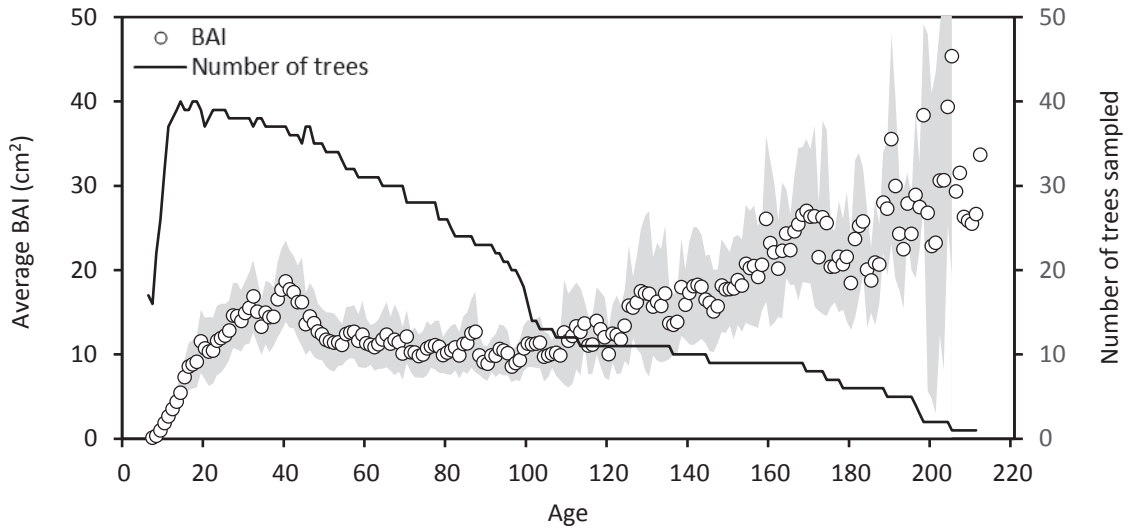


Figure 4-2: Average basal area increment growth of cottonwoods growing along the Red Deer River in Dinosaur Provincial Park by age. The shaded area represents 95% confidence intervals.

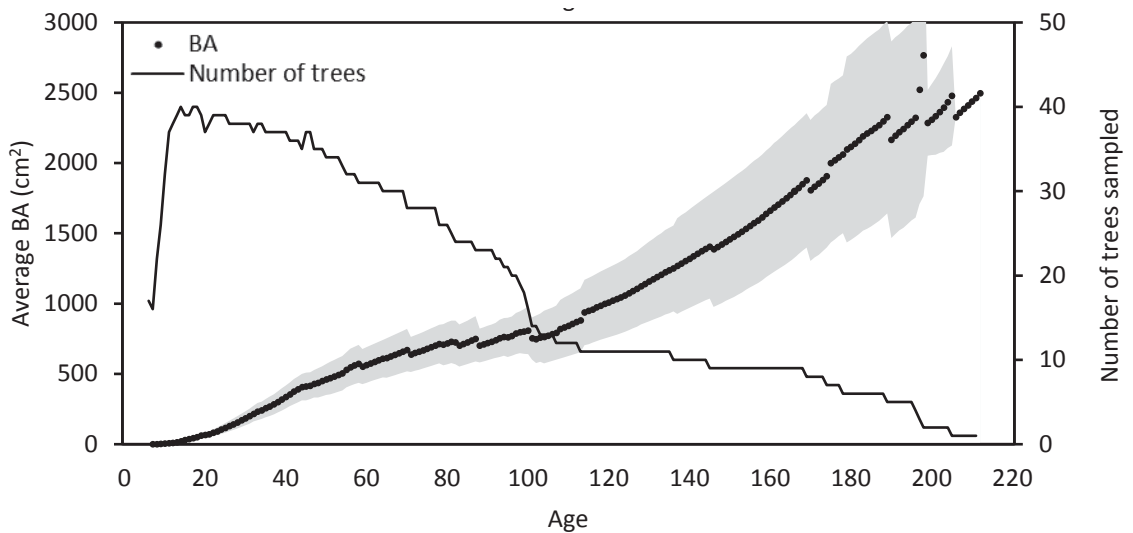


Figure 4-3: Average basal area of cottonwoods growing along the Red Deer River in Dinosaur Provincial Park by age. Note the apparent inflection at approximately 100 years of age. The shaded area represents 95% confidence intervals.

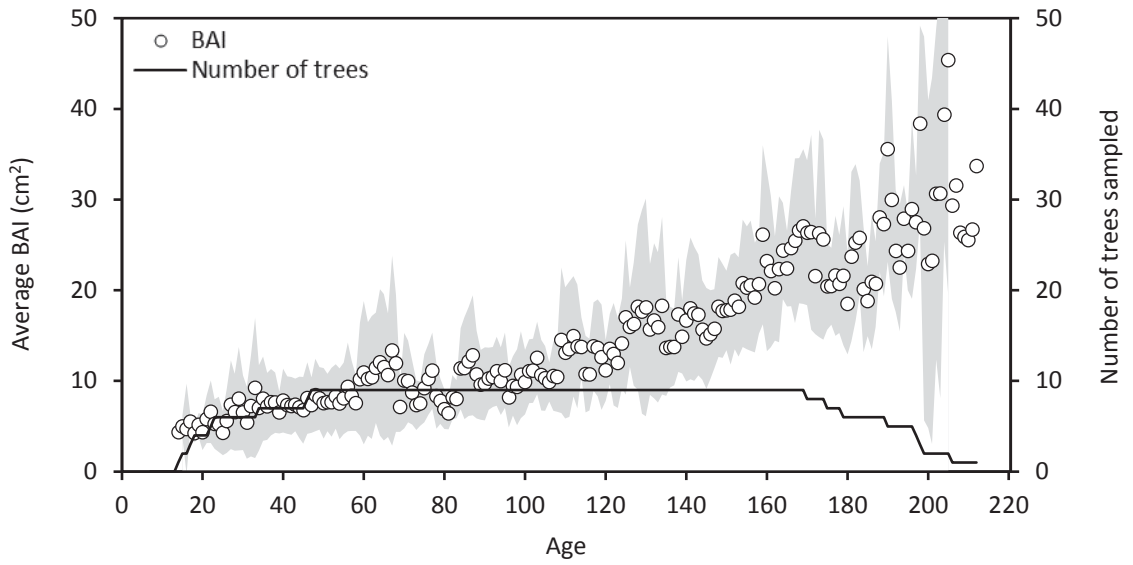


Figure 4-4: Average basal area increment growth of cottonwoods older than 150 years growing along the Red Deer River in Dinosaur Provincial Park by age. The shaded area represents 95% confidence intervals.

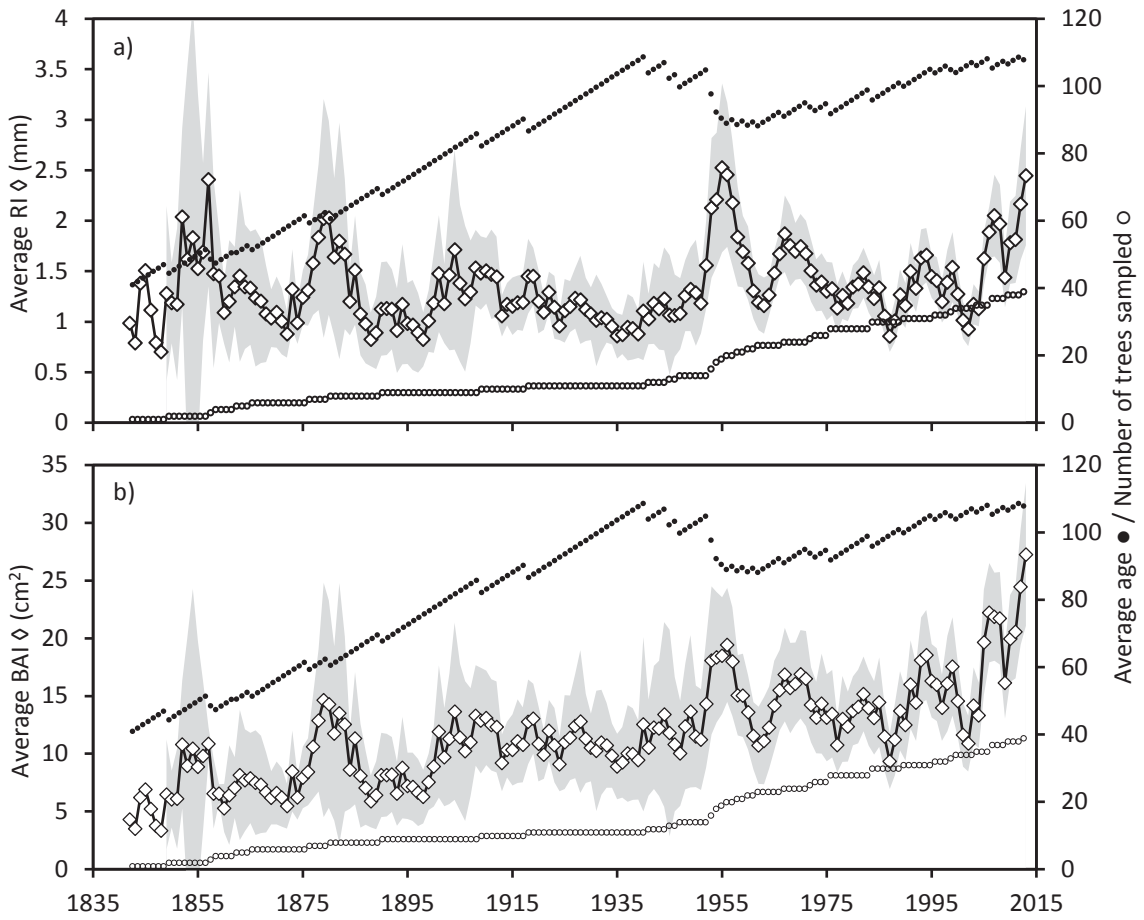


Figure 4-5: (a) Average radial increment growth and (b) average basal area increment growth of cottonwoods from 1842 to 2013 sampled along the Red Deer River. Averages were limited to growth that occurred when trees were of 40 years of age or greater. Shaded area represents 95% confidence intervals.

4.3.2 Correlations

The residual BAI chronology was strongly correlated with streamflow from 1912 to 2013 (Table 4-1) (Figure 4-6) and was also positively correlated with precipitation (Figure 4-7a). There was no correlation with Hargreaves derived evapotranspiration (Figure 4-7b) or the PDO (Figure 4-7c). Residual BAI values were, however, negatively correlated with evapotranspiration when it was lagged by one year.

Similar to the residual chronology, unadjusted BAI and RI values were significantly correlated with annual average discharge, but, unlike the residual chronology, were also (negatively) correlated with the PDO (Table 4-1). RI growth in particular, displayed a stronger negative correlation with the PDO. BAI and RI were also negatively correlated with both evapotranspiration and lagged evapotranspiration. Unadjusted BAI and RI values were not correlated with precipitation.

Evapotranspiration, annual average discharge, and precipitation were not correlated with the PDO, however, they were all correlated with each other, with precipitation and annual discharge being positively correlated with each other and negatively correlated with evapotranspiration. A 5-year moving average of annual average discharge was significantly negatively correlated with the PDO (Table 4-1).

Table 4-1: Pearson correlation analysis between radial increment growth (RI), basal area growth (BAI), basal area growth residuals (BAIR), log transformed annual discharge (Q), log transformed annual discharge 5-year moving average (Q_{5ma}), Hargreaves evapotranspiration (ETP), lag 1 evapotranspiration (ETPL), precipitation (PPT), and the Pacific Decadal Oscillation (PDO) from 1912 to 2013. The correlation coefficients (r^2) are below and the p-values are above the diagonal. Statistically meaningful patterns are distinguished using three levels of confidence: a probable trend (*t*) for $p < 0.1$, a significant pattern (*) for $p < 0.05$ and a highly significant pattern (**) for $p < 0.01$.

	RI	BAI	BAIR	Q	Q_{5ma}	ETP	ETPL	PPT	PDO
RI	–	<0.001	<0.001	0.034	0.004	0.016	<0.001	0.847	<0.001
BAI	0.820**	–	<0.001	0.024	0.005	0.019	<0.001	0.497	0.001
BAIR	0.235**	0.321**	–	<0.001	<0.001	0.215	0.022	0.006	0.167
Q	0.044*	0.050*	0.127**	–	<0.001	0.045	0.030	0.004	0.119
Q_{5ma}	0.080**	0.079**	0.168**	0.371**	–	0.615	0.187	0.099	<0.001
ETP	0.057*	0.053*	0.015	0.040*	0.003	–	<0.001	<0.001	0.818
ETPL	0.120**	0.116**	0.052*	0.047*	0.018	0.268**	–	0.613	0.843
PPT	<0.001	0.006	0.091*	0.099*	0.033 ^t	0.196**	0.003	–	0.697
PDO	0.235**	0.108**	0.019	0.024	0.106**	0.001	<0.001	0.002	–

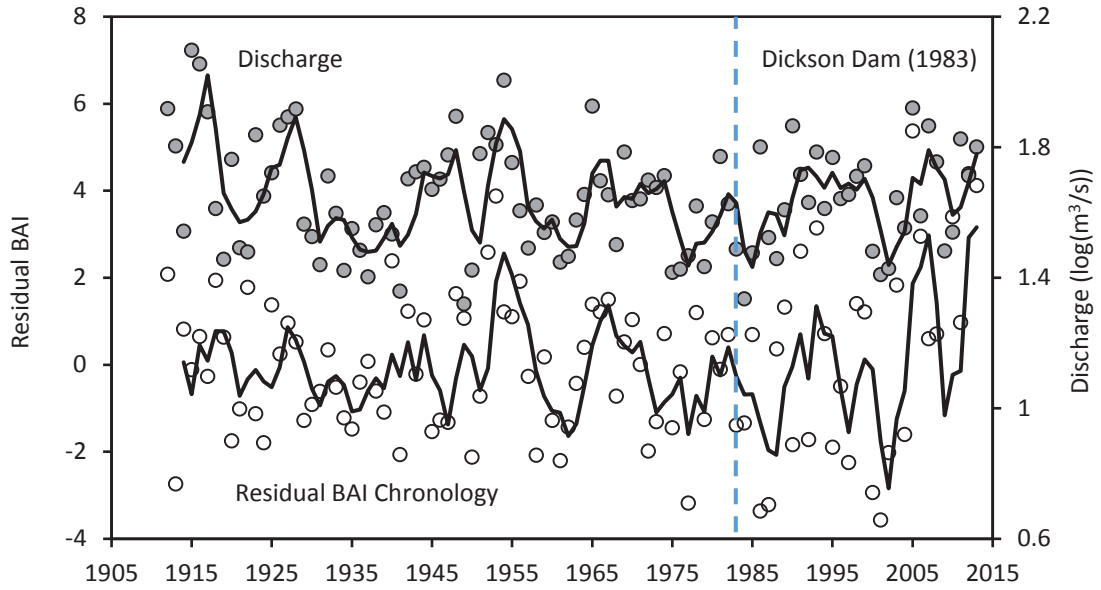


Figure 4-6: Annual average discharge for the Red Deer River at Red Deer and basal area increment growth residual chronology (1912 – 2013). Solid lines represent 3 year moving averages ($r^2 = 0.34$). Vertical dashed line indicates the year the Dickson Dam was completed.

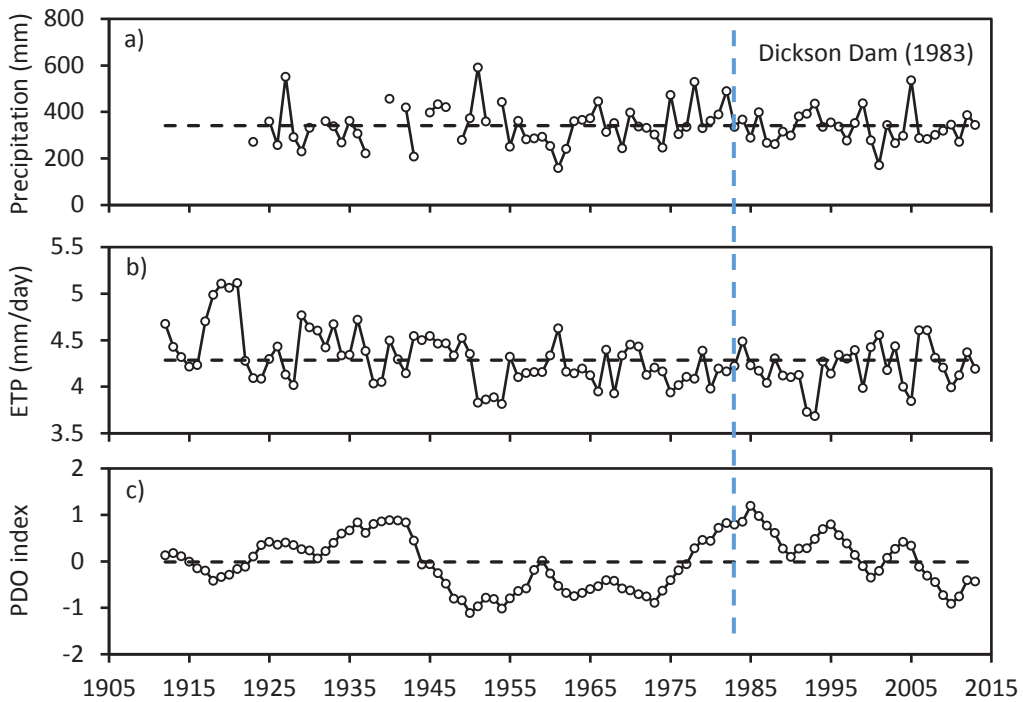


Figure 4-7: (a) Annual precipitation as gauged at Brooks, Alberta, (b) average summer daily evapotranspiration for Brooks, Alberta, and (c) 5-year moving average of the PDO index. The vertical dashed line indicates the year the Dickson Dam was completed. The horizontal dashed lines represent the mean.

4.3.3 Pre- and post-dam comparison

Unadjusted average BAI values were slightly greater 30 years before the construction of the dam as compared to afterward. Conversely, for the BAI residual chronology, average growth appeared to be slightly lower before the construction of the dam than afterward. Differences, however, were not found to be statistically significant (Table 4-2).

Average annual streamflow before and after the construction of the Dickson dam was very similar and did not differ. Summer evapotranspiration and precipitation were also very comparable before and after and means were not different.

The only factor that differed significantly for the 30 years before the construction of the Dickson Dam compared to after was the five moving average of the PDO. The majority of the period before the construction of the Dickson Dam, from 1953 to 1982, appears to be in a cool phase of the PDO and the period after, from 1984 to 2013, a warm phase.

For average monthly minimum flows, post-dam streamflow was significantly greater than pre-dam for the months of November, December, January, February, March and April (Figure 4-8). Pre-dam minimum flows were only found to be significantly greater than post-dam for the month of June. Compared to other months, average minimum flows for August and September were found to be the most similar pre-and-post dam.

Table 4-2: Mean values of basal area increment growth, basal area increment residuals, annual discharge (Q), evapotranspiration (ETP), precipitation (PPT) and the Pacific Decadal Oscillation (PDO) index before (1953-1982) and after (1984-2013) the construction of the Dickson Dam. Significant differences were tested using the Wilcoxon signed-rank test. Correlation significant at a 95% confidence level.

	Mean		Z	p
	1953 - 1982	1984 - 2013		
BAI	13.6	13.2	-0.339	0.734
BAI residuals	-0.166	0.115	-0.566	0.572
Annual Q	44.8	46.8	-0.771	0.441
ETP	4.17	4.21	-0.874	0.382
PPT	341	332	-0.681	0.496
PDO index	-0.364	0.159	-2.58	0.01

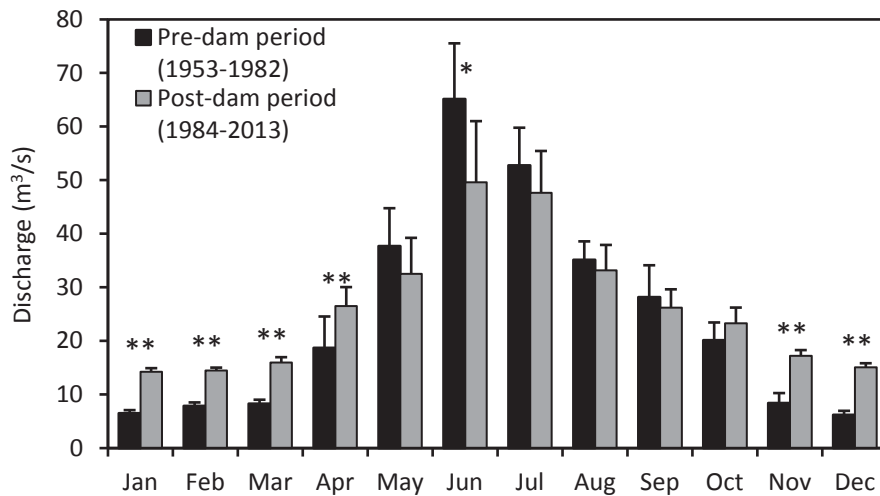


Figure 4-8: Average monthly minimum flows for the Red Deer River at Red Deer before (1953-1982) and after (1984-2013) the construction of the Dickson Dam. Significant differences are indicated (Wilcoxon signed-rank, * $p < 0.05$, ** $p < 0.01$). Error bars represent 95% confidence intervals.

4.4 Discussion

While there is natural variability in streamflow and cottonwood growth, dams and diversions can lead to dewatering and alterations to the natural streamflow pattern that can cause prolonged stress in cottonwoods. This has been a contributing factor in the decline of riparian woodlands downstream of dams and diversions along many rivers in Southern Alberta (Rood and Heinze-Milne, 1989; Rood et al., 1995). Fortunately, it is the pattern of management rather than the mere presence of a dam that result in these impacts and efforts to introduce environmentally beneficial flows have been largely successful in the recovery of cottonwoods (Braatne et al., 2007; Rood et al., 1998; Rood et al., 2016; Rood et al., 2005). Along the Red Deer River, the impact of water management on cottonwood growth has not been studied and operations of the Dickson Dam have continued mostly unchanged since 1983. The intent of this study was to identify if streamflow alterations following construction of the Dickson Dam along the Red Deer River have impacted growth of cottonwoods downstream. Understanding the relationship between streamflow, management and tree growth will aid in our understanding of how streamflow alterations affect riparian woodlands and help us to manage streamflow in a way that minimizes environmental impacts.

4.4.1 Tree growth patterns

The growth of trees typically approximates a sigmoidal curve, with an accelerated growth rate during the first few years of growth followed by a decreasing growth rate as trees mature and age (Fritts, 1976; Weiner and Thomas, 2001). Along the Oldman River in Alberta, Willms et al. (2005) observed a slightly different pattern for cottonwoods, identifying four growth phases: 1) the establishment phase, characterized by slow shoot

growth as seedling preferentially allocate resources for root growth, 2) growth acceleration once roots are established, 3) peak growth at about 20 years of age, and 4) mature growth, characterized by relatively consistent BAI. This characterization of growth, however, did not extend past 40 years of age and while growth of plains cottonwood along the lower Red Deer River begin to follow this pattern, with accelerated growth until approximately 40 years of age and decreasing growth thereafter, at approximately 100 years of age another apparent transition occurs and growth begins to increase once again. This was unexpected and is likely the result of tree growth being released from the constraints of competition with neighboring trees (Figure 4-3). Plains cottonwood, like those in Dinosaur Provincial Park, typically only live to be 100 years of age and as they die trees within a stand — in this case, a recruitment band (Rood et al., 1998) — they are not replaced (Shaw, 1976). This is because sexual reproduction rarely occurs within established stands and asexual reproduction in form of suckering is uncommon for plains cottonwood (Rood et al., 1994). Consequently, competition between trees slowly decreases with stand age as less robust trees die and the stand thins. Growth in the superior trees that are left subsequently accelerates, as there is greater space for canopy expansion and less competition for resources such as water. Release from competition can be readily observed in many older trees, with some trees, many of which were greater than 200 years of age, having very large and dense canopies (Figure 4-9).

Epicormic branches may also play a role in the acceleration of BAI in some trees.

Epicormic branches are formed from dormant buds on shoots of previous growth (Meier et al., 2012). Their formation has been generally attributed as a response to light exposure

from pruning or thinning, or from a sudden stress, such as fire or crown dieback, and have been shown to be an important component in maintenance of aging crowns (Blum, 1963; Burrows, 2008; Lanner, 2002; Remphrey and Davidson, 1992). In cottonwoods, crown dieback is a common response to drought stress, especially in older trees (Rood et al., 2000). Damage to the crown and the collapse of branches from other factors, such as wind, can result in substantial epicormic shoot production. Similar to coppice growth, regrowth from epicormic shoots is considerably more rapid than initial shoot growth, providing a form of rejuvenation which would likely enhance tree BAI growth (Dickmann and Stuart, 1983; Lanner, 2002).

An additional contributor to the formation of epicormic shoots is wildlife activity. In some mature trees, vigorous shoot production appeared to be the result of extensive girdling of branches in the canopy from porcupine browsing (Figure 4-10). This activity, while harmful in the short-term, may enhance growth by inducing shoot production.



Figure 4-9: Cottonwood in Dinosaur Provincial Park greater than 200 years of age with a large canopy displaying extensive shoot production. December 2015. (Photo: L. Philipsen)



Figure 4-10: Cottonwood in Dinosaur Provincial Park showing extensive shoot production in response to porcupine browsing. February 2016. (Photo: L. Philipsen)

4.4.2 Streamflow and tree growth

Tree growth was found to be best correlated with annual average discharges. Correlations with different periods of streamflow, including average growing season (May-October) and summer streamflow, were explored but did not have as strong a relationship with tree growth as annual streamflow. Other studies on riparian tree growth have returned similar results (Stromberg, 2001; Stromberg and Patten, 1990). It has been suggested that this is the result of streamflow outside the growing season contributing to aquifer recharge which would subsequently help to maintain higher water table levels in the summer and increase the availability of water for tree growth (Stromberg, 2001). Additionally, when only summer streamflow is considered, large, short duration flood events can greatly increase the average streamflow. This greater than average streamflow may not accurately reflect the streamflow for the entire growing season.

As cottonwood tree growth is often linked to streamflow (Amlin and Rood, 2003; Shafroth et al., 2000; Stromberg et al., 1996), it is likely that alterations in streamflow would have a direct impact on downstream cottonwood growth; however, when tree growth was compared before and after the construction of the Dickson Dam, no significant differences were found (Table 4-2).

Annual streamflow did not differ before and after the construction of the Dickson Dam (Table 4-2). This was expected as the Dickson Dam does not divert water and the relatively small reservoir, the Gleniffer Reservoir, has little year to year carry over. Consequently, while the pattern of streamflow may change, total annual streamflow remains the same. More important than the annual volume of streamflow for tree growth, is minimum flows during the growing season. Stream dewatering, particularly during the

hot and dry period of mid-to-late summer, has been found to be a substantial contributor to cottonwood stress and mortality (Rood et al., 2003). For the Red Deer River, this does not appear to be a problem, with pre-and-post dam monthly minimum streamflow being very similar for the months of August and September (Figure 4-8). The only significant difference between pre-and-post monthly minimum streamflow was in June. This is likely when the reservoir captures and stores the majority of water for release in the winter. June streamflow is significantly greater than streamflow in the late summer. By capturing streamflow in June, the Dickson Dam does not dewater the river to a point where it would impact tree growth. If the reservoir was filled later in the growing season when natural streamflow volume is substantially lower, the Dickson Dam may have an impact on tree growth, but dewatering would have to be extreme with ground water depths being considerably reduced (Horton et al., 2001).

4.4.3 Other climatic factors

Understanding the potential impacts of streamflow management on riparian cottonwoods requires an integrated understanding of the relationship between tree growth and other climatic factors in addition to streamflow. We analyzed the relationship of tree growth with precipitation, evapotranspiration and a long-term climatic cycle, the pacific decadal oscillation.

Adjusted BAI was significantly correlated with precipitation (Table 4-1). However, this correlation is likely not causal. It is well established that riparian cottonwoods primarily rely on ground water sourced from adjacent streamflow for growth rather than from precipitation (Busch et al., 1992; Mahoney and Rood, 1998; Orchard, 2015). This is especially true in arid and semi-arid regions, such as the lower Red Deer River, where

precipitation alone is not abundant enough and too intermittent to support the growth of large trees (Rood et al., 2011). It is more likely the positive association between precipitation and tree growth is the result of wet years also being correlated with years of lower evapotranspiration and greater streamflow rather than precipitation directly increasing water availability and, subsequently, tree growth.

Unlike precipitation, evapotranspiration has a more direct impact on cottonwood tree growth. Adjusted BAI was significantly correlated with evapotranspiration when it was lagged by one year (Table 4-1). This suggests that years of greater evapotranspiration and drought stress have a greater impact on the subsequent years of growth rather than the current year. This is likely due to drought stress reducing photosynthate storage important for tree growth processes in the following year (D'arrigo and Jacoby, 1992).

The Pacific Ocean is a major source of moisture for precipitation in Southern Alberta, especially during the winter (Gobena and Gan, 2009). As the majority of streamflow in southern Alberta is derived from snowmelt, the PDO — the dominant pattern of North Pacific sea surface temperature variability — can have a substantial impact on streamflow volumes and, consequently, tree growth (Mantua et al., 1997). This is evident by the correlation between RI growth, BAI growth, and a 5-year moving average of annual discharge, with the PDO (Table 4-1). Warm cycles in the PDO generally result in drier conditions and lower streamflow and cooler cycles generally result in greater streamflow (Mantua and Hare, 2002; Whited et al., 2007). The 30-year period before the construction of the Dickson Dam was characterized by a cool cycle and after a warm cycle. This, however, likely does not have a substantial enough impact on annual streamflow before

and after the construction of the Dickson Dam to impact tree growth and is consequently not a confounding factor in our analysis.

We also found that the PDO was not correlated with the adjust BAI (Table 4-1). This was expected as the PDO impacts climate on a decadal scale and long term trends in tree growth resulting from the PDO are likely removed through the “whitening” process.

Compared to the more southern rivers in the South Saskatchewan River Basin, the correlation between streamflow and the PDO is less strong (Rood et al., 2013; St. Jacques et al., 2010). A relatively small proportion of the Red Deer River lies within the Rocky Mountains and, while snowmelt still is the main contributor to streamflow, a substantial proportion of streamflow is sourced from rainfall. Consequently, as the PDO is primarily associated winter precipitation, cycles in the PDO index will have less of an impact on streamflow of the Red Deer River.

4.4.4 Streamflow and climate reconstruction potential

The sensitivity of tree growth to the above mentioned climatic factors provides an opportunity to reconstruct a history of the climate and streamflow of the Red Deer River. Trees act as sentinels of environmental change (Briffa, 2000). Within their annual growth rings, trees record sequences of favourable and unfavourable conditions over time (Fritts, 1976). In certain locations, where growth is limited by specific physical factors, such as the availability of water in semi-arid regions, the response of tree growth to environmental change can be particularly strong, producing considerable variation in growth rings (Fritts, 1976). Correlations with streamflow, evapotranspiration and other climatic indices can provide a history of the recurrence of extreme events, like droughts,

and can reveal both oscillating and directional climatic changes (Axelson et al., 2009; Rood et al., 2013).

Dendroclimatological analyses of riparian cottonwoods have typically been avoided for a variety of reasons (Edmondson et al., 2014). Tree ring identification is often difficult as cottonwoods produce faint, double and complacent rings (Everitt, 1968; Fritts, 1976). Woodlands are often heavily impacted by human activities (Johnson and Haight, 1984). And most populations lack trees over 150 years old (Bradley and Smith, 1986). However, this is not always the case. Along the Little Missouri River in western North Dakota, Edmondson et al. (2014) were able to construct a 368-year tree-ring chronology using plains cottonwood. Their success was attributed to a cold dry climate facilitating the presence of slow-growing trees in excess of 250 years of age that produced distinct annual rings with substantial inter-annual variability. This tree ring chronology provides an *in situ* climate proxy in a region lacking in trees and typically avoided for dendrochronological analysis (Edmondson et al., 2014).

Similar to North Dakota, the prairies of western Canada have few tree-ring chronologies with most analyses being limited to the eastern slopes of the Rocky Mountains (Figure 4-11). Woodlands along the Red Deer River may provide an opportunity to fill this gap. Along the lower Red Deer River, riparian woodlands contain the most northern and westerly extension of plains cottonwood and, like cottonwoods along the Little Missouri River, the cold dry climate facilitates the survival of exceptionally old trees (Brayshaw, 1965). In Dinosaur Provincial Park, the oldest cottonwoods were found to have diameters up to 167 cm with ages likely in excess of 250 years. This is contrary to generally accepted notion that cottonwoods grow fast and die young (Edmondson et al., 2014).

While not the primary focus of this study, our analysis allowed us to produce a 172-year tree ring chronology that displayed substantial annual variability with climate (Figure 4-12). This chronology demonstrates the dendrochronological potential of cottonwoods along the lower Red Deer River to provide an *in situ* reconstruction of climatological variables, such as streamflow, for the prairies.

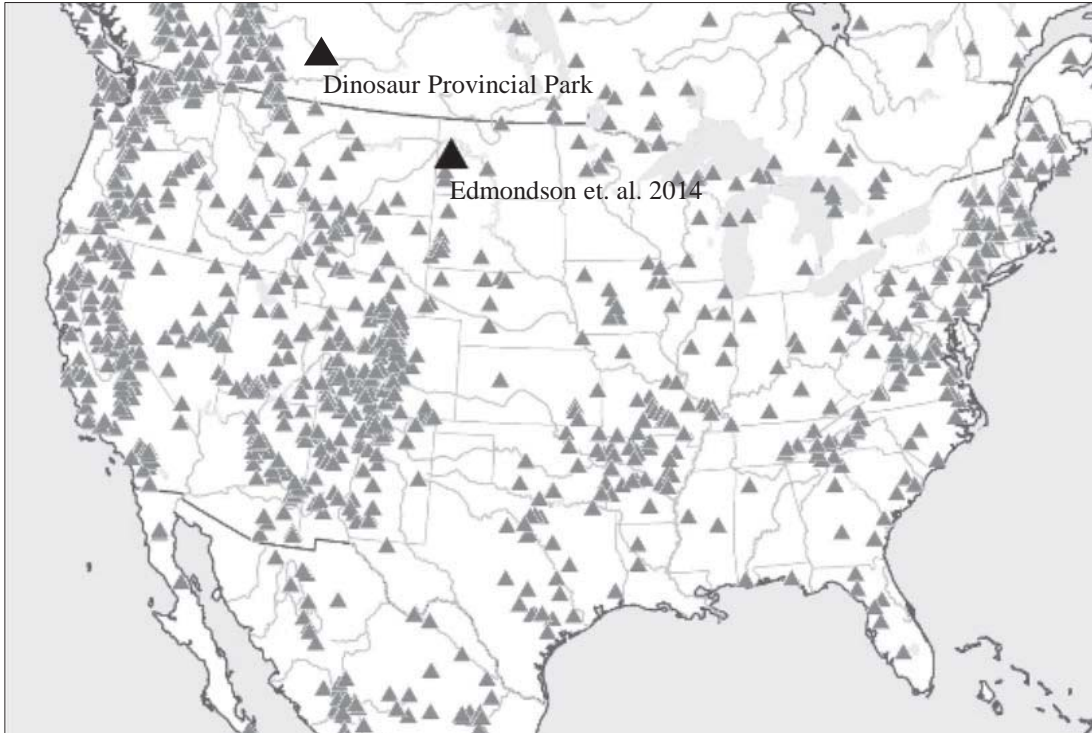


Figure 4-11: Tree ring chronologies from the International Tree-Ring Data Bank (2012) extending before 1800 for North America. The location of the Edmondson et al. (2014) *P. deltoides* chronology and Dinosaur Provincial Park are indicated. Note the substantial gap in tree ring chronologies within the prairies of western Canada. Figure adapted from Edmondson et al. (2014).

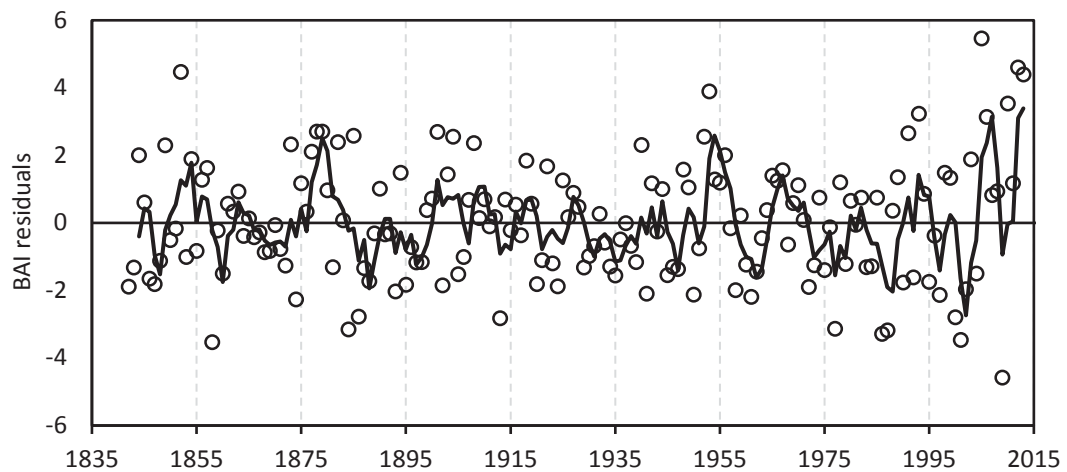


Figure 4-12: Adjusted BAI growth for *P. deltoides* from 1842 to 2013 in Dinosaur Provincial Park along the lower Red Deer River.

4.5 Conclusion

Growth of plains cottonwood along the lower Red Deer River did not differ before and after construction of the Dickson Dam. The relationship of tree growth with evapotranspiration, precipitation and the PDO index were all explored, but, while being correlated with growth, were not associated with pre- and post-dam differences. The Dickson Dam does not alter the annual volume of streamflow of the Red Deer River but does change the natural streamflow pattern. By storing water for release during the winter, the Dickson Dam restricts the availability of water during the growing season. However, this does not appear to impact tree growth. This is likely due to the preservation of natural late-summer streamflow volumes. This difference distinguishes the management of streamflow on the Red Deer River from other rivers in semi-arid regions of North America, where damming and diversion has resulted in the diminished growth and the successive dieback of cottonwoods populations.

Presently, cottonwood populations along the lower Red Deer River appear to be healthy. However, tree growth was found to be very sensitive to streamflow and other climatic factors and it is likely that future alterations in management and water demand would have implications for cottonwood health along this river.

4.6 References

- Albertson FW, Weaver JE, 1945. Injury and death or recovery of trees in prairie climate. *Ecological Monographs*, 15(4): 393-433. DOI:Doi 10.2307/1948428
- Amlin NM, Rood SB, 2003. Drought stress and recovery of riparian cottonwoods due to water table alteration along Willow Creek, Alberta. *Trees*, 17(4): 351-358. DOI:10.1007/s00468-003-0245-3
- Appelquist MB, 1958. A simple pith locator for use with off-center increment cores. *Journal of Forestry*, 56(2): 141.
- Auble GT, Scott ML, Friedman JM, Back J, Lee VJ, 1997. Constraints on establishment of plains cottonwood in an urban riparian preserve. *Wetlands*, 17(1): 138-148. DOI:10.1007/bf03160725
- Axelsson JN, Sauchyn DJ, Barichivich J, 2009. New reconstructions of streamflow variability in the South Saskatchewan River Basin from a network of tree ring chronologies, Alberta, Canada. *Water Resources Research*, 45(9): n/a-n/a. DOI:10.1029/2008WR007639
- Baker BL, Telang SA, 1985. Abundances of oxygen and organics in the Red Deer River: Comparison with Marmot Basin streams. *Canadian Water Resources Journal*, 10(2): 19-27. DOI:10.4296/cwrj1002019
- Biondi F, Qeadan F, 2008. A theory-driven approach to tree-ring standardization: Defining the biological trend from expected basal area increment. *Tree-Ring Research*, 64(2): 81-96. DOI:10.3959/2008-6.1
- Blum BM, 1963. Excessive exposure stimulates epicormic branching in young northern hardwoods. *Research Note NE-9*, Upper Darby, PA.
- Box G, Jenkins J, 1970. *Time series analysis: forecasting and control*. Holden-Day, San Francisco.
- Braatne JH, Jamieson R, Gill KM, Rood SB, 2007. Instream flows and the decline of riparian cottonwoods along the Yakima River, Washington, USA. *River Research and Applications*, 23(3): 247-267. DOI:10.1002/rra.978
- Braatne JH, Rood SB, Heilman PE, 1996. Life history, ecology, and conservation of riparian cottonwoods in North America, *Biology of Populus and its implications for management and conservation*. NRC Research Press, Ottawa, ON, Canada, pp. 57-85.
- Bradley CE, Reintjes F, Mahoney JM, 1991. The biology and status of riparian poplars in southern Alberta. *Alberta Forestry, Lands and Wildlife*, 85 pp.

- Bradley CE, Smith DG, 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. *Canadian Journal of Botany*, 64(7): 1433-1442. DOI:10.1139/b86-195
- Brayshaw TC, 1965. Native poplars of southern Alberta and their hybrids. Canada, Department of Forestry, Petawawa Experiment Station, Ottawa, Publication 1109.
- Briffa KR, 2000. Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quaternary Science Reviews*, 19(1-5): 87-105. DOI:10.1016/S0277-3791(99)00056-6
- Bryan RB, Campbell IA, 1980. Sediment entrainment and transport during local rainstorms in the Steveville Badlands, Alberta. *CATENA*, 7(1): 51-65. DOI:10.1016/S0341-8162(80)80003-8
- Burrows GE, 2008. Syncarpia and Tristaniopsis (Myrtaceae) possess specialised fire-resistant epicormic structures. *Australian Journal of Botany*, 56(3): 254-264. DOI:10.1071/BT07164
- Busch DE, Ingraham NL, Smith SD, 1992. Water uptake in woody riparian phreatophytes of the southwestern United States: A stable isotope study. *Ecological Applications*, 2(4): 450-459. DOI:10.2307/1941880
- Cleverly JR, Dahm CN, Thibault JR, McDonnell DE, Coonrod JEA, 2006. Riparian ecohydrology: regulation of water flux from the ground to the atmosphere in the Middle Rio Grande, New Mexico. *Hydrological Processes*, 20(15): 3207-3225. DOI:10.1002/hyp.6328
- Clipperton G, Koning C, Locke A, Mahoney J, Quazi B, 2003. Instream flow needs determinations in the South Saskatchewan River Basin, Alberta. Alberta Environment and Sustainable Resource Development, Pub No T/719, Calgary, Alberta, Canada: 271.
- Cooper DJ, D'amico DR, Scott ML, 2003. Physiological and morphological response patterns of *Populus deltoides* to alluvial groundwater pumping. *Environmental Management*, 31(2): 0215-0226. DOI:10.1007/s00267-002-2808-2
- Cordes LD, Getty MA, Hughes F, 1993. Red Deer River instream flow studies: riparian vegetation component, Alberta Environmental Protection, Edmonton, 125 pp.
- Cordes LD, Hughes FMR, Getty M, 1997. Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: The Red Deer River, Alberta, Canada. *Journal of Biogeography*, 24(5): 675-695. DOI:10.1111/j.1365-2699.1997.tb00077.x
- D'arrigo RD, Jacoby GC, 1992. A tree-ring reconstruction of New Mexico winter precipitation and its relation to El Niño/Southern Oscillation events. In: Diaz,

- H.F., Markgraf, V. (Eds.), El Niño: Historical and paleoclimatic aspects of the southern oscillation, pp. 243-257.
- Dickmann DI, Stuart KW, 1983. The culture of poplars in eastern North America. Department of Forestry, Michigan State University, East Lansing, Michigan.
- Edmondson J, Friedman J, Meko D, Touchan R, Scott J, Edmondson A, 2014. Dendroclimatic potential of plains cottonwood (*Populus deltoides* Subsp. *Monilifera*) from the northern Great Plains, USA. Tree-Ring Research, 70(1): 21-30. DOI:10.3959/1536-1098-70.1.21
- Everitt BL, 1968. Use of the cottonwood in an investigation of the recent history of a flood plain. American Journal of Science, 266(6): 417-439. DOI:10.2475/ajs.266.6.417
- Finch DM, Ruggiero LF, 1993. Wildlife habitats and biological diversity in the Rocky Mountains and northern Great Plains. Nat Area J, 13(3): 191-203.
- Foster S, 2016. Cottonwood evaluation following environmental flow implementation along the Waterton River, Alberta, University of Lethbridge, Lethbridge, Alberta, Canada, 1-160 pp.
- Fritts H, 1976. Tree rings and climate. Academic Press Inc., London
- Gobena AK, Gan TY, 2009. The Role of Pacific Climate on Low-Frequency Hydroclimatic Variability and Predictability in Southern Alberta, Canada. Journal of Hydrometeorology, 10(6): 1465-1478. DOI:10.1175/2009jhm1119.1
- Hargreaves GH, Samani ZA, 1985. Reference crop evapotranspiration from temperature. Applied engineering in agriculture, 1(2): 96-99. DOI:10.13031/2013.26773
- Hornbeck JW, Smith RB, 1985. Documentation of red spruce growth decline. Canadian Journal of Forest Research, 15(6): 1199-1201. DOI:10.1139/x85-199
- Horton JL, Kolb TE, Hart SC, 2001. Physiological response to groundwater depth varies among species and with river flow regulation. Ecological Applications, 11(4): 1046-1059. DOI:10.2307/3061011
- Johnson RR, Haight LT, 1984. Riparian problems and initiatives in the American Southwest: A regional perspective. In: Warner, R.E., Hendrix, K.M. (Eds.), California riparian systems: Ecology, conservation and productive management. University of California Press, Berkeley CA, pp. 404-412.
- Johnson WC, Burgess RL, Keammerer WR, 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. Ecological Monographs, 46(1): 59-84. DOI:10.2307/1942394

- Knopf FL, Johnson RR, Rich T, Samson FB, Szaro RC, 1988. Conservation of riparian ecosystems in the United States. *The Wilson Bulletin*, 100(2): 272-284.
- Lanner RM, 2002. Why do trees live so long? *Ageing Research Reviews*, 1(4): 653-671. DOI:10.1016/S1568-1637(02)00025-9
- Mahoney JM, Rood SB, 1993. A model for assessing the effects of altered river flows on the recruitment of riparian cottonwoods. *Riparian management: common threads and shared interests*: 4-6.
- Mahoney JM, Rood SB, 1998. Streamflow requirements for cottonwood seedling recruitment—An integrative model. *Wetlands*, 18(4): 634-645. DOI:10.1007/bf03161678
- Mantua NJ, Hare SR, 2002. The Pacific decadal oscillation. *Journal of oceanography*, 58(1): 35-44. DOI:10.1023/A:1015820616384
- Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC, 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, 78(6): 1069-1079. DOI:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2
- Marken S, 1993. Plains cottonwoods and riparian plant communities on the lower Red Deer River, Department of Geography, University of Calgary, Calgary, Alberta.
- Meier AR, Saunders MR, Michler CH, 2012. Epicormic buds in trees: a review of bud establishment, development and dormancy release. *Tree Physiology*, 32(5): 565-584. DOI:10.1093/treephys/tps040
- Monserud RA, 1986. Time-series analyses of tree-ring chronologies. *Forest Science*, 32(2): 349-372.
- Monserud RA, Marshall JD, 2001. Time-series analysis of $\delta^{13}\text{C}$ from tree rings. I. Time trends and autocorrelation. *Tree Physiology*, 21(15): 1087-1102. DOI:10.1093/treephys/21.15.1087
- Orchard T, 2015. Water requirements of a Southern Alberta riparian cottonwood ecosystem, Lethbridge, Alta.: University of Lethbridge, Dept. of Biological Sciences.
- Patten DT, 1998. Riparian ecosystems of semi-arid North America: Diversity and human impacts. *Wetlands*, 18(4): 498-512. DOI:10.1007/bf03161668
- Polzin ML, Rood S, 2000. Effects of damming and flow stabilization on riparian processes and black cottonwoods along the Kootenay River. *Rivers*, 7(3): 221-232.

- Reily PW, Johnson WC, 1982. The effects of altered hydrologic regime on tree growth along the Missouri River in North Dakota. *Canadian Journal of Botany*, 60(11): 2410-2423. DOI:10.1139/b82-294
- Remphrey WR, Davidson CG, 1992. Spatiotemporal distribution of epicormic shoots and their architecture in branches of *Fraxinus pennsylvanica*. *Canadian Journal of Forest Research*, 22(3): 336-340. DOI:10.1139/x92-043
- Riitters KH, 1990. A comparison of chronologies from tree rings. *Canadian Journal of Forest Research*, 20(1): 76-83. DOI:10.1139/x90-011
- Rood SB, Ball DJ, Gill KM, Kaluthota S, Letts MG, Pearce DW, 2013. Hydrologic linkages between a climate oscillation, river flows, growth, and wood $\Delta^{13}\text{C}$ of male and female cottonwood trees. *Plant, cell & environment*, 36(5): 984-993.
- Rood SB, Bigelow SG, Hall AA, 2011. Root architecture of riparian trees: river cut-banks provide natural hydraulic excavation, revealing that cottonwoods are facultative phreatophytes. *Trees*, 25(5): 907-917. DOI:10.1007/s00468-011-0565-7
- Rood SB, Braatne JH, Hughes FM, 2003. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology*, 23(16): 1113-1124. DOI:10.1093/treephys/23.16.1113
- Rood SB, Heinze-Milne S, 1989. Abrupt downstream forest decline following river damming in southern Alberta. *Canadian Journal of Botany*, 67(6): 1744-1749. DOI:10.1139/b89-221
- Rood SB, Hillman C, Sanche T, Mahoney JM, 1994. Clonal reproduction of riparian cottonwoods in southern Alberta. *Canadian Journal of Botany*, 72(12): 1766-1774. DOI:10.1139/b94-217
- Rood SB, Kalischuk AR, Mahoney JM, 1998. Initial cottonwood seedling recruitment following the flood of the century of the Oldman River, Alberta, Canada. *Wetlands*, 18(4): 557-570. DOI:10.1007/bf03161672
- Rood SB, Kaluthota S, Gill KM, Hillman EJ, Woodman SG, Pearce DW, Mahoney JM, 2016. A twofold strategy for riparian restoration: Combining a functional flow regime and direct seeding to re-establish cottonwoods. *River Research and Applications*, 32(5): 836-844. DOI:10.1002/rra.2919
- Rood SB, Mahoney JM, Reid DE, Zilm L, 1995. Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. *Canadian Journal of Botany*, 73(8): 1250-1260. DOI:10.1139/b95-136
- Rood SB, Patiño S, Coombs K, Tyree MT, 2000. Branch sacrifice: cavitation-associated drought adaptation of riparian cottonwoods. *Trees*, 14(5): 248-257. DOI:10.1007/s004680050010

- Rood SB, Samuelson GM, Braatne JH, Gourley CR, Hughes FM, Mahoney JM, 2005. Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment*, 3(4): 193-201. DOI:10.2307/3868463
- Sabo JL, Sponseller R, Dixon M, Gade K, Harms T, Heffernan J, Jani A, Katz G, Soykan C, Watts J, 2005. Riparian zones increase regional species richness by harboring different, not more, species. *Ecology*, 86(1): 56-62. DOI:10.1890/04-0668
- Scott ML, Shafroth PB, Auble GT, 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management*, 23(3): 347-358. DOI:10.1007/s002679900191
- Shafroth PB, Stromberg JC, Patten DT, 2000. Woody riparian vegetation response to different alluvial water table regimes. *Western North American Naturalist*, 60(1): 66-76.
- Shaw RK, 1976. A taxonomic and ecologic study of the riverbottom forests on St. Mary River, Lee Creek, and Belly River in southwestern Alberta, Canada. *The Great Basin Naturalist*, 36(3): 243-271.
- Smith DG, Reynolds DM, 1983. Trees scars to determine the frequency and stage of high magnitude river ice drives and jams, Red Deer, Alberta. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, 8(3): 77-94. DOI:10.4296/cwrj0803077
- St. Jacques J-M, Sauchyn DJ, Zhao Y, 2010. Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability? *Geophysical Research Letters*, 37(6). DOI:10.1029/2009GL042045
- Stromberg J, 1993. Fremont cottonwood-Goodding willow riparian forests: a review of their ecology, threats, and recovery potential. *Journal of the Arizona-Nevada Academy of Science*: 97-110.
- Stromberg JC, 2001. Influence of stream flow regime and temperature on growth rate of the riparian tree, *Platanus wrightii*, in Arizona. *Freshwater Biology*, 46(2): 227-239. DOI:10.1046/j.1365-2427.2001.00651.x
- Stromberg JC, Patten DT, 1990. Riparian vegetation instream flow requirements: A case study from a diverted stream in the Eastern Sierra Nevada, California, USA. *Environmental Management*, 14(2): 185-194. DOI:10.1007/bf02394035
- Stromberg JC, Patten DT, 1996. Instream flow and cottonwood growth in the eastern Sierra Nevada of California, USA. *Regulated Rivers: Research & Management*, 12(1): 1-12. DOI:10.1002/(SICI)1099-1646(199601)12:1<1::AID-RRR347>3.0.CO;2-D

- Stromberg JC, Tiller R, Richter B, 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona. *Ecological Applications*, 6(1): 113-131. DOI:10.2307/2269558
- Tyree MT, Kolb KJ, Rood SB, Patiño S, 1994. Vulnerability to drought-induced cavitation of riparian cottonwoods in Alberta: a possible factor in the decline of the ecosystem? *Tree Physiology*, 14(5): 455-466. DOI:10.1093/treephys/14.5.455
- Weiner J, Thomas SC, 2001. The nature of tree growth and the "age-related decline in forest productivity". *Oikos*, 94(2): 374-376. DOI:10.1034/j.1600-0706.2001.940219.x
- West PW, 1980. Use of diameter increment and basal area increment in tree growth studies. *Canadian Journal of Forest Research*, 10(1): 71-77. DOI:10.1139/x80-012
- Whited DC, Lorang MS, Harner MJ, Hauer FR, Kimball JS, Stanford JA, 2007. Climate, hydrologic disturbance, and succession: drivers of floodplain pattern. *Ecology*, 88(4): 940-953. DOI:10.1890/05-1149
- Whitfield PH, Moore RD, Fleming SW, Zawadzki A, 2010. Pacific decadal oscillation and the hydroclimatology of western Canada—Review and prospects. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, 35(1): 1-28. DOI:10.4296/cwrj3501001
- Willms CR, Pearce DW, Rood SB, 2006. Growth of riparian cottonwoods: a developmental pattern and the influence of geomorphic context. *Trees*, 20(2): 210-218.

CHAPTER 5: SUMMARY AND KEY FINDINGS

5.1 Historic and prospective future flows of the Red Deer River

Changes in the volume and pattern of streamflow resulting from climatic change will have both environmental and economic implications. In chapter two, annual and monthly streamflow for the Red Deer River and its headwater tributaries was forecasted for the period around the year 2055 through the extension historical trends and through hydroclimatic modelling.

Similar to other rivers within the South Saskatchewan River Basin, we expected trends of earlier snowmelt and earlier peak runoffs in the historical streamflow data for the Red Deer River (Rood et al., 2016; Rood et al., 2008). While there was some evidence of increasing winter discharges, no trend towards earlier peak discharges was found for the upper Red Deer River Basin. We also expected that annual streamflow volumes may be decreasing, however, no significant trend in historical annual streamflow was observed for the Red Deer River from 1912 to 2012.

Hydroclimatic modelling projected increasing streamflow for the Red Deer River at Red Deer on an annual basis and for most months. This is in contrast to projections for the more southern tributaries of the South Saskatchewan River, where decreases in annual streamflow volumes are forecasted (St. Jacques et al., 2013).

Overall, hydrological modelling of the Red Deer River Basin appears to be difficult. While our model was able to simulate streamflow at higher elevations with a relatively high degree of accuracy, we were less successful at simulating historical streamflow for the lower tributaries. In terms of climate projections, modelling may be more successful

with regional circulation models. Regional circulation models employ coarse-scale GCM global climate outputs to drive a limited area model with higher resolution and incorporates factors such as bodies of water, vegetation and topography (Giorgi, 1990). However, other studies forecasting streamflow for the Red Deer River — some of which have employed regional circulation models — have also returned variable results, with some studies projecting an increase in annual streamflow and others a decrease. The difficulty in modelling streamflow for the Red Deer River may be the result of the basin's location within a transition zone between southern Alberta, where streamflow is projected to decrease and the boreal regions of central and northern Alberta, where streamflow is projected to increase (Intergovernmental Panel on Climate, 2013).

A warming climate is predicted to have the greatest impact on the hydrological cycle of higher latitude, snow-dominated basins, such as the Red Deer River Basin (Barnett et al., 2005; Nogués-Bravo et al., 2007). While our modelled streamflow forecasts were variable and there are no clear trends in the historical streamflow data, the basin is warming, particularly during the winter months, and it is probable that as the global climate continues to warm there will be earlier snowmelt and peak streamflow along the Red Deer River. Potential changes in the volume of streamflow are less clear.

5.2 Cottonwood recruitment and streamflow management along the lower Red Deer River

Significant declines in the abundance and health of cottonwood woodlands have been reported downstream of dams and diversions along many streams in southern Alberta (Rood and Bradley, 1993; Rood and Heinze-Milne, 1989; Rood et al., 2005; Rood et al., 1999). These reductions are the result of a combination of many factors, most of which

can be attributed to water management (Poff et al., 1997; Rood and Mahoney, 1990). In chapter 3, we analyzed water management along the Red Deer River and the impacts on the recruitment and health of cottonwood communities along the lower river through Dinosaur Provincial Park.

Despite early studies suggesting that streamflow management would limit the likelihood of future cottonwood recruitment along the Red Deer River (Clipperton et al., 2003; Cordes et al., 1997; Marken, 1993), the construction of the Dickson Dam in 1983 has not had a substantial impact on the reproduction or health of riparian cottonwood populations along the lower reach of this river.

We found that the Dickson Dam has a substantial capacity to attenuate floods. However, this does not appear to have a significant impact on cottonwood reproduction. Despite being attenuated floods in 2005 and 2013 resulted in extensive cottonwood recruitment. The overall pattern of streamflow, as opposed to the magnitude of a flood event, appears more important for the successful recruitment of cottonwoods. The operation of the Dickson Dam accelerates the natural rate of streamflow decline following floods. This has been found to be a key factor in the reduction of riparian cottonwood recruitment downstream of dams along many rivers in semi-arid regions (Mahoney and Rood, 1998; Rood and Mahoney, 1990; Scott et al., 1999). Compared to these rivers, management along the Red Deer River is less extreme and, while the rate of streamflow decline following floods is accelerated, it is not extreme enough to completely limit seedling establishment. However, limiting alluvial water-table declines to around 4 cm/day following floods would likely reduce drought-induced mortality of seedlings and ensure successful recruitment events (Mahoney and Rood, 1991; Mahoney and Rood, 1993).

This would be relatively easy to implement on the Red Deer River with limited risk to supply as – unlike the other major tributaries to the South Saskatchewan River – the Red Deer River is not heavily allocated. Woodlands along the Red Deer River in Dinosaur Provincial Park are primarily composed of mature trees greater than 100 years of age. As these trees continue to age and die, continued recruitment events will be necessary to maintain woodlands at their current extent.

5.3 Cottonwood growth, climate, and streamflow management along the lower Red Deer River

The ability of cottonwoods to survive in riparian environments in semi-arid regions can be attributed to their ability to tap into alluvial water supplied by adjacent rivers (Rood et al., 2011). This dependence of cottonwoods on alluvial aquifers makes cottonwoods sensitive to natural and anthropogenic changes in streamflow. In chapter 4, dendrochronology was used to assess the relationship between cottonwood growth along the lower Red Deer River with streamflow, streamflow management and climate.

Annual tree growth of riparian trees, including cottonwoods, can often be complacent with growth years exhibiting a low degree of variation (Braatne et al., 2007; Fritts, 1976). This was not the case for *P. deltoides* along the lower Red Deer River. Tree growth displayed considerable variation from year to year and was correlated with variation in streamflow and other climatic factors including evapotranspiration. We expected that, as tree growth was correlated with streamflow, that annual increment growth rings may be different before and after the construction of the Dickson Dam, however, we did not find any differences. This is likely the result of the limited impact of the Dickson Dam on monthly minimum streamflow. In other river systems, cottonwood stress resulted from a

reduction in minimum flows, particularly during the hot and dry period of mid-to-late summer (Rood et al., 2003). Along the Red Deer River, average mid-to-late summer minimum streamflow did not differ before and after the construction of the Dickson Dam.

The prairies of western Canada have few tree-ring chronologies, with most analyses being limited to the eastern slopes of the Rocky Mountains. In Dinosaur Provincial Park, cottonwood ages were found to be in excess of 250 years and tree growth demonstrated strong links with streamflow. This demonstrates the dendrochronological potential of cottonwoods along the lower Red Deer River to provide an *in situ* reconstruction of climatological variables, such as streamflow, for the prairies.

5.4 References

- Barnett TP, Adam JC, Lettenmaier DP, 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066): 303-9. DOI:10.1038/nature04141
- Braatne JH, Jamieson R, Gill KM, Rood SB, 2007. Instream flows and the decline of riparian cottonwoods along the Yakima River, Washington, USA. *River Research and Applications*, 23(3): 247-267. DOI:10.1002/rra.978
- Clipperton G, Koning C, Locke A, Mahoney J, Quazi B, 2003. Instream flow needs determinations in the South Saskatchewan River Basin, Alberta. Alberta Environment and Sustainable Resource Development, Pub No T/719, Calgary, Alberta, Canada: 271.
- Cordes LD, Hughes FMR, Getty M, 1997. Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: The Red Deer River, Alberta, Canada. *Journal of Biogeography*, 24(5): 675-695. DOI:10.1111/j.1365-2699.1997.tb00077.x
- Fritts H, 1976. *Tree rings and climate*. Academic Press Inc., London
- Giorgi F, 1990. Simulation of regional climate using a limited area model nested in a general circulation model. *Journal of Climate*, 3(9): 941-963. DOI:10.1175/1520-0442(1990)003<0941:SORCUA>2.0.CO;2
- Intergovernmental Panel on Climate C, 2013. Long-term climate change: Projections, commitments and irreversibility Pages 1029 to 1076, *Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 1029-1136. DOI:10.1017/CBO9781107415324.024
- Mahoney JM, Rood SB, 1991. A device for studying the influence of declining water table on poplar growth and survival. *Tree Physiology*, 8(3): 305-314. DOI:10.1093/treephys/8.3.305
- Mahoney JM, Rood SB, 1993. A model for assessing the effects of altered river flows on the recruitment of riparian cottonwoods. *Riparian management: common threads and shared interests*: 4-6.
- Mahoney JM, Rood SB, 1998. Streamflow requirements for cottonwood seedling recruitment—An integrative model. *Wetlands*, 18(4): 634-645. DOI:10.1007/bf03161678
- Marken S, 1993. *Plains cottonwoods and riparian plant communities on the lower Red Deer River*, Department of Geography, University of Calgary, Calgary, Alberta.

- Nogués-Bravo D, Araújo MB, Errea MP, Martínez-Rica JP, 2007. Exposure of global mountain systems to climate warming during the 21st Century. *Global Environmental Change*, 17(3–4): 420-428. DOI:10.1016/j.gloenvcha.2006.11.007
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC, 1997. The natural flow regime. *BioScience*, 47(11): 769-784. DOI:10.2307/1313099
- Rood SB, Bigelow SG, Hall AA, 2011. Root architecture of riparian trees: river cut-banks provide natural hydraulic excavation, revealing that cottonwoods are facultative phreatophytes. *Trees*, 25(5): 907-917. DOI:10.1007/s00468-011-0565-7
- Rood SB, Braatne JH, Hughes FM, 2003. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology*, 23(16): 1113-1124. DOI:10.1093/treephys/23.16.1113
- Rood SB, Bradley CE, 1993. Assessment of riparian cottonwoods along the Bow River downstream from Calgary, Alberta. Final Report to Trout Unlimited Canada, University of Lethbridge, Calgary, Alberta.
- Rood SB, Foster SG, Hillman EJ, Luek A, Zanewich KP, 2016. Flood moderation: Declining peak flows along some Rocky Mountain rivers and the underlying mechanism. *Journal of Hydrology*. DOI:10.1016/j.jhydrol.2016.02.043
- Rood SB, Heinze-Milne S, 1989. Abrupt downstream forest decline following river damming in southern Alberta. *Canadian Journal of Botany*, 67(6): 1744-1749. DOI:10.1139/b89-221
- Rood SB, Mahoney JM, 1990. Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. *Environmental Management*, 14(4): 451-464. DOI:10.1007/BF02394134
- Rood SB, Pan J, Gill KM, Franks CG, Samuelson GM, Shepherd A, 2008. Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, 349(3–4): 397-410. DOI:10.1016/j.jhydrol.2007.11.012
- Rood SB, Samuelson GM, Braatne JH, Gourley CR, Hughes FM, Mahoney JM, 2005. Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment*, 3(4): 193-201. DOI:10.2307/3868463
- Rood SB, Taboulchanas K, Bradley CE, Kalischuk AR, 1999. Influence of flow regulation on channel dynamics and riparian cottonwoods along the Bow River, Alberta. *Rivers*, 7(1): 33-48.
- Scott ML, Shafroth PB, Auble GT, 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management*, 23(3): 347-358. DOI:10.1007/s002679900191

St. Jacques J-M, Lapp SL, Zhao Y, Barrow EM, Sauchyn DJ, 2013. Twenty-first century central Rocky Mountain river discharge scenarios under greenhouse forcing. *Quaternary International*, 310: 34-46. DOI:10.1016/j.quaint.2012.06.023

Appendix A: Naturalization correction equations

Recorded mean monthly discharge (Q_m) from the Dickson Dam, Medicine River and the Little Red Deer River were summed to produce a ‘tributary’ Q_m value. This value accounts for the majority of the discharge recorded at Red Deer. The ‘tributary’ Q_m value and the gauged discharge at Red Deer were log transformed to normalize the data, grouped seasonally and fit with linear equations (figure A-1). These equations were subsequently applied to the sum of the mean monthly inflow into Gleniffer Reservoir and the discharges of the Medicine River and the Little Red Deer River to produce naturalized Q_m data from 1984 to 2012.

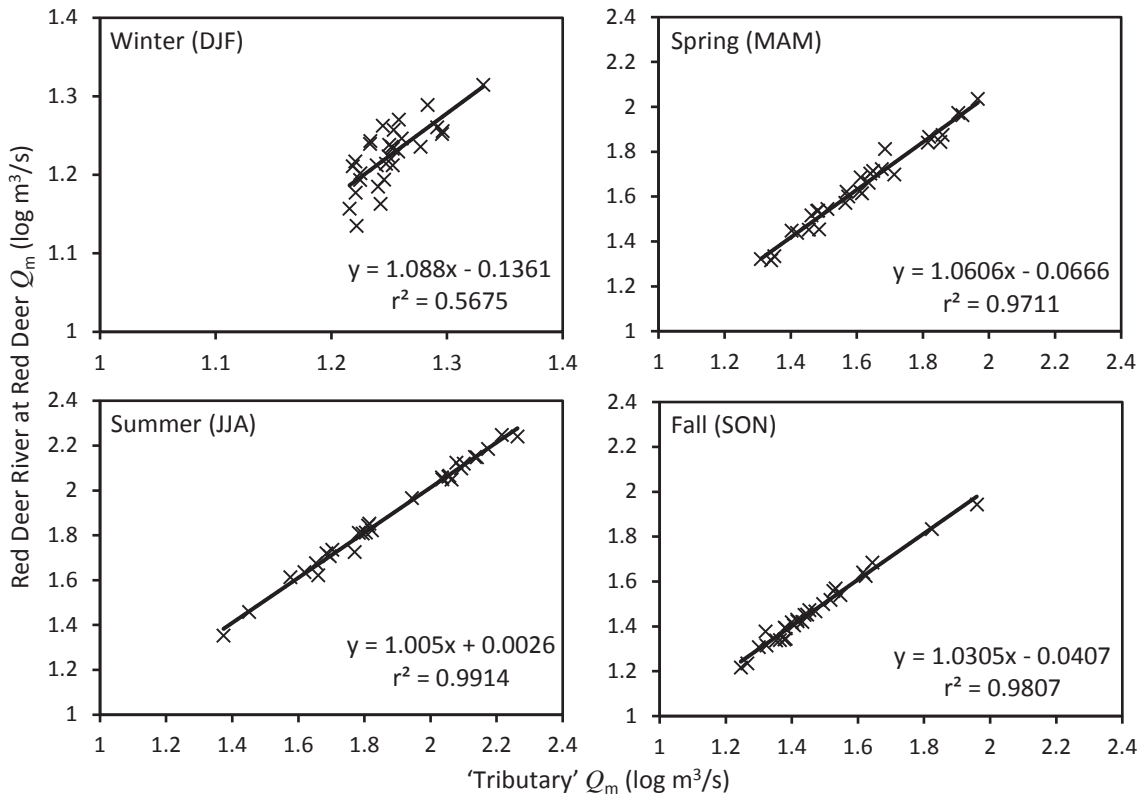


Figure A-1: Relationship between the mean monthly discharges of the Red Deer River gauged at Red Deer and the mean monthly discharge of the upstream ‘tributary’ inputs grouped by seasons. The ‘tributary’ input is comprised of the sum of the mean monthly discharge from the Dickson Dam, the Medicine River and the Little Red Deer River.

This same process was performed using the gauging stations along the upper tributaries (Red Deer River below Burnt Timber, Raven River at Raven, Medicine River near Eckville and the Little Red Deer River near the mouth) rather than inflow/outflow data from the Dickson Dam. The sum of the discharges of these naturally flowing tributaries was coordinated with the Red Deer River at Red Deer gauging station before the construction of the Dickson Dam in 1983 in order to produce seasonal naturalization equations. These equations were then applied to the sum of the tributary discharges after 1983 to produce naturalized flows. This method produced high coefficients of

determination but was not as accurate as using inflow/outflow data, it does however provide an alternative if inflow/outflow data from the reservoir is not available.

The naturalization correction equation for May, June and July flood flows was generated by plotting the 3 day moving average of the sum of daily discharges from the Dickson Dam, Medicine River and the Little Red Deer River with the max daily discharge of the Red Deer River at Red Deer. This equation was then applied to the max discharge of the three day moving average of the sum of the inflow into Gleniffer Reservoir and the discharges of the Medicine River and the Little Red Deer River to produce naturalized max daily discharges for the Red Deer River at Red Deer (Figure A-2).

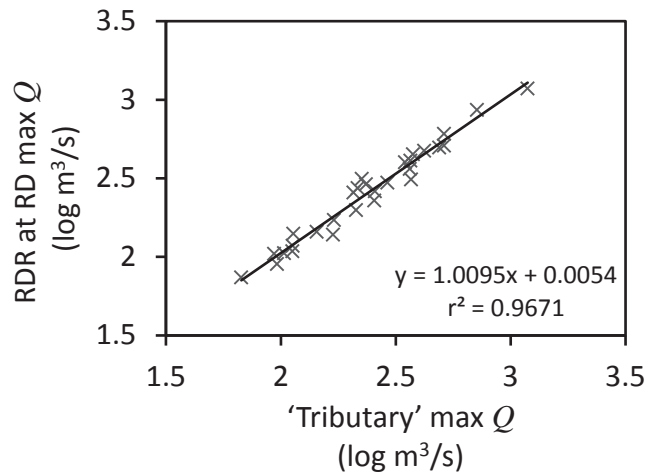


Figure A-2: Relationship between max values of the three day moving average of the sum of daily discharges from the Dickson Dam, Medicine River and Little Red Deer River tributaries (x axis) and max daily discharge of the Red Deer River at Red Deer (y axis) for May, June and July.

Appendix B: Flow variability along the Red Deer River

The Red Deer River has greater variability in discharge than the Oldman River and Bow River over the course of a year. All three rivers show high variability in weekly discharge over the freshet when mountain snow melt combines with spring and early summer rains, but only the Red Deer River shows similar variability in the shoulder seasons. Figure B-1 depicts mean weekly discharges of the three major tributaries of the South Saskatchewan River. Variability in mean discharge is demonstrated with standard deviations above and below the mean. The Oldman River (Lethbridge) and Bow River (Calgary) are heavily regulated compared to the Red Deer River (Red Deer), but this does not appear to reduce variability in weekly discharge. When the gauged (managed) and naturalized weekly discharges are compared in Figure B-1, it appears that management actually increases variability. This is probably the result of decreased spring and summer flows resulting from diversion and reservoir storage.

The timing of peak flows from year to year are more variable on the Red Deer River. High flows from localized snowmelt from the foothills in the spring and late summer rains can often be greater than peak discharges from mountain snowmelt (Figure B-2). This is less common on the Oldman and Bow River as a greater proportion of their basins are in high elevation mountains resulting in greater discharge from snowmelt.

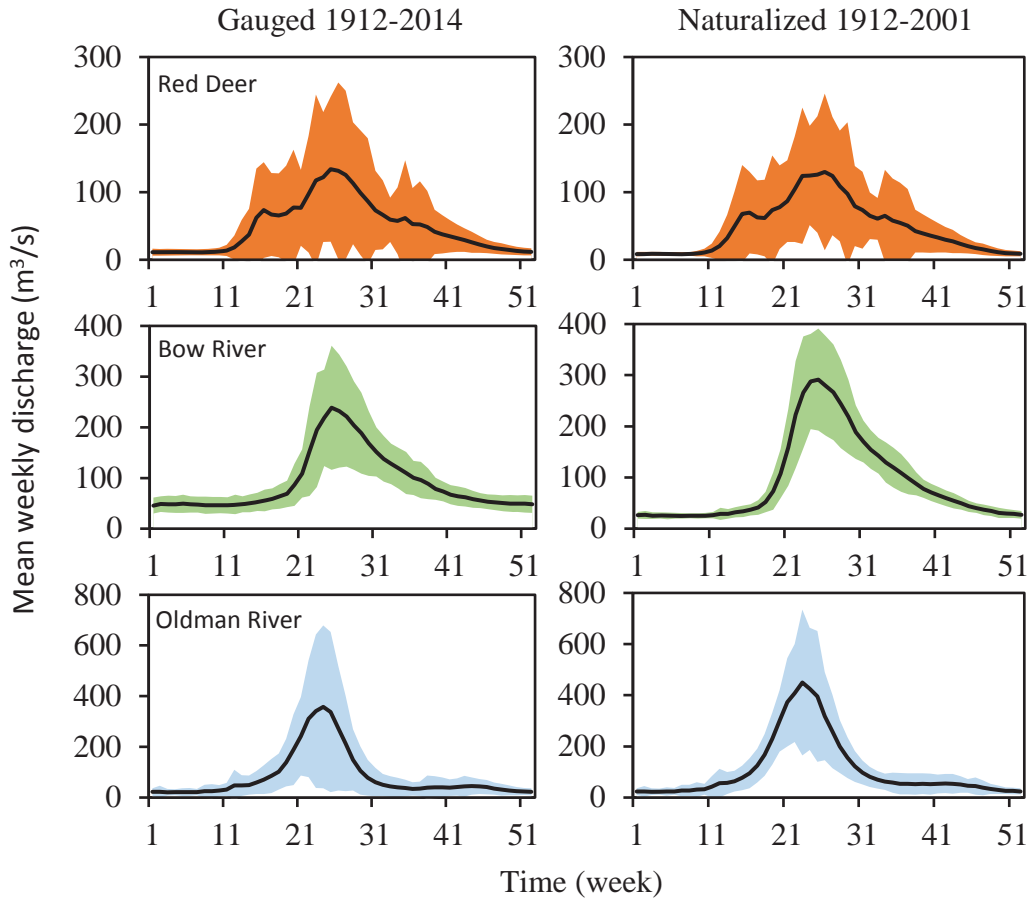


Figure B-1: Comparison of mean weekly discharges of the three major tributaries of the South Saskatchewan River. Naturalized weekly discharges were obtained from Alberta Environment’s naturalized dataset. Gauged data was obtained from Environment and Climate Change Canada’s HYDAT database. Upper and lower standard deviations are depicted by the shaded area.

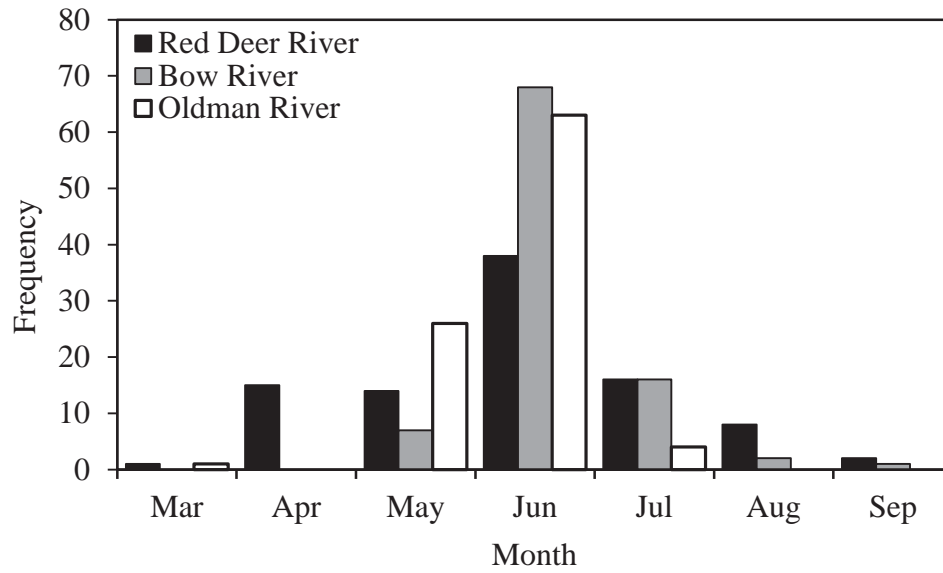


Figure B-2: Month of occurrence of annual max daily discharges for the Red Deer River, Bow River and Oldman River for the period of 1912 to 2014. Years where peak discharge data was not available for each river were removed (1934, 1949-1952, 1954-1956).

Appendix C: Streamflow trends P values

Table C-1: P values of trends calculated using Pearson Product-Moment correlation and Mann-Kendall analysis of mean annual discharges, and monthly discharges, with time from 1912 to 2012. Significant P values less than 0.1 in bold

	RDR at Red Deer		RDR below Burnt Timber Creek		James River		Raven River		Medicine River		Little RDR	
	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ	Pearson r	Kendall τ
Annual	0.216	0.549	0.188	0.375	0.610	0.974	0.583	0.891	0.102	0.073	0.474	0.816
Jan	0.554	0.646	0.784	0.734			0.000	0.000	0.073	0.353	0.624	0.621
Feb	0.994	0.796	0.051	0.037			0.064	0.011	0.119	0.213	0.471	0.513
Mar	0.094	0.076	0.823	0.939			0.008	0.055	0.012	0.102	0.997	0.467
Apr	0.896	0.769	0.003	0.001	0.951	0.981	0.137	0.241	0.357	0.363	0.606	0.589
May	0.465	0.380	0.563	0.546	0.536	0.720	0.505	0.142	0.339	0.460	0.643	0.519
Jun	0.394	0.442	0.996	0.886	0.407	0.449	0.617	0.148	0.998	0.699	0.164	0.148
Jul	0.575	0.891	0.159	0.199	0.361	0.425	0.852	0.326	0.002	0.013	0.961	0.600
Aug	0.114	0.816	0.018	0.047	0.129	0.395	0.430	0.712	0.252	0.303	0.676	0.694
Sep	0.166	0.629	0.089	0.512	0.422	0.580	0.632	0.311	0.422	0.435	0.761	0.081
Oct	0.222	0.435	0.231	0.520	0.954	0.580	0.262	0.133	0.140	0.378	0.078	0.015
Nov	0.312	0.688	0.180	0.401			0.010	0.002	0.672	0.243	0.344	0.385
Dec	0.312	0.719	0.596	0.376			0.000	0.000	0.737	0.858	0.737	0.977

Appendix D: Transect locations

Table D-1: Red Deer River seedling survey transect locations.

Transect	Start		End		Date
	Latitude	Longitude	Latitude	Longitude	
1	50.769681	-111.555165	50.770325	-111.555067	24/08/2015
2	50.76935	-111.558894	50.770264	-111.558742	04/10/2014
3	50.763541	-111.536292	50.763163	-111.537645	24/08/2015
4	50.76453	-111.520277	50.764946	-111.520714	25/08/2015
5	50.772653	-111.497111	50.771875	-111.497345	25/08/2015
6	50.772041	-111.495132	50.771275	-111.495723	12/10/2014
7	50.777438	-111.474209	50.777861	-111.47427	25/08/2015
8	50.765217	-111.455861	50.765404	-111.457711	11/10/2014
9	50.757712	-111.44674	50.758211	-111.44631	25/09/2014

Appendix E: Flood recurrence analysis

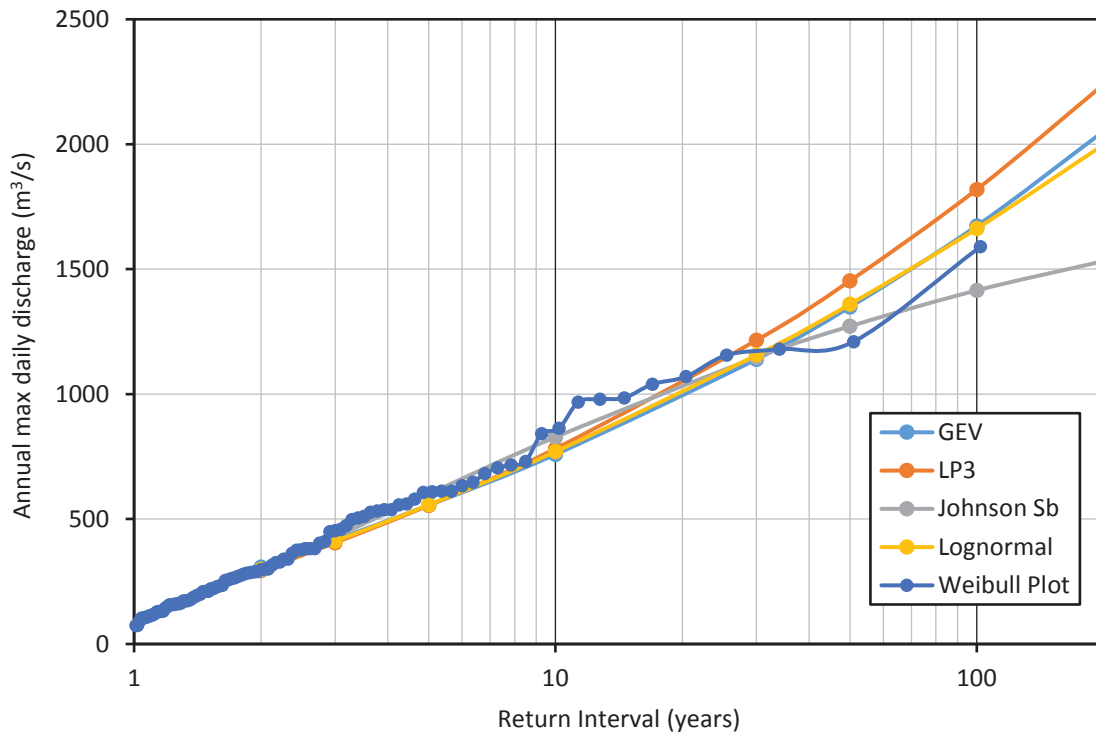


Figure E-1: Flood recurrence analysis of max daily discharges for the Red Deer River at Red Deer from 1912 to 2013 comparing Generalized Extreme Value (GEV), Log Pearson Type III (LP3), Johnson SB, Log-normal and Weibull Plot distributions. Max daily discharges occurring during ice cover were replaced with the next largest max daily discharge.

Table E-1: Comparison of flood recurrence probabilities (p), return interval (years) and discharge (x) in m^3/s for Generalized Extreme Value (GEV), Log Pearson Type III (LP3), Johnson SB and Log-normal distributions for max daily discharges from 1912 to 2013 for the Red Deer River at Red Deer. Max daily discharges occurring during ice cover were replaced with the next largest max daily discharge.

Distribution		GEV	LP3	Johnson Sb	Lognormal
Variables	k	0.23	α 174.89	γ 1.65	σ 0.74
	σ	176.66	β 0.06	δ 0.85	μ 5.70
	μ	239.67	γ -4.09	λ 1981.70	ν 0.00
				ζ 46.61	
Interval	P	x(p)	x(p)	x(p)	x(p)
200	0.995	2051.98	2239.62	1532.37	1998.03
100	0.990	1673.35	1819.16	1415.17	1662.43
50	0.980	1348.98	1453.46	1271.43	1359.83
30	0.967	1139.62	1215.38	1147.01	1156.42
10	0.900	758.63	781.75	827.85	769.67
5	0.800	555.40	554.70	599.86	556.53
3	0.667	416.68	405.28	428.27	411.11
2	0.500	307.19	293.66	295.31	299.29
Goodness of fit					
Anderson Darling stat		0.94	0.58	0.27	0.65
Critical value (0.05)		2.50			