THE INFLUENCE OF GEOMORPHOLOGY AND FLOW REGULATION ON RIPARIAN COTTONWOODS

CHAD RYAN WILLMS
Bachelor of Science, University of Alberta, 1998

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

MASTER OF SCIENCE

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

ABSTRACT

This study investigated the influence of geomorphic context and flow regulation on cottonwood (*Populus*) age structure, stand size, recruitment rates, and annual radial growth patterns along the Oldman River in southern Alberta. Dendrochronological techniques were used to age trees, establish population structures, and measure annual radial growth on three reaches in differing geomorphic contexts. Cottonwoods within a narrow, 'constrained' reach were more negatively impacted by partial dewatering of the river, but responded more favorably to increased late-summer flows combined with suitable recruitment conditions than the trees within a wide, 'alluvial' reach. A positive linear relationship between early-summer peak discharge and annual radial growth was found only on the alluvial reach. However, these trees also had the slowest growth rates, likely due to competition between trees because alluvial reaches often support large, dense stands of cottonwoods. This study demonstrates the need to consider the geomorphic context when studying cottonwood responses to river regulation.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank Stewart Rood for sharing with me his passion and dedication to the conservation of cottonwoods and rivers. Stew's enthusiasm for his work and play is contagious. He is truly a great mentor in life. John Mahoney, David Pearce and Jim Byrne all endlessly shared their time, expertise and advice. In particular I would like to thank David for sharing his office, wisdom and friendship with me.

Thanks to Sarah Bigelow, Kevan Berg and Bobbi George – my paddling partners, tree huggers, and friends with whom I spent many weeks on the Oldman River working on this project. Also, to the Cottonwood Crew in the Rood Lab for their support, wisdom, advice and for being baristas of fine coffee.

A huge thanks to my partner in life, Kim Kiel, for facing hurricane force winds, hillbillies and cockroaches all with a sense of humor and incredible support for me while I pursued intellectual advancement. Thanks also for all the time that was spent editing this thesis, though she shall not be held responsible for any errers contained within.

Thanks to Craig Coburn, Joanne Golden, Ralph Cartar, Jaqueline Montain (University of Lethbridge), Tim Davis (Water Survey of Canada), and Neil Assmus (Alberta Environment) who all provided technical assistance. And finally, to Andy Hurly and all of the other landowners along the Oldman River from whom I had permission to access their land and count their trees.

Gratefully acknowledged is the support for this project from Alberta Environment, the Alberta Ingenuity Centre for Water Research, the Natural Sciences and Engineering Research Council of Canada and the University of Lethbridge.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANCOVA – analysis of covariance

ANOVA – analysis of variance

BAI – basal area increment

DBH – diameter at breast height

LNID – Lethbridge Northern Irrigation District

ORD – Oldman River Dam

RI – radial increment

SRI – standardized radial increment

SBAI – standardized basal area increment

CHAPTER 1 THE IMPORTANCE AND UNDERSTANDING OF *POPULUS* IN A SEMI-ARID ENVIRONMENT

1.1 THESIS STRUCTURE

This thesis is composed of four chapters including an introduction, the two body chapters written as stand-alone research papers that describe the work conducted along the Oldman River, and an integrative summary chapter.

Chapter 1, 'The importance and understanding of *Populus* in a semi-arid environment', reviews the current literature to present a brief summary of cottonwood ecology, its importance in the riparian ecosystem, and factors affecting cottonwoods, with an emphasis on stream flow regulation. This chapter also introduces the work performed for this research-based thesis project.

Chapter 2, 'Riparian cottonwood response to partial dewatering and seasonal rewatering across a fluvial geomorphic transition zone in southern Alberta', is a stand-alone research paper. It describes the impacts of flow regulation caused by both the Lethbridge Northern Irrigation District (LNID) weir and the Oldman River Dam (ORD) on cottonwood population structures. The assessment of cottonwood populations considers the geomorphic context of the river reaches, thus describing the responsiveness or sensitivity of the trees along a wide, alluvial floodplain reach versus two narrower, constrained channel reaches.

Chapter 3, 'Cottonwood growth along the Oldman River, Alberta', is also written as a stand-alone research paper. It investigates the annual growth patterns of cottonwood trees in relation to stream flows, and introduces the complexity of the cottonwood growth curve.

Chapter 4 summarizes the results and provides direction for further investigations in the field of riparian research.

Additionally, Appendix A summarizes the hydrologic assessment that was performed for the Oldman River discharge to analyze the impacts of the LNID weir and the ORD. Finally, Appendix B provides the detailed statistical analyses for Chapters 2 and 3.

1.2 INTRODUCTION

1.2.1 Background

Populus trees are abundant and diverse, growing throughout the Northern Hemisphere. They are fast-growing temperate trees that can propagate both sexually and asexually, making them excellent vegetational pioneers (Eckenwalder 1996). Cottonwoods, or riparian poplars, are *Populus* trees found along river valley bottoms. As phreatophytes, they are linked to and rely upon the saturated groundwater to meet their water uptake requirements, making only occasional use of surface water infiltration (Busch et al. 1992; Snyder and Williams 2000). Restricted to floodplains, these trees do not form large forests as do many other tree species such as many conifers, or the upland *Populus* species, aspens. However, the ecological value of an individual cottonwood is probably higher than that of other tree species as cottonwoods are the principal tree in semi-arid, prairie landscapes.

Cottonwoods fill important ecological roles by providing critical habitats for birds and other wildlife (Finch and Ruggiero 1993; Farley et al. 1994; Martinsen and Whitham 1994), by providing nutrients important for the adjacent aquatic food web (Wallace et al. 1997), and by providing important microhabitat for a wide range of fish species (Beschta 1991). From a hydrogeomorphic perspective they influence factors such as channel roughness, bank stability, sediment deposition, dissipation of stream energy and precipitation interception, and they also filter runoff and waste (Beschta 1991; Patten 1998). Cottonwoods also have substantial human value as they provide shelter for livestock, can be used for building materials and fuel, contribute to aesthetics, and have cultural, spiritual and recreational values.

1.2.2 Hybridization

Southern Alberta contains four species of riparian cottonwoods from two taxonomic sections. Three species are from section *Tacamahaca: Populus angustifolia* James (narrowleaf cottonwood), *P. balsamifera* L. (balsam poplar), and *P. trichocarpa* Torrey and Gray (black cottonwood). *P. trichocarpa* is often accepted as a separate species but has also been treated in North America as a subspecies of P. *balsamifera* L. (Brayshaw 1965b; Moss 1992; Farrar 1995). Section *Aigeiros* is represented by *P. deltoides* Bartr. ex Marsh (plains cottonwood) in southern Alberta. All four species are capable of interbreeding, thus creating complex assemblages of intrasectional and intersectional hybrids (Brayshaw 1965a; Rood et al. 1986; Floate 2004).

Zones of hybridization between two *Populus* species are common (Eckenwalder 1996; Stettler et al. 1996). However, southern Alberta uniquely contains a four-species hybrid swarm composed of black cottonwood, balsam poplar, narrowleaf cottonwood and plains cottonwood (Rood et al. 1986; Gom and Rood 1999a; Floate 2004). Interestingly, bidirectional introgression occurs between section *Tacamahaca* species but unidirectional introgression occurs between section *Tacamahaca* and section *Aigeiros* species, with F_1 hybrids only backcrossing with the *Tacamahaca* parent (Floate 2004). These hybrids are centres of arthropod richness and abundance, that provide better habitat for regional distributions of nesting birds than pure cottonwood stands (Whitham 1989; Floate and Whitham 1993; Martinsen and Whitham 1994; Floate 2004).

Southern Alberta is not only unique and significant for the complex hybrid assemblage, but also for the size and extent of it. Alberta's portion of the South Saskatchewan River Basin, including the rivers and tributaries of the Red Deer, Bow and Oldman sub-basins, have more than 1000 river km of relatively healthy cottonwood forest with zones of species overlap and hybridization at least 700 river km in length (Floate 2004). Hybrid zones also encompass novel genotypes that exist nowhere else within the distribution of the parental species. These hybrids may have traits desirable for commercial propagation or for continued survival of riparian forests with future climate change (Floate 2004).

1.2.3 Reproduction and recruitment

Cottonwoods are successful pioneers of disturbed sites partly because they can reproduce both sexually and asexually. Sexual propagation occurs through pollination of flowers producing small seeds borne by fluffy, cotton-like hairs, which disperse by wind and water (Braatne et al. 1996). Asexual propagation occurs through rooting of branch fragments and suckering of roots (Braatne et al. 1996; Rood et al. 2003c). Cottonwoods are dioecious, having either male or female trees that bear flowers clustered in catkins.

Observations suggest that most seeds are deposited within a few hundred metres of the maternal plant, though the potential of long-range dispersal exists (Braatne et al. 1996).

Cottonwood seeds are tiny, containing very little endosperm, thus requiring ideal microsite conditions for establishment and growth (Horton et al. 1960; Fenner et al. 1984). As only a fraction will successfully establish, seeds are dispersed in large quantities, up to an estimated 25 million in some mature trees (Bessey 1904). Seeds require a barren, moist substrate on which germination occurs as seedling survival requires little or no competition. Receding post-peak spring-time river flows provide fresh alluvium to the banks of channels and are often associated with establishment events (Horton et al. 1960; Rood et al. 1998; Cooper et al. 1999).

Cottonwoods often do not have a root system fully established in the saturated water zone and become phreatophytic until their third or fourth growth year; prior to this time, they are sensitive to drought, particularly in their first year (Cooper et al. 1999). To prevent desiccation, roots must remain moist, usually achieved by elongation to maintain contact with the water table. The rate of root elongation varies across species and substrates (Fenner et al. 1984; Mahoney and Rood 1991; Mahoney and Rood 1992) but under optimal conditions seedlings are generally capable of surviving water table recessions of 2.5 cm/day (Mahoney and Rood 1998). Once cottonwoods have rooted to the late-summer groundwater table depth, long-term survival often becomes limited by biotic rather than abiotic factors (Cooper et al. 1999).

The topographic position that allows for cottonwood recruitment is bound by water availability and scour (Mahoney and Rood 1998; Johnson 2000). If the seedling becomes established too high above base flow, the roots will not be able to maintain contact with the falling water table and will suffer from drought-induced mortality by late-summer. At low elevations, subsequent floods or spring ice movements will damage or destroy seedlings and saplings (Cooper et al. 1999; Smith and Pearce 2000). River processes including sediment deposition, channel meandering, and channel realignment also contribute to the spatial patterning of cottonwoods, causing formation of linear bands of same-age cohorts that follow gradients of floodplain height and distance from the channel (Stromberg et al. 1991).

Another reproductive strategy that is widespread among riparian cottonwoods is their capacity for asexual, or clonal, reproduction (Braatne et al. 1996). Root suckering is a common form of clonal reproduction where the growth of adventitious shoots originates from preexisting parental roots due to crown damage or the disturbance of shallow roots (Schier and Campbell 1976; Rood et al. 1994). Root suckering appears limited to *Tacamahaca* species, though flood training has led to shoot suckering in *Aigeiros* species (Rood et al. 1994).

Crown breakage and branch fragment propagation following physical disturbance provides another common form of asexual reproduction (Rood et al. 2003c). Broken branch fragments can become buried in sediment where they sprout shoots and develop adventitious roots. Flooding allows for this form of reproduction as fresh sediment is laid down providing a barren, moist substrates reducing the stress of competition from other plants. The physical destructiveness of floods can also create a massive influx of broken branches in the river system. Wind and ice-scour also contribute to the shedding of branches that have the potential for clonal reproduction (Dewit and Reid 1992; Rood et al. 2003c).

Cladoptosis, another form of asexual colonization, is the abscission of branches that serve as clonal propagules. Recent evidence (Rood et al. 1994; Rood et al. 2003c) suggests, however, that it is not as common as previously thought (Galloway and Worrall 1979; Dewit and Reid 1992; Peterson et al. 1996).

In a study conducted in southern Alberta's Oldman River Basin, 52% of the saplings excavated originated as seedlings, and the remaining 48% were of clonal origin (Rood et al. 1994). Those of clonal origin came from root suckers (30% of total), shoot suckers (18%), and only two saplings (<1%) originated through cladoptosis. The formation of adventitious roots and shoots occurs in both sections of cottonwoods (Schier and Campbell 1976). However, branch propagation and cladoptosis occur in section *Tacamahaca* but rarely in *Aigeiros* (Dewit and Reid 1992; Rood et al. 1994; Rood et al. 2003c). The lack of branch propagation in section *Aigeiros* may be due to the hot, dry ecoregions this species occurs in, though evidence also suggests a genetic difference (Kranjcec et al. 1998; Rood et al. 2003c).

1.2.4 Annual increment interpretation

Dendrochronology involves the study of tree rings to investigate the year of tree establishment and to analyze temporal and spatial patterns in growth. Tree rings, or annual radial increments, form with the transition in wood formation from one year to the next. Wood of low density is usually produced early in the growing season and is called early-wood. The wood produced later in the growing season is of higher density and is called late-wood. The wood density in angiosperms depends on cell diameter, wall thickness and on the proportion of the various cells present (Kozlowski and Pallardy 1997). This proportion is relatively constant within a species but varies within a season.

It is the annual transition from late-wood to early-wood that produces the tree ring. This provides a permanent record in the wood of a tree showing the amount of growth that occurred in, normally, one season.

Cottonwood tree rings are especially difficult to interpret. Cottonwoods are diffuse-porous trees having vessels with relatively small diameters, and those formed in the early-wood are of similar diameter to those formed in the late-wood. This often produces faint rings that are difficult to identify. Cottonwoods can also produce complacent or double rings in a single season. As riparian cottonwoods are directly linked to the water table they experience xeric conditions when the adjacent river is low, and hydric conditions when the river is high. When environmental conditions change during the growing season, such as from a drought period to a wet period, a double ring or false ring can form (Everitt 1968; Fritts 1976). Cottonwoods can also produce complacent rings – rings with insufficient variation in widths to produce any recognizable sequence (Stokes and Smiley 1968). Attempts have been made to correct for double or missing rings in cottonwoods with mixed success by cross-dating between tress or within a tree if multiple cores were extracted (Everitt 1968; Scott et al. 1997; Galuszka and Kolb 2002).

In addition to the challenge of annual increment analysis, other complications arise when estimating the true age of cottonwoods. Sediment deposition will raise the ground level over time preventing accurate age estimation unless the root crown is excavated allowing for coring at the point of establishment (Everitt 1968; Scott et al. 1997). Flood-training, scouring from ice, and animal browse can also lead to an underestimation of true age (Everitt 1968; Mahoney et al. 1990). Suckering also complicates aging of trees when determining establishment of the original seedlings (Rood et al. 1994).

1.2.5 River regulation

The water table in riparian areas is often directly linked to the adjacent stream and has been shown to fluctuate with changes to river stage (Amlin and Rood 2003). Dams can severely change the flow regime of the river by reducing spring peaks, creating sharp changes in flow, and changing peak flows from spring to late-summer or even winter (Williams and Wolman 1984; Johnson 1998; Patten 1998). Consequently, cottonwoods downstream of dams and weirs have often been negatively impacted by river regulation (Bradley and Smith 1986; Rood and Heinze-Milne 1989; Rood and Mahoney 1995; Friedman et al. 1998).

Factors leading to riparian forest declines downstream from dams have been categorized as changes to hydrology and geomorphology (Rood and Mahoney 1990). Hydrologic change that reduces flooding can limit seedling establishment (Johnson et al. 1976; Scott et al. 1997), and reduced flows can diminish seedling survival (Rood and Heinze-Milne 1989; Scott et al. 1999; Amlin and Rood 2003). Geomorphic change resulting from hydrologic alteration can cause decreases in meander rates, reducing potential seedbeds for establishment (Johnson et al. 1976; Bradley and Smith 1986; Friedman et al. 1998; Shields et al. 2000), and reduced suspended sediment loads (Williams and Wolman 1984; Bradley and Smith 1986). With proper management and operations, dams can not only reduce their negative impacts on the river, but may actually be beneficial over prior conditions, thus allowing for successful cottonwood recruitment (Rood and Mahoney 2000; Rood et al. 2003b; Willms 2004).

1.2.6 Fluvial geomorphology

Leopold (1994) recognized that a river channel is formed by the relationship between the water flow, the quantity and character of the mobile sediments, and the character or composition of the materials, including vegetation, that make up the bed and banks of the channel. Alluvial river channels can be differentiated on the basis of force-resistance relationships as these are the channel forming processes (Nanson and Croke 1992). As such, fluvial geomorphic variations largely form the basis for channel and floodplain classification systems (Kellerhals et al. 1972; Nanson and Croke 1992; Rosgen 1994). However, some variations can also be linked to riparian vegetation (Bendix and Hupp 2000).

Riparian vegetation is affected by both flood processes and the characteristics of landforms that are shaped by floods. In many instances, species can be linked directly to specific fluvial landforms (Bendix and Hupp 2000). For instance, Scott, et al. (1996) found the relation between streamflow and the establishment of cottonwoods and willows (*Salix*) is conditioned by the dominant fluvial process or processes acting along a stream. The likelihood of a given species vigorously growing on a particular landform is a function of (i) the suitability of the site for germination and establishment, and (ii) the ambient environmental conditions at the site that permit persistence until reproductive age (Hupp and Osterkamp 1996).

Much research has been devoted to investigating channel responses to changes in the flow regime (Williams and Wolman 1984; Benn and Erskine 1994; Johnson 1994; Friedman et al. 1998; Shields et al. 2000). Dams may lead to reductions in streamflow, peak discharge, and sediment loads. As a result, channels may widen or narrow, aggrade or degrade, have a reduction in migration rates, and abandon floodplains, depending on the hydrogeomorphic context. This will often lead to an initial increase in riparian vegetation due to encroachment, followed by a maturing of the woody plants without juvenile replacement, or possible decline in health and size of the population (Williams and Wolman 1984; Rood and Mahoney 1995; Scott et al. 1996; Friedman et al. 1998).

Water management decisions have been hampered by the apparent variability of responses of riparian tree communities to flow alteration. When the relationships between streamflow and tree establishment are placed in a geomorphic context, much of that variability may be explained, and prediction of changes in the tree community is improved (Scott et al. 1996). In fluvial systems, the distribution of vegetation across landforms may be driven largely by the tolerance of species to specific hydrogeomorphic conditions and processes, making these the most limiting factors affecting the establishment, growth, and reproduction of riparian vegetation (Hupp and Osterkamp 1996).

1.3 STUDY REGION

Geomorphic transition zones are ideal locations for studying riparian vegetation responses to landforms. Southern Alberta has many transition points along all of the major rivers, but the most dramatic and abrupt occurrence is found along the Oldman River at Rocky Coulee. Here the river reach changes from a relatively freely meandering, alluvial channel within a wide floodplain, to a narrow, linear and constrained reach. For this study, 'constrained' refers to the restriction in lateral movement on the erosional outside of bends by a cliff wall, while 'confined' represents an area where the river is bound between two narrow, steep valley walls. Both channels forms are restricted by the geology, but constrained is not entrenched in a valley like the confined is. 'Alluvial' is used to describe reaches where the channel form is controlled predominantly by streamflow, which differentiates it from the constrained reach (Gordon et al. 2004). The channel is dynamic and wandering resulting in a meandering course that is partially braided in sections.

The Rocky Coulee transition zone allowed for a comparative study of the interaction between hydrologic and geomorphic influences on the establishment and survival of cottonwood trees. The river reaches above and below the transition share the similar flow regime, and weather and climate patterns. The reaches also share similar upland and floodplain land use practices as this region of southern Alberta is dominated by a semi-arid, agricultural landscape, and the Oldman River is a major source of irrigation water. The river is therefore partially regulated and water is extensively diverted for agricultural use. This flow regulation provides a basis for assessing cottonwood responsiveness to changes in river flow regime across contrasting geomorphic contexts.

The primary water management infrastructure along the Oldman River was the Lethbridge Northern Irrigation District (LNID) weir on the Peigan Indian Reserve #147. The weir began diverting water on May 1, 1923, but a flood on May 31, 1923 damaged the weir until repairs were complete in 1925. Therefore, this study considers the summer of 1925 as the first year of operation for the LNID weir. The weir has been used subsequently to divert water into off-stream storage reservoirs, leaving the Oldman River with reduced flows, particularly in the late-summer when natural flows are already low and irrigation demand is high.

The subsequent headworks infrastructure of the Oldman River Dam (ORD) and the events leading to its construction and operation were highly controversial. During the approval process, several legal precedents were set, including the requirements for federal and provincial reviews of environmental impact assessments. Construction of the ORD was completed in 1991, full supply level of the reservoir was reached in 1993, and operating guidelines were implemented in 1994. The guidelines included flow regulation for the purpose of meeting interprovincial apportionment, domestic and municipal use, irrigation, and ecological needs. Part of the operations strategy includes compensating for water withdrawals at the LNID weir, thus partially restoring summer flows of the river downstream of the weir.

The study sites above and below the geomorphic transition zone are located downstream from both the ORD and the LNID weir. Both reaches have therefore experienced partial dewatering and subsequent seasonal rewatering from the two water regulation structures. A third study site was established immediately below the ORD. This river reach is moderately constrained and has only experienced flow regulation since commissioning of the ORD. The lack of major tributary inflow between the study sites and the water regulating structures allowed for study of the influence of both river regulation and geomorphic context on cottonwood population structure, establishment, survival and growth.

CHAPTER 2 RESPONSE OF RIPARIAN COTTONWOODS TO PARTIAL DEWATERING AND SEASONAL REWATERING ACROSS A FLUVIAL GEOMORPHIC TRANSITION ZONE IN SOUTHERN ALBERTA

2.1 INTRODUCTION

The number of dams worldwide has increased over the past century to meet the increasing demand for fresh water. It is reported that there are now over 45,000 large dams in operation in the world (WCD 2000), and approximately three quarters of river discharge in the northern third of the world is dammed and regulated (Dynesius and Nilsson 1994). Water management has been concerned with requirements for human needs – to ensure a supply for agricultural, industrial and domestic use, hydroelectricity, and flood control – resulting in very unnatural flow regimes. This has severely impacted riparian (streamside) community health by altering flow patterns, isolating species, and severing the connectivity of corridors (Jansson et al. 2000; Nilsson and Berggren 2000; Nilsson 2002; Hughes and Rood 2003). These impacts have occurred in southern Alberta where nearly every major river is regulated by dams and/or weirs resulting in the disruption of riparian processes (Rood and Mahoney 1990; Rood et al. 1999).

Cottonwoods (*Populus* spp.) are the principal tree found alongside streams and rivers in western North America. Being phreatophytes, they are reliant upon the water table for survival and are therefore restricted to riparian areas in arid and semi-arid regions (Busch et al. 1992). The water table is directly linked to the adjacent river along influent or losing streams and is generally at a similar elevation as the river stage (Rood et al. 1995; Amlin and Rood 2003). Thus, changes in the flow regime will affect the water table level and consequently the water supply to cottonwoods (Busch et al. 1992;

Mahoney and Rood 1998; Amlin and Rood 2003). Cottonwoods are adapted to the natural seasonal timing of streamflows and alteration to the timing and magnitude of the flows has resulted in the deterioration of many riparian woodlands (Bradley and Smith 1986; Rood and Mahoney 1990; Friedman et al. 1998).

In southern Alberta, the Oldman River's flow regulation history began in 1922 when the Lethbridge Northern Irrigation District (LNID) completed a weir on the Peigan Indian Reserve #147 west of Fort Macleod. Operation of the weir did not commence until the summer of 1925 due to flood damage in the spring of 1923. The Oldman River Dam (ORD) was built upstream of the LNID weir and was commissioned in 1992. It functions primarily for water storage for irrigation, but operations permit the release of water in a pattern that restores a more natural flow regime downstream of the LNID weir. Water management strategies have been successfully implemented creating more favorable conditions for cottonwood survival and propagation both along the Oldman River (Willms 2004) and other regulated rivers (Rood and Mahoney 2000; Rood et al. 2003b).

This study assessed the impact of flow regulation on riparian vegetation in different geomorphic contexts. The primary focus was on two geomorphic settings: an 'alluvial' reach that is a dynamic, meandering or wandering channel within a broad valley, versus a 'constrained' reach in which the channel form is predominantly controlled by the geology having very little lateral movement within a narrow valley (Gordon et al. 2004). Because changes in geomorphic structure of the river valley lead to changes in floodplain dynamics and consequently vegetation composition (Bendix and Hupp 2000), it is of interest to determine whether an altered flow regime will affect the riparian cottonwoods differently. A third study reach that is partially constrained was selected to further assess the impacts of an altered flow regime on cottonwoods within constrained reaches.

This study focused on cottonwoods since they are responsive to changes in the flow regime, they provide the foundation for riparian woodlands and they are highly valued for both ecological and cultural reasons (Bradley 1993). Placing study sites on either side of a geomorphic transition zone allowed for surveying of cottonwood trees that share the same flow regime, but occur within extremely different geomorphic contexts. The purpose of this study was to determine how hydrology and the geomorphic context influence the establishment of cottonwoods and whether trees in physically constrained river reaches are more sensitive to changes in the flow regime than the alluvial reach.

2.2 STUDY AREA

Observations of topographic maps and aerial photos identified sixteen abrupt transition zones separating narrow, confined and wide, alluvial floodplains within the South Saskatchewan River and Milk River basins in southern Alberta. The present study took place across the most abrupt and dramatic geomorphic transition zone which occurs near Rocky Coulee along the Oldman River approximately 30 km northwest of Lethbridge between the municipalities of Fort Macleod and Monarch (Figure 2-1A). A third study site located just downstream of the Oldman River Dam was intermediate in geomorphic context relative to the two reaches at the Rocky Coulee transition (Figure 2-1B). All three reaches are of different geomorphology and have been impacted by river regulation structures (Table 2-1).

The 'Fort Macleod Reach' is upstream of the transition zone and extends for 34 km in river length between the town of Fort Macleod and the Rocky Coulee transition zone (Figure 2-2). This reach, characterized by an extensive gallery cottonwood forest, is part of a larger alluvial reach extending upstream nearly to the ORD. The channel along this alluvial reach is sinuous and wandering, contained within a wide, flat-bottomed valley (Figure 2-3A). Progressive arcuate bands, scroll bars, recent large avulsions and oxbows demonstrate the dynamic nature of the river in this reach.

The 'Monarch Reach' begins at the Rocky Coulee transition zone and continues downstream for 15 km in river length to the town of Monarch (Figure 2-2). It has very low sinuosity and is constrained by a narrow valley with steep valley walls. The near-vertical valley walls occur on the cut-banks of every bend restricting erosional processes and subsequent lateral movement. Resulting from the narrow floodplain and lack of river dynamics, the cottonwood patches are reduced to narrow bands along the channel edge (Figure 2-3B).

The geomorphic transition is unusual in the abruptness and the extreme difference in geomorphic context between the two study reaches. The transition has the appearance of being a link made between an old and a young channel. The alluvial Fort Macleod Reach may follow a paleo-channel while the constrained Monarch Reach may involve a new channel alignment. The differences in geomorphic context are not solely due to age and therefore the amount of time for valley widening, but also due to the underlying geologic formations. The alluvial reach is within the Willow Creek Formation, material that is more easily erodable than the St. Mary River Formation that contains the constrained reach (GSC 1967). The constrained reach shows signs of erosion taking place, but due to the harder material to erode, and the relative shortness in time that erosion has taken place, the Monarch Reach still remains a narrow valley.

This geomorphic transition may have formed by glacial activity during the Wisconsin glaciation (Stalker and Barendregt 1993). Based on the surrounding kettle features on the landscape, an ice sheet had apparently advanced over this region. It is possible that the ice sheet influenced the river course, redirecting it from the paleo-channel down a fault in the underlying sandstone, giving the Monarch Reach the current linear channel form.

An additional study site was surveyed upstream of the LNID weir and that reach was free-flowing prior to the commissioning of the Oldman River Dam in 1993. The 'Summerview Reach' is 3 km downstream from the Oldman River Dam and extended for 3.5 km (Figure 2-2). This reach was surveyed to provide a constrained control for the Monarch Reach and would thus contribute to the assessment of impacts of the LNID weir on cottonwood recruitment. However, it is actually of intermediate geomorphic form between the Monarch and Fort Macleod reaches.

Along all three reaches balsam poplar (*Populus balsamifera* L.) and narrowleaf cottonwood (*P. angustifolia* James) are found. Plains cottonwood (*P. deltoides* Bartr. ex Marsh) also occurs sparsely along the Fort Macleod and Monarch reaches. These three cottonwood species interbreed forming a hybrid swarm (Rood et al. 1986; Floate 2004). There may actually be the hybridization of four cottonwood species since black cottonwood (*P. trichocarpa* Torrey and Gray) is often accepted as a separate species instead of a subspecies of balsam poplar and may be found along these river reaches (Brayshaw 1965b; Moss 1992; Farrar 1995). Species discrimination is easily disputed in this region, however this study regarded 'balsam-like' trees as balsam poplar and not black cottonwood following the identification used by other studies in this region (Gom and Rood 1999a; Floate 2004). This stand is of international significance for the size of this hybrid swarm. It occurs uninterrupted for over 60 km in the Oldman River valley from the Summerview Reach to the Fort Macleod Reach providing one of the largest remaining natural riparian cottonwood stands in the world.

2.3 MATERIALS AND METHODS

2.3.1 Channel characteristics

Measurements with an opisometer (a map wheel) and 1:50,000 NTS topographic maps (82 H/11, 82 H/12 and 82 H/14) allowed for calculation of the river and valley characteristics of sinuosity, longitudinal profile (slope), valley width, and distance to reference points. Sinuosity was calculated as the ratio of channel (thalweg) distance to down-valley distance (Gordon et al. 2004). Sinuosity measurements were calculated using river distances twice the mean meander length of the Fort Macleod Reach (4.6 river km). Because both the Monarch and Summerview reaches are quite straight, sinuosity was calculated using the same distances as the Fort Macleod Reach. Longitudinal profiles (slope) and valley width were measured using the contour lines on the topographic maps. Channel slope was determined by measuring river length between contour lines that intersected the river. A floodplain width measurement was taken at approximately every fifth river kilometer using elevational contour lines.

2.3.2 Hydrology

Environment Canada's Surface Water and Sediment Database (GEG 2002) was used to compile hydrologic data. The primary gauging stations used for the analyses along the Oldman River were near Brocket (gauge number 05AA024) located at the downstream end of the Summerview Reach, near Fort Macleod (05AB007) at the upstream end of the Fort Macleod Reach, and Monarch (05AD019) at the downstream end of the Monarch Reach (Figure 2-2).

Base flow, a reference low flow, is often considered as the flow exceeded 95% of the time (Leopold 1994). However, for this study the base flow was determined based on cottonwood physiology (Mahoney and Rood 1998). The dormancy period of cottonwoods is typically from mid-October to the beginning of April (Braatne et al. 1996; Gom and Rood 1999a). Thus, flows during the growing period were analyzed to determine base flow. The lowest flows typically occurred shortly before the onset of cottonwood dormancy and consequently October daily mean discharge was analyzed and the lowest mean value in the hydrologic record was set as the base flow.

Discharge reconstruction to complete the hydrological record after the Fort Macleod gauging station was decommissioned in 1948 was calculated as follows:

1949 to 1965: Monarch – Willow Creek (05AB021)

1966 to 2001: Brocket + Pincher Creek (05AA004) – LNID diversions (05AB016 and 05AB019)

This generated a nearly complete data set for the Oldman River near Fort Macleod from 1910 to 2001.

2.3.3 Cottonwood population structure

2.3.3.1 Field Data Collection

Sampling of the cottonwood stands on the three study reaches of the Oldman River took two field seasons to complete. In the fall of 2002, eleven transects were established over 15 km of the Oldman River from the Rocky Coulee transition zone to the Highway 3A bridge near Monarch. This reach was delineated into 1.6 km (1 mile) segments along which at least one transect was established. Given the lack of cottonwood stands along this reach, transect locations were based on stand size and visible range of tree ages with an attempt to sample the full range of age classes.

The Fort Macleod and Summerview reaches were sampled over the summer of 2003. The Fort Macleod Reach had seven transects established over 34 km and the Summerview Reach had five transects established over 3.5 km. The densities and sizes of the cottonwood stands along these reaches were higher than along the Monarch Reach, and transects were consequently positioned on well-formed meander lobes that contained a wide range of tree sizes.

The cross-sectional belt transects were positioned perpendicular from river edge to the opposite woodland edge, usually the edge of the floodplain. Transect elevations were surveyed and trees were then surveyed for location along the transect and elevation. Measurements were made of trunk diameter at breast height (DBH, at 1.3 m above ground), and sapling height was measured for smaller trees (< 5 m tall). For each tree, the species was identified based on leaf shape (Eckenwalder 1977; Rood et al. 1986; Gom and Rood 1999a), and the health was assessed using a five point system where 0=healthy, 1-3=degrees of healthiness, and 4=dead.

Tree measurements were made along 2 m wide belts on both sides of the transect line along the Fort Macleod and Summerview reaches. No restrictions were placed on numbers of trees per site, only that transects ended in even aged, mature trees. This usually occurred at the transition from the floodplain to the sloping coulee bank. Along the Monarch Reach the trees were found to grow in linear bands. Consequently, no restrictions were placed on distance from the transect line that trees were measured at. Instead, approximately 50 trees were measured at each site, and some of these were tens of metres from the transect line.

A total of 510 trees were measured along the Monarch Reach, 545 trees along the Fort Macleod Reach, and 322 along the Summerview Reach. Every fifth tree had an increment core or disc extracted for aging and growth analysis. Swedish increment borers (4.3 and 5.1 mm diameter) were used to extract cores from trees with a basal diameter of 10 cm or greater. Cores were taken as low as possible, approximately 30 cm above the ground surface allowing sufficient height for rotation of the increment borer. Discs, cross-sections of the tree trunk, were cut at ground level for the young trees. The cores and discs were brought back to the lab for analysis.

2.3.3.2 Increment / Growth Analysis

Cores were mounted on wooden planks and sanded with progressively finer sandpaper down to 320 grit. Disc rings were easier to assess and required sanding to 220 grit. Further surfacing was performed with a razor on some cores and discs to create a sharply cut smooth surface that made rings more visible. For some cores, faint rings were treated with a lignin stain (80 % HCl: 20 % H_2O, saturated with phloroglucinol) that also facilitated ring identification.

An increment measuring machine with 0.002 mm precision (Velmex stage, Acu-Rite encoder from Velmex Inc., Bloomfield, New York; and MeasureJ2X software from VoorTech Consulting, Holderness, New Hampshire) and a dissecting microscope (typically set at 10 – 20X magnification) were used for analyses of the increment cores and discs.

Annual radial growth of the cottonwoods was measured and graphed onto composite skeleton plots (multiple tree growth plotted together) allowing for comparisons to be made in growth patterns between individual trees. This technique aids in detecting abnormalities due to missing or double rings (Stokes and Smiley 1968). Some sections that had minor damage to the annual rings due to twisting or breaking of the core could also be corrected by matching high and low growth years with samples from neighboring trees.

Cottonwood trees often do not grow radially symmetrical and this complicates core extraction of the pith. In cases were the pith was missed, a concentric circle ruler was printed on a transparency to deduce the distance from the last visible ring to the pith. Average ring width was then used to estimate the number of missed rings. Two additional years were added to all core counts to compensate for the extraction height of 30 cm.

2.3.3.3 Aerial photo interpretation

Cottonwood abundance along the Monarch Reach was measured to investigate possible changes in stand size over recent decades. Black and white aerial photos at 1:20,000 scale, or enlarged to this scale, were assessed from 1951, 1961, 1970, 1985, 1993 and 1999. Transparencies were placed over the air photos and the river, and 1 mm segments were traced on the transparency. Using the linear ticking method of Rood and Heinze-Milne (1989) cottonwood abundance was assessed by counting the number of segments covered by cottonwoods. This method does not consider the two-dimensional forest area, but instead inventories the one-dimensional lineal distance and is considered appropriate for cottonwood stands found in narrow bands. Forest abundance was then compared between years.

Stand densities were also measured by digitizing aerial photos and entering these into ArcView 3.2 (ESRI, Redlands, California). Cottonwood, floodplain, and cropland areas within the floodplain were measured, as was river and valley distances. From these measurements, the percentage of the floodplain covered by cottonwoods and cottonwood coverage per river length were calculated for the three river reaches.

2.3.4 Statistical analysis

Linear regression analysis was used to investigate relationships between tree size, both height and DBH, and tree age. The height versus age regression lines were forced through the origin so that a seedling of zero years in age was 0 cm tall, and thus prevented unrealistic age extrapolations. The DBH versus age regressions were not forced through the origin but determined with the least squares, line of best fit.

To compare population age structures of the different river reaches chi-square (χ^2) and exponential decay analyses were used. Due to differing sampling sizes of the three reaches, the number of trees established in each year was converting into a proportion of the total trees established over the entire time period. A χ^2 analysis then compared the age structures of the Fort Macleod and Monarch reaches to assess the impact of different geomorphic contexts on cottonwood recruitment when both reaches experienced the seasonally restored flow regime. A similar analysis was used to compare the age structures of the Monarch and Summerview reaches to assess the impact of different flow regimes on cottonwood recruitment on these two reaches with similar geomorphology.

An exponential decay function [$f(t)=Ae^{-kt}$, where A is a constant, k is a positive constant, and t is time] was used to compared the age structures of all three reaches for both one and two decade periods.

To compare cottonwood age with elevation, the trees were grouped into decadal age classes, except for the youngest trees which were divided into two five-year categories (ages 0-4, 5-9, 10-19, 20-29, etc). Analysis of variance was used to compare survival elevations of age classes both within and across reaches.

JMP 5.0 (SAS Institute Inc., Cary, North Carolina) was used for calculations of chi-squares and analysis of variance, and Microsoft Excel 97 (Microsoft Corporation, Redmond, Washington) was used for regression analysis and descriptive statistics.

2.4 RESULTS

2.4.1 Channel characteristics

The Fort Macleod valley was the widest of the three study reaches with an average width of approximately 1.5 km (Figure 2-4 and 2-5). The Summerview Reach valley width was just over 0.5 km, twice the width of the Monarch Reach at less than 0.25 km. The sinuosity of the channel in the Fort Macleod Reach was much higher than the Monarch or Summerview channels (Figure 2-4 and 2-5). A sinuosity value of 1.5 has been estimated to distinguish straight from meandering channels (Knighton 1998; Gordon et al. 2004) and thus the Fort Macleod Reach has a meandering channel while the channels in both the Summerview and Monarch reaches are relatively straight. The abrupt change in geomorphic structure of the river valley is the feature that divides the Fort Macleod and Monarch reaches. The valley changes abruptly from being wide with a meandering channel to a very narrow valley and linear channel (Figures 2-1 and 2-5).

The longitudinal gradients for both the Oldman River channel and valley are steepest along the Summerview Reach (Figure 2-4). The river valley gradient is steeper along the Fort Macleod than the Monarch Reach, but the river channel is steeper along the Monarch than the Fort Macleod Reach due to differences in sinuosity. The stream channel through the Fort Macleod Reach is somewhat braided, has numerous islands, and has diagonal, transverse, side and point bars. The Monarch Reach stream channel has diagonal bars, long straight sections and occasional mid-channel islands. The Summerview Reach has mid-channel and diagonal bars, but no islands.

2.4.2 Hydrology

Pincher Creek (05AA004) and Willow Creek (05AB021) are the only tributaries large enough to have gauging stations through the study sections along the Oldman River. Pincher Creek drains into the Oldman River 10.5 km downstream of the ORD, and Willow Creek at 73.2 km from ORD. Both are small streams with mean growing season (April to October) discharges of 1.75 and 4.58 m^3/s respectively. These flows are quite small relative to the mean growing season discharge of the Oldman River near Fort Macleod (1910-48) of 59.6 m^3/s. The Willow Creek confluence is approximately mid-way along the Fort Macleod Reach and most of the Fort Macleod study sites therefore had a similar flow regime as the Monarch Reach.

The base flows for the Monarch, Fort Macleod and Summerview reaches were all calculated to be 14 m^3/s. Ratings curves, a comparison between stream stage and stream discharge, were calculated based on real-time discharge for the three gauging stations, Oldman River near Monarch, near Fort Macleod, and near Brocket (Figure 2-6). This produced a base stage of 0.37 m at Monarch, 0.72 m at Fort Macleod, and 0.69 m at Summerview.

A hydrologic analysis of the response of the Oldman River to flow regulation due to the operation of both the LNID weir and the ORD was performed (see Appendix A). Diversions generally occur from April to October with the mean maximum weekly diversion of 13.2 m^3/s occurring in late-July. Mean maximum daily discharge was 20.2 m^3/s (se = 7.77) but daily highs reached 43.5 m^3/s. With the diversion capacity upgraded to 45 m^3/s in the mid-1980s, the weir had the capability to divert the whole river offstream during periods of low flow prior to commissioning of the ORD. Prior policy provided a minimum of only about 1 m^3/s (30 cubic feet per second) to be passed downstream (J. Mahoney, pers. comm.). Prior to the implementation of the Oldman River Dam and its associated operations strategy in 1993, there were times that the weir did only allow the minimum required flow downstream. Total annual diversions at the weir have increased over the record period by 224 % and recent maximum daily and annual withdrawals have further increased.

The operation strategy of the Oldman River Dam was implemented in 1994 and attempted to return a more natural flow regime to the river (Rood et al. 1998). Peak flows in the spring and early summer were trapped for release in the late-summer to compensate for withdrawals made by the LNID weir. This brought the mean late-summer discharge downstream from the weir to near pre-weir conditions (Figure 2-7). Median values for the mean discharges of August and September over the pre-weir, post-weir and post-dam periods were 19.9, 8.38, and 17.6 m^3/s respectively.

A recurrence analysis was performed on the data from the gauging station near Lethbridge (05AD007), as this is the longest data set for the Oldman River (1912 to 2001). Regression of this data set with the shorter Fort Macleod data set showed a fairly close correlation ($r^2 = 0.782$) giving confidence to the expectation of similar return interval at both gauging stations. A log Pearson Type III analysis of annual daily maximum events suggested that the "flood of the century" in 1995 (Rood et al. 1998) was actually greater than a one in two hundred year event (Q_{200}). This was the seventh flood greater than a Q_{10} on record, but the first since the commissioning of the ORD (Figure 2-8).

2.4.3 Cottonwood population structure

2.4.3.1 Aerial photo interpretation

The lineal ticking method of aerial photo analysis revealed that in 1961, 40.5% of the Monarch Reach was covered with cottonwoods. By 1993, the year the dam became operational, the cottonwoods had dropped to 34.7% but had apparently recovered slightly by 1999 (Figure 2-9). This translates into a 14% decrease in cottonwood coverage between 1951 and 1993 followed by a 9% increase between 1993 and 1999. With aerial photos at a 1:20,000 scale, individual mature trees were identifiable. An observation of the sequential aerial photos revealed mortality of mature trees with little recruitment of new trees.

Cottonwood abundance in 1999 along the three reaches was calculated with GIS software as the area of riparian cottonwoods per river length (Figure 2-10A). The Monarch Reach had the least extensive woodlands with 21 m^2/m compared to the Summerview Reach that was over 6-fold greater at 138 m^2/m. The Fort Macleod woodlands was the most extensive at 302 m^2/m, about 15-fold greater than along the Monarch Reach. The Summerview Reach had the highest cottonwood coverage of the floodplain at 59.3%, followed by Fort Macleod with 43.3%, and the Monarch woodlands occupied only 19.3% of the floodplain (Figure 2-10B). The forest on the constrained Monarch reach is small not only due to the limited floodplain coverage, but also by the small size of the floodplain. Cottonwood coverage near Monarch was thus very limited compared to the other two reaches, particularly relative to the Fort Macleod Reach.

2.4.3.2 Population structure analysis

Regression analysis revealed positive linear relationships between height and age, and DBH and age to be highly significant ($p<0.0001$) along all three study reaches of the Oldman River. This resulted in moderate correlation coefficients for the saplings aged along the Summerview ($r^2 = 0.397$), Fort Macleod ($r^2 = 0.644$), and Monarch ($r^2 = 0.716$) reaches (Figure 2-11). Even closer associations were observed for trunk diameters of larger trees at Summerview ($r^2 = 0.897$), Fort MacLeod ($r^2 = 0.832$), and Monarch ($r^2 = 0.842$) (Figure 2-12). This analysis allowed for the estimation by extrapolation of the ages of the remaining trees that were surveyed but were not aged by ring counts.

A chi-square (χ^2) analysis was performed on the proportional cottonwood age distribution at Fort Macleod and Monarch for the period 1983 to 2002 to capture 10 years of both pre- and post-dam data (Figure 2-13). There was a trend toward decreased proportions of trees along the Monarch Reach in the 10 year period (1983 to 1992) prior to the operation of the dam ($\chi^2 = 3.6$, df = 1, p = 0.058), but no difference found for the 10 year period (1993 to 2002) after operations began ($\chi^2 = 1.6$, df = 1, p = 0.206) (Table B-1). The pre-ORD trend was confirmed with analysis of the pre-flood of 1995 period

(1983 to 1994) as there were consistently proportionally more trees established along the Fort Macleod than Monarch reach ($\chi^2 = 8$, df = 1, p = 0.005). After the flood of 1995 there was an increase in the proportional establishment along the Monarch Reach ($\chi^2 = 4.5$, df = 1, p = 0.034) (Table B-2). Thus, the combination of the seasonally restored summer flow due to the ORD and the major flood of 1995 contributed to the restoration of cottonwood colonization along the Monarch Reach.

A χ^2 analysis was performed on the proportional cottonwood age distributions at Summerview and Monarch for the same time period as the Monarch versus Fort Macleod analyses. This analysis investigated the possible change in the age structure relating to the commissioning of the ORD or the flood of 1995 (Figure 2-14). There was no significant difference in the age structures during pre-dam ($\chi^2 = 1.6$, df = 1, p = 0.206) or post-dam ($\chi^2 = 0.4$, df = 1, p = 0.527) periods (Table B-3). There was also no significant difference in pre-flood ($\chi^2 = 2$, df = 1, p = 0.157) or post-flood ($\chi^2 = 0.5$, df = 1, p = 0.480) periods (Table B-4). Thus, the proportional age distributions along the two constrained reaches were generally similar despite the differing flow regimes.

The age distributions of all three reaches demonstrate typical cottonwood patterns with a large cohort of seedlings and saplings and a progressive reduction in older trees (Figure 2-15). Using an exponential decay equation, Fort Macleod was found to have the slowest rate of population decline of the three reaches (Figure 2-16). The age structure showed an annual decline of 10% at Fort Macleod compared to the Summerview and Monarch reaches that had similar declines of approximately 17%. Based on the 10 years since the Oldman River Dam was complete, the Fort Macleod Reach showed a 7%

annual decline in age structure versus 31% along the Summerview Reach and 22% along the Monarch Reach (Figure 2-17).

2.4.4 Survival elevations

Surface elevations of the cottonwoods relative to base flows were compared across the three reaches (Figure 2-18). Analysis of variance (ANOVA) found a significant difference between decadal age classes ($p<0.0001$), and an age class – reach interaction ($p=0.0002$) (Table B-5). All three reaches had seedlings and saplings established at low elevations, but after 10 years there is a separation between elevations along the constrained and the alluvial reaches. Trees older than 10 years on the constrained reaches were limited to higher elevations (greater than ~ 200 cm), whereas on the alluvial reach positions are still highly variable with trees found at both high and lower elevations.

Large woody debris, remnant from the flood of 1995, were found along the banks of the Monarch Reach. They were surveyed up to 230 cm above base flow, with an average elevation of 198 cm. This reflects the elevational limit of the flood and corresponded with the lower limit of mature trees along this reach.

2.5 DISCUSSION

2.5.1 Hydrologic changes

With an increase in human population, industry and irrigation in southern Alberta, there are increased demands being placed on the southern rivers. Irrigation is the largest consumer making up 71% of the consumed surface water in Alberta (Government of Alberta 2003). In southern Alberta, irrigation is responsible for many of the water development projects. These projects have lead to the attenuation of flood flows, reductions of annual discharge, and changes in the flow regime, resulting in the deterioration and eventual collapse of some cottonwood forests (Rood and Heinze-Milne 1989; Rood and Mahoney 1990).

The Oldman River is consistent with the trends. The LNID weir has been diverting larger quantities of water since 1925. However, it is not solely the quantity of the water diverted that is the problem for the cottonwoods. The timing of the diversions are especially critical. In the early-summer there is a high natural discharge of the Oldman River resulting in a relatively small percentage of total flow being diverted. It is the late-summer diversions when flows are naturally low that diversions have the greatest impact on the river and riparian ecosystem. Prior to commissioning of the ORD, seedlings established in the appropriate elevational band (Mahoney and Rood 1998) were often desiccated due to the artificially low late-summer river stage.

The Oldman River Dam's operation strategy attempts to balance the benefits to water users and to ecological functioning. Flow is attenuated in the spring and early-summer as a portion of the peak flow is captured and is released in the late-summer to compensate for withdrawals made by the LNID weir. This allows for maximum withdrawals throughout the summer when irrigation demands are highest. This management strategy has favoured cottonwood survival because late-summer flows were partially restored (Rood et al. 1998; Kalischuk et al. 2001; Willms 2004).

2.5.2 Cottonwood population structure

With the establishment of cottonwoods on the freshly deposited sediment on point bars, the progression of river meanders are essentially mapped out. By aging the trees, contour lines or isochrones can be established showing the rate of channel migration

(Everitt 1968; Nanson and Beach 1977). The forest age map can therefore be interpreted as a map of recent history of channel migration and floodplain development (Everitt 1968).

As cottonwood seedlings can become established at densities exceeding 1000 individuals/m^2 (Braatne et al. 1996), the young population undergoes an essential natural thinning due to environmental stresses and competition. A healthy stand structure that is not affected by water regulation will have relatively large numbers of seedlings and saplings with the number tapering over time to relatively few old trees in a mature population (Samuelson and Rood 2004). Mortality among young seedlings is extremely high, partially due to stage fluctuations following the germination period. Once germination has ended, the new cohort of seedlings is generally at greatest risk during the summer of the first year when the roots are shallow, and in the first winter and spring when ice and high stream flows will scour away seedlings at low elevations (Johnson 2000).

In the North American prairie region, natural cottonwood seedling mortality is primarily due to desiccation from climatic or streamflow drought and erosion from flowing water and ice scour. In one study, tree seedlings died on approximately 90% of all sample plots before reaching their first birthday (Johnson 2000). Artificially low streamflows, and livestock grazing also have extremely negative impacts on seedlings. Consistent with these interpretations, extensive seedling establishment and subsequent mortality occurred along the Oldman River after the 1995 flood (Rood et al. 1998; Kalischuk et al. 2001).

Along free-flowing streams, cottonwood seedling establishment is positively correlated to stream discharge rate during and following the seed germination period (Stromberg et al. 1991; Mahoney and Rood 1998). These cohorts of similarly aged cottonwoods result in spikes of recruitment within a population (Scott et al. 1997). This has been termed the 'punctuated progressive age structure' or sawtooth-shaped structure typical of cottonwood populations that undergo recruitment events timed with periodic flood pulses (Samuelson and Rood 2004). Even though there are few trees remaining in the population from prior to 1980 along the Oldman River, each study reach shows the punctuated progressive age structure (Figure 2-19). These peaks in cottonwood numbers are often associated with recruitment events corresponding with floods.

The sample sizes along the Fort Macleod and Monarch reaches were larger than that of the Summerview Reach but the relative percentages are generally similar until approximately the last two decades. It is primarily in the last 20 years that the stands' age structures vary. The exponential decay function shows that the Fort Macleod Reach has a gradual rate of decline in tree numbers over the past 20 years. The stand seems only minimally affected by changes in the flow regime due to seasonal dewatering of the river from the LNID weir, seasonal rewatering from the ORD, or influence of the flood of 1995. The Monarch Reach shows a sharper increase in trees over the past 20 years (Figure 2-13). Prior to the flood of 1995 there were few cottonwoods annually recruited to the population, and after the flood there was a proportional increase in cottonwood establishment. This is likely due to the creation of more barren safe sites at higher elevations that are needed for cottonwood recruitment along this constrained river reach.

Thus it was the flood that allowed for seedling establishment, but it is likely that the restored flow regime following the ORD allowed for greater survival of these seedlings.

The Summerview Reach also had an increase in recruitment after the flood of 1995, a similar pattern to that along the Monarch Reach (Figure 2-14). This was unexpected as the Summerview Reach floodplain is wider, and the cottonwood forest is more extensive than along the Monarch Reach. Although partially constrained, the Summerview Reach is of intermediate geomorphic context between the two other reaches. Additional complexities with the Summerview site relate to the commissioning and operation of the ORD. Reservoirs can trap more than 99% of the suspended sediments entering them (Williams and Wolman 1984), the stream below the dam experience flows that include sufficient power to erode, suspend and transport significant quantities of material without the natural load. This release of clear water, or 'hungry water' (Kondolf 1997) results in a downstream zone with depleted suspended sediment that has been termed the 'silt shadow' (Rood and Mahoney 1990). This zone exists downstream of most dams, causing subsequent removal of sediments, channel deepening, and armoring of the bed and banks (Williams and Wolman 1984; Brandt 2000). This may reduce the recruitment potential of the reach immediately downstream by reducing point bar development, the normal location of seedling establishment.

Associated with the change in downstream flow regime, there is sometimes a surge of cottonwood expansion after a dam becomes operational (Benn and Erskine 1994; Friedman et al. 1998; Johnson 1998). This is due to forest encroachment when there is narrowing of the channel, and a lowering of the recruitment zone due to attenuated spring peaks. This dam-induced pulse could be partially responsible for the increased numbers of new trees along the Summerview Reach since the commissioning of the ORD in 1993.

2.5.3 Geomorphic influence on cottonwood recruitment

River channel patterns are naturally developed based on the dissipation of energy of the moving water, and the erosion, transportation and deposition of alluvial sediments (Rosgen 1996; Knighton 1998). Channel and valley morphology are major controlling factors in riverine processes and these affect riparian tree establishment. Cottonwoods along the constrained reaches were found to have a different recruitment pattern than those on the alluvial reach. This is due to the geomorphic context which affects energy distribution, scour, survival elevations and surface area available for establishment.

There is typically little change in the channel form of narrow, deep channels (Williams and Wolman 1984). Contained within a narrow valley, the river lacks the meanders and lateral point bar accretion typically associated with wider, alluvial valleys. The Monarch Reach is confined to, and restricted by the valley walls with little opportunity for lateral migration or meandering. This is also true, but to a lesser degree, along the Summerview Reach. The natural channelization of the linear and constrained reaches results in increased stream velocity and power, providing the capacity to erode and transport more material (Rosgen 1996; Knighton 1998). Discharge is a product of wetted cross-sectional area and stream velocity. With steeper banks and smaller cross-sectional areas along the constrained reaches than the alluvial reach, the velocity during high flows will be greater. This increased energy puts more shear stress on the channel-bank interface and will more readily scour newly established vegetation. Cottonwood survival would therefore be restricted to positions higher up on the banks, on sites safe from flood and ice scour (Scott et al. 1997).

All cottonwood seedlings at low positions along the banks are at risk of scour from flood flows or ice (Johnson 1994; Mahoney and Rood 1998; Patten 1998; Smith and Pearce 2000). However, the progressive lateral movement of the channel along dynamically meandering reaches protects trees and shrubs on point bars from flood or ice disturbance. This results in the survival of a large number of even-aged cohorts on the floodplain (Scott et al. 1996). The Oldman River does not have progressive incremental lateral movement as on sandy river systems, but accretion does take place and over time the floodplain surface will elevate reducing the potential for scour of established cottonwoods. The alluvial reach has a wide, flat floodplain so the cross-sectional area during large, overbank flood flows is greater in the alluvial reach than in the constrained Summerview and especially Monarch reaches. With increases in discharge, the water can spread out over the larger, wider floodplain, reducing the velocity and dissipating the energy. Cottonwoods therefore do not need to be established at elevations as high on the banks to be safe from subsequent scour. With a lower elevation for colonization, drought stress is diminished and subsequently survival would be improved along the Fort Macleod Reach, a conclusion consistent with the observation of population age structure and decay in this study.

The geomorphic context also changes the size of the surface areas suitable for colonization. The constrained reaches have steeper banks than the alluvial reach and with typical recruitment elevations of 60-200 cm above late summer flow, this results in a narrower recruitment zone along the constrained reaches (Figure 2-20). Consequently there are smaller potential recruitment sites on the constrained reaches, and fewer recruitment opportunities because the constrained reaches require larger floods for recruitment.

2.5.4 Additional factors affecting recruitment

Livestock grazing pressure is a major factor limiting cottonwood recruitment in riparian areas (Auble and Scott 1998). Cattle impact cottonwood establishment in two ways: (i) cottonwood seedlings and young saplings are trampled and uprooted (Kauffman and Krueger 1984), and (ii) cattle will eat seedlings and saplings since these are as palatable as grasses and other herbaceous plants (Patten 1998). Long-term grazing reduces the structural complexity of riparian vegetation (Johnston and Naiman 1990; Scott et al. 2003), inhibits shoot growth (Andersen and Cooper 2000), and can prevent the correlation of flood pulses with cottonwood recruitment (Kalischuk et al. 2001; Beschta 2003; Samuelson and Rood 2004).

The cottonwood population structure would likely have been different if not for the impact of cattle along the Oldman River. The correlation of recruitment events with flood events may have been stronger without grazing that has occurred along all reaches in this study. Livestock and native ungulates are abundant along the entire study area of the Oldman River, but a lack of information about historic grazing pressure excludes a quantitative analysis of how these impacted cottonwood recruitment along the study reaches.

Another recruitment strategy that cottonwoods have is asexual reproduction. Cottonwoods, particularly those in section *Tacamahaca* (*P. balsamifera* and *P. angustifolia*), can regenerate asexually by means of root suckering due to crown damage, root disturbance, or occasionally rooting of branch fragments (Braatne et al. 1996; Gom and Rood 1999b; Rood et al. 2003c). Asexual reproduction does not follow the seedling establishment pattern, but instead suckers will change the age structure by filling in gaps between episodic seedling recruitment events.

Asexual reproduction may have occurred along the Oldman River to allow for the continued replenishment of the forest in the decades when summer flows were artificially low and seedling survival was sparse. It is therefore expected that many of the cottonwoods, particularly those middle aged along the Monarch reach, were established asexually and not from seeds.

2.5.5 Cottonwood conservation

Cottonwoods are a keystone species in riparian communities as their presence, or lack there of, affects many other species (Savoy 1991; Finch and Ruggiero 1993; Farley et al. 1994). This makes them an important species to study and to protect to ensure their long-term survival. The presence of cottonwoods not only increases riparian biodiversity, but flows associated with the maintenance of cottonwoods are consistent with river management efforts that support a diversity of riparian and aquatic species, as well as essential geomorphic processes (Nilsson 1992; Sparks 1995; Hupp and Osterkamp 1996).

Recent studies have demonstrated the interactions and dependency of arthropods and cottonwood hybrids (Whitham 1989; Floate et al. 1997; Waltz and Whitham 1997); birds and cottonwood community structure (Savoy 1991; Martinsen and Whitham 1994; Scott et al. 2003); and mammals and cottonwood growth (Ripple and Beschta 2003). These consistently demonstrate the fundamental role of cottonwoods in riparian ecosystems. Cottonwoods also have positive benefits to aquatic systems. The addition of detritus into streams has been shown as an important component for the aquatic food web (Wallace et al. 1997). The management of flows for riparian cottonwood needs can also meet the instream flow needs of some fish species, and *vice versa* (Clipperton et al. 2003; Rood et al. 2003b). The interactions between species in riparian areas are complex and create a large assemblage of organisms that co-exist in a small, but biologically diverse patch of the landscape (Nilsson 2002).

With continued pressure being placed on rivers for agricultural, municipal, and industrial use, the regulation of rivers, now more than ever, needs to consider ecological consequences. Damming of rivers can cause old cottonwood forests to occupy a larger area than young forests, eventually reducing cottonwood forests into relict stands and reducing their functionality as habitat for wildlife (Johnson 1992). River regulation can be managed for the maintenance of natural processes (Clipperton et al. 2003) and some dams have been managed to restore cottonwood abundance and community structure (Rood and Mahoney 2000; Rood et al. 2003b; Willms 2004).

2.5.6 Conclusion

This case study demonstrates that cottonwoods respond differently to flow regulation depending on the local geomorphic context. The alluvial Fort Macleod Reach had a greater proportion of trees established prior to the ORD, and was less dependent on the instream flow pattern. Cottonwoods along the alluvial reach were not as negatively impacted from seasonal dewatering of the river, nor as positively impacted from seasonal rewatering of the river as on the adjacent constrained reach. However, flow alteration by the ORD has been shown to improve cottonwood recruitment over pre-ORD conditions on alluvial reaches of the Oldman River between the LNID weir and the Fort Macleod Reach (Willms 2004). Thus, river flow pattern is indeed important for riparian cottonwoods but the sensitivity of the population to hydrologic alteration is strongly influenced by the geomorphic context.

Both constrained reaches currently have relatively high numbers of seedlings and saplings resulting from both a large flood, and the flow regime provided by the ORD. The observation that both constrained reaches had similar cottonwood population structures suggests that the geomorphic context greatly limits cottonwood expansion. It was expected that the age structure along the Summerview Reach would be different than the Monarch Reach due to the different flow regimes resulting from diversions at the LNID weir. Given that the flood of 1995 likely scoured some of the previously established vegetation on these reaches, it acted as a 'resetting event' and created substantial nursery sites for cottonwood establishment. It is expected that if the ORD did not augment late-summer flows, there would be far fewer surviving seedlings along the Monarch Reach than the Summerview Reach following the flood. The Summerview Reach now experiences artificially high late-summer flows which will decrease drought-induced mortality of seedlings. Thus, the observed similarity in recent population structure suggests that the innovative operation regime from the ORD is succeeding in restoring cottonwood recruitment through the Monarch Reach.

Table 2-1: River regulation structures and their hydraulic impacts on the three study reaches along the Oldman River.

Reach	Geomorphic context	Channel form	River regulation structures [a]	Hydrologic impacts
Summerview	moderately constrained	linear, single channel	1. ORD (1993)	1. reduced spring flooding, increased summer flows
Fort Macleod	alluvial	meandering, partially braided	1. LNID (1925), 2. ORD (1993)	1. reduced summer flows, 2. reduced spring flooding, partially restored summer flows
Monarch	constrained	linear, single channel	1. LNID (1925), 2. ORD (1993)	1. reduced summer flows, 2. reduced spring flooding, partially restored summer flows

[a] LNID (Lethbridge Northern Irrigation District) weir (1925)
ORD (Oldman River Dam) (1993)

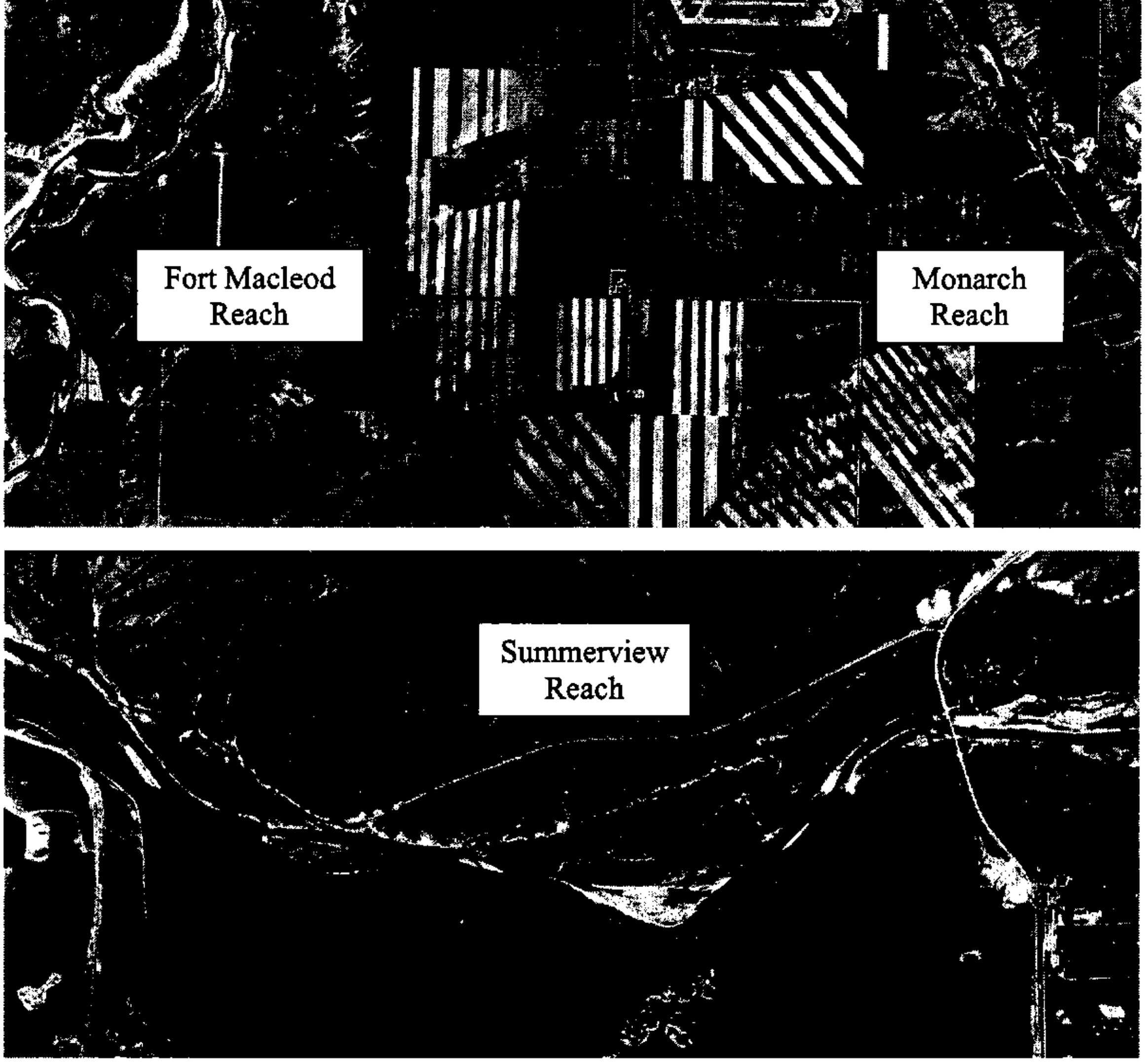

Figure 2-1: Aerial photos of the Oldman River at: (A) the Rocky Coulee geomorphic transition, July 30, 1992, and (B) the Summerview Reach, September 5, 1987. The Fort Macleod Reach extends for 34 river km upstream of the transition, and the Monarch Reach extends for 15 river km downstream. The entire Summerview Reach is in the photo, contained between the bars intersecting the river. Note the differences in scale between the two pictures.

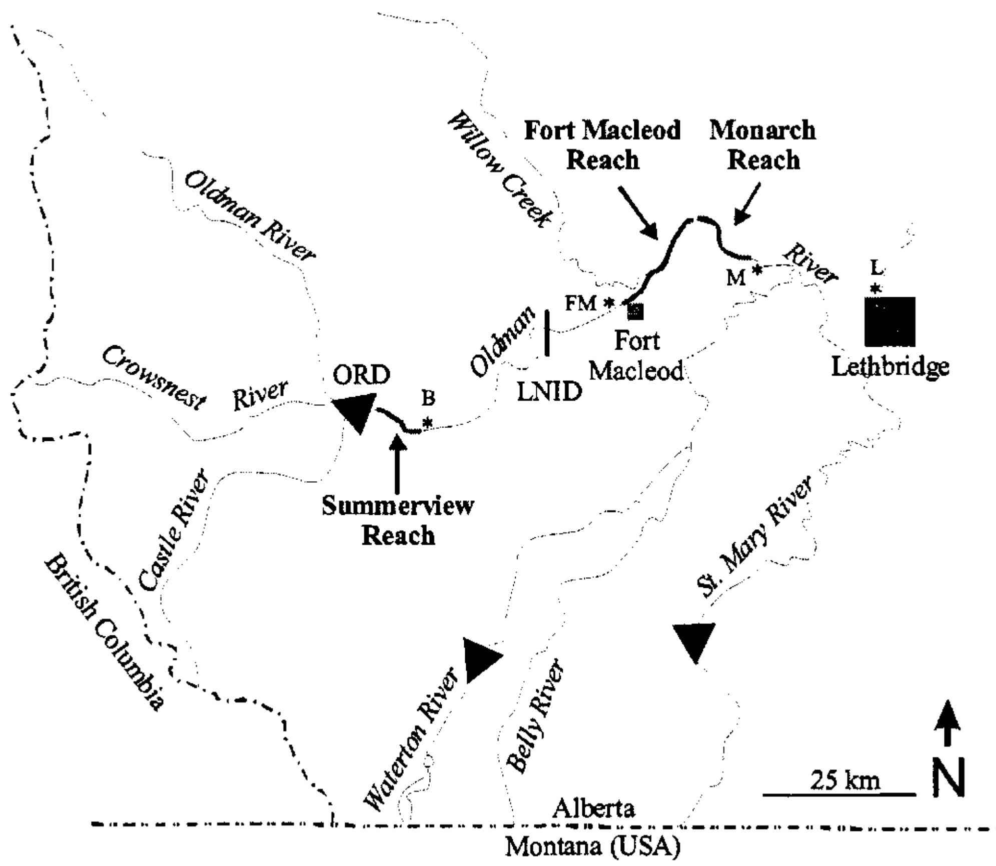

Figure 2-2: Map of the Oldman River and tributaries in southern Alberta. Labels include the three study reaches, the Oldman River Dam (ORD), the Lethbridge Northern Irrigation District (LNID) weir and hydrometric gauging stations (*) along the Oldman River at; Brocket (B), Fort Macleod (FM), Monarch (M), Lethbridge (L). Major dams are marked with triangles.

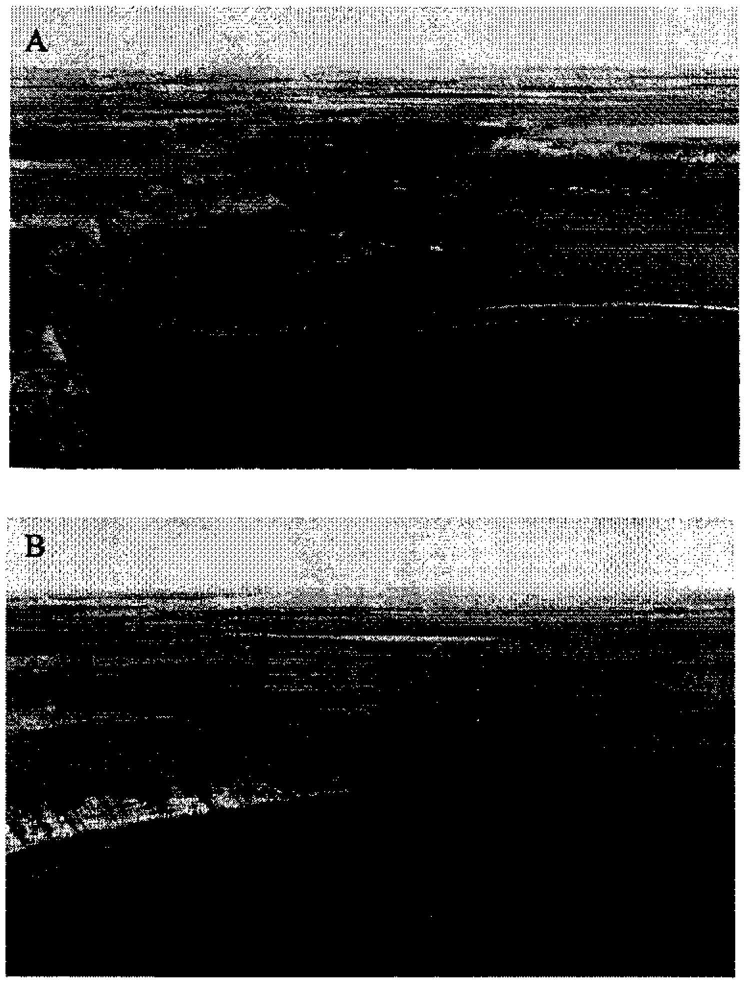

Figure 2-3: Oblique aerial photographs of: (A) the wide, alluvial Fort Macleod Reach looking downstream towards the geomorphic transition, and (B) the narrow, constrained Monarch Reach looking downstream away from the geomorphic transition.

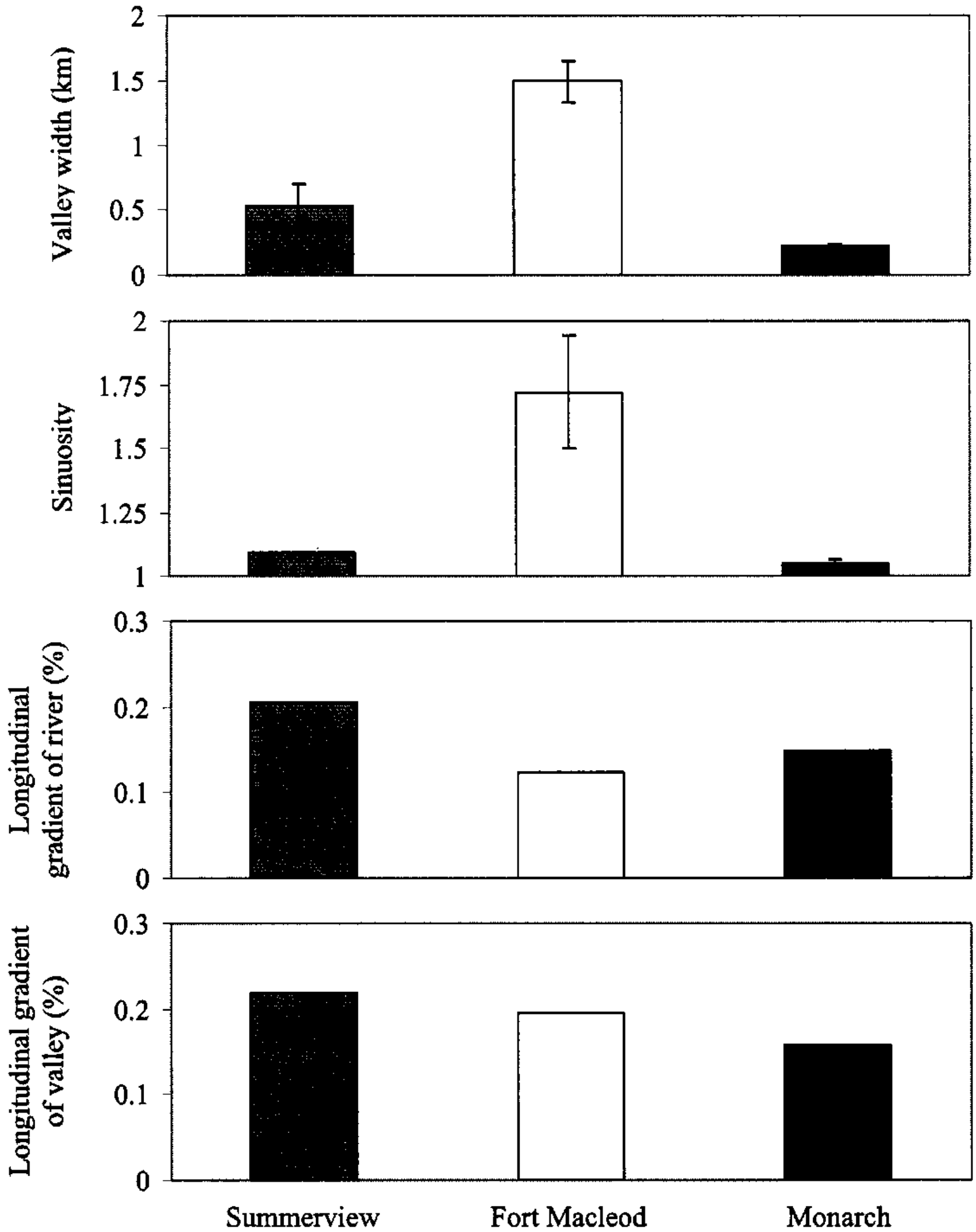

Figure 2-4: Channel characteristics of the three study reaches along the Oldman River.

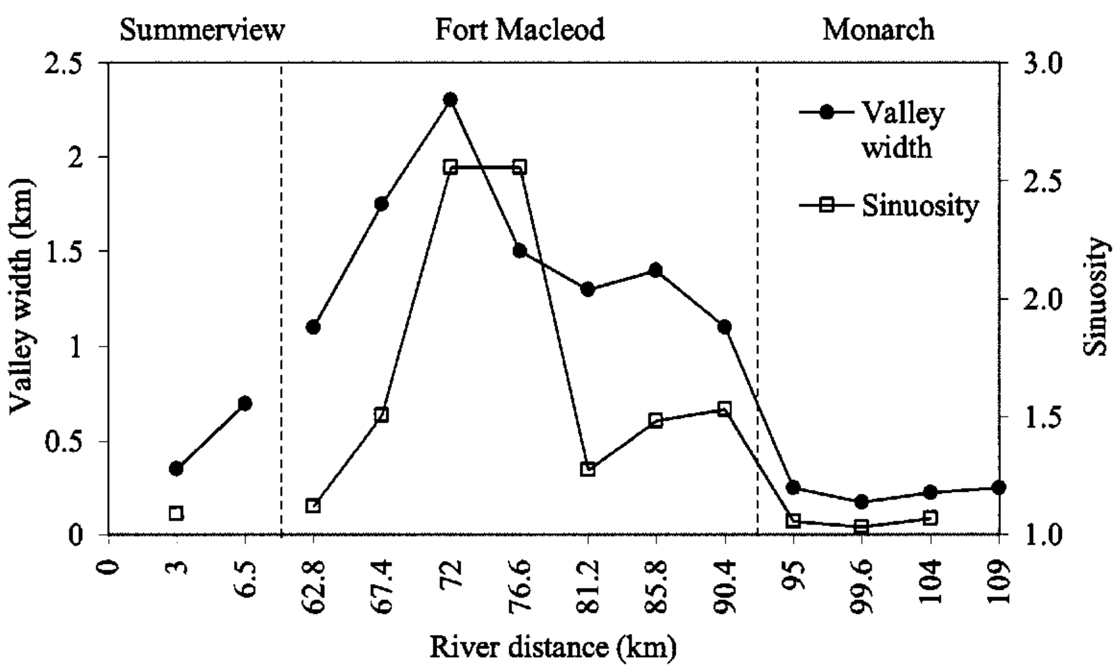

Figure 2-5: Channel characteristics across the geomorphic transition zone separating the Summerview, Fort Macleod and Monarch reaches. River distance is in kilometers from the Oldman River Dam. Note the break in river distance between Summerview and Fort Macleod.

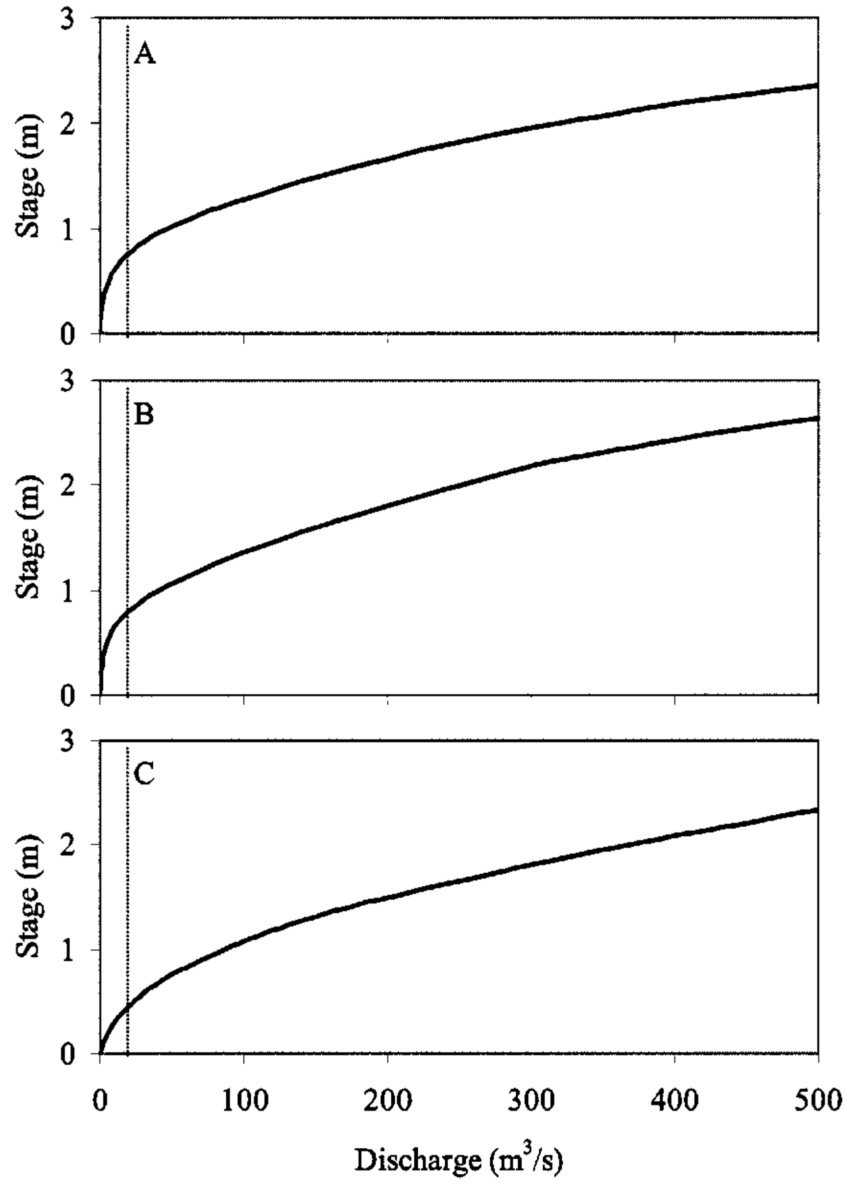

Figure 2-6: Ratings curves for the gauging stations along the Oldman River (A) near Brocket (downstream end of Summerview reach), (B) near Fort Macleod (upstream end of Fort Macleod reach), and (C) near Monarch (downstream end of Monarch reach). Dashed line shows base flow of 14 m^3/s.

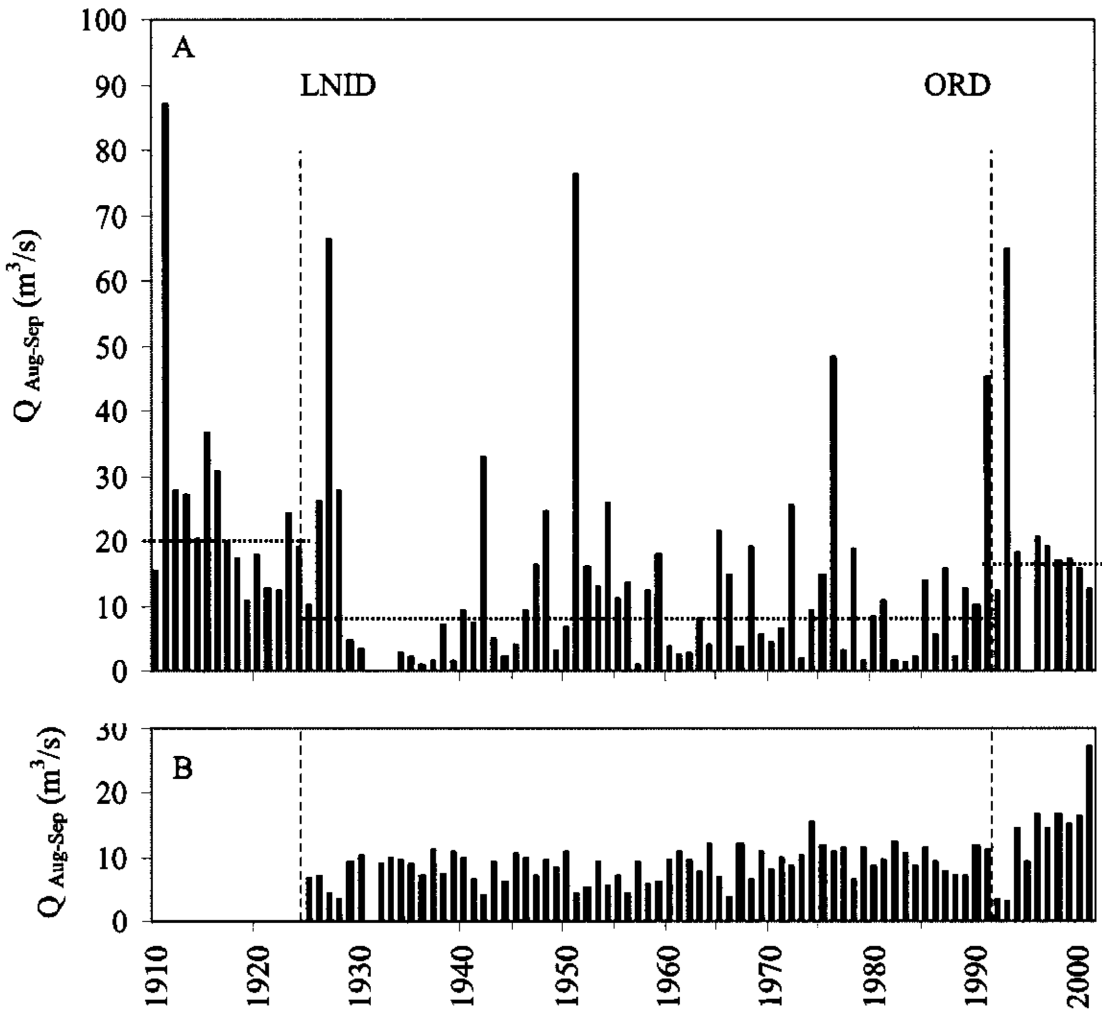

Figure 2-7: Mean late-summer ($Q_{Aug\text{-}Sep}$) discharge of: (A) Oldman River near Fort Macleod (05AB007) and (B) diversions from Lethbridge Northern Irrigation District (LNID) weir (05AB016, 05AB019). Vertical dashed lines indicate when LNID weir and Oldman River Dam (ORD) became operational. Gaps in the early 1930s and 1995 are due to missing data. Horizontal dashed lines show median discharges: 19.9 m^3/s pre-LNID, 8.4 m^3/s LNID operational, 17.6 m^3/s ORD operational.

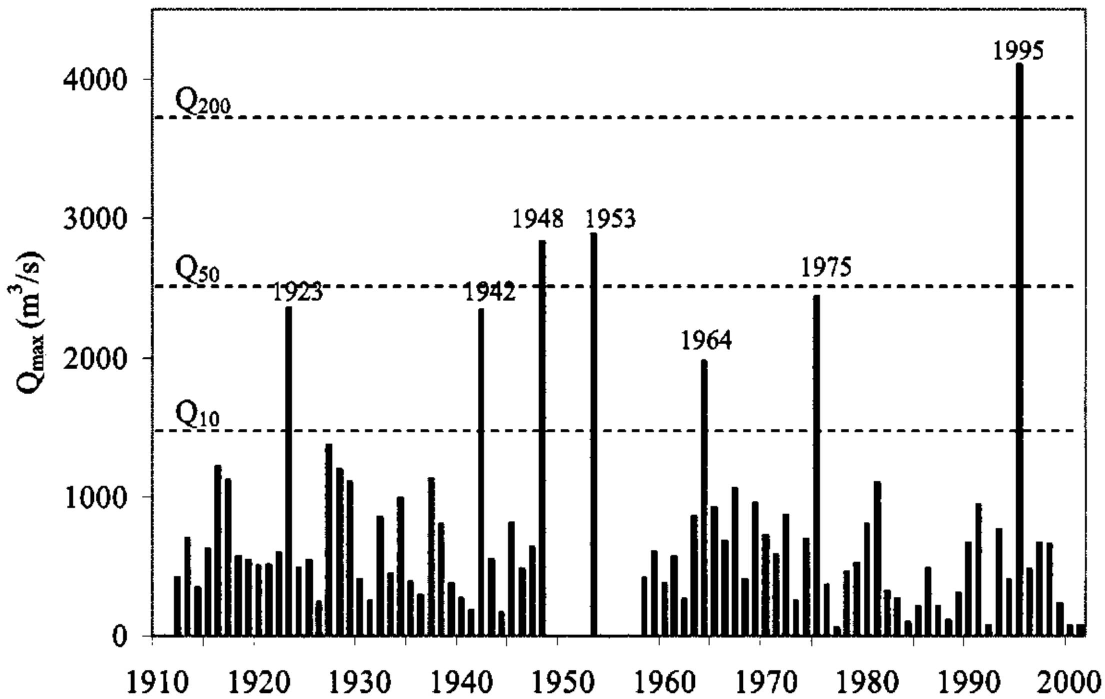

Figure 2-8: Annual maximum mean daily discharge (Q_{max}) of the Oldman River near Lethbridge. Return intervals based on log Pearson Type III analysis. Data gaps in the 1950s due to missing data.

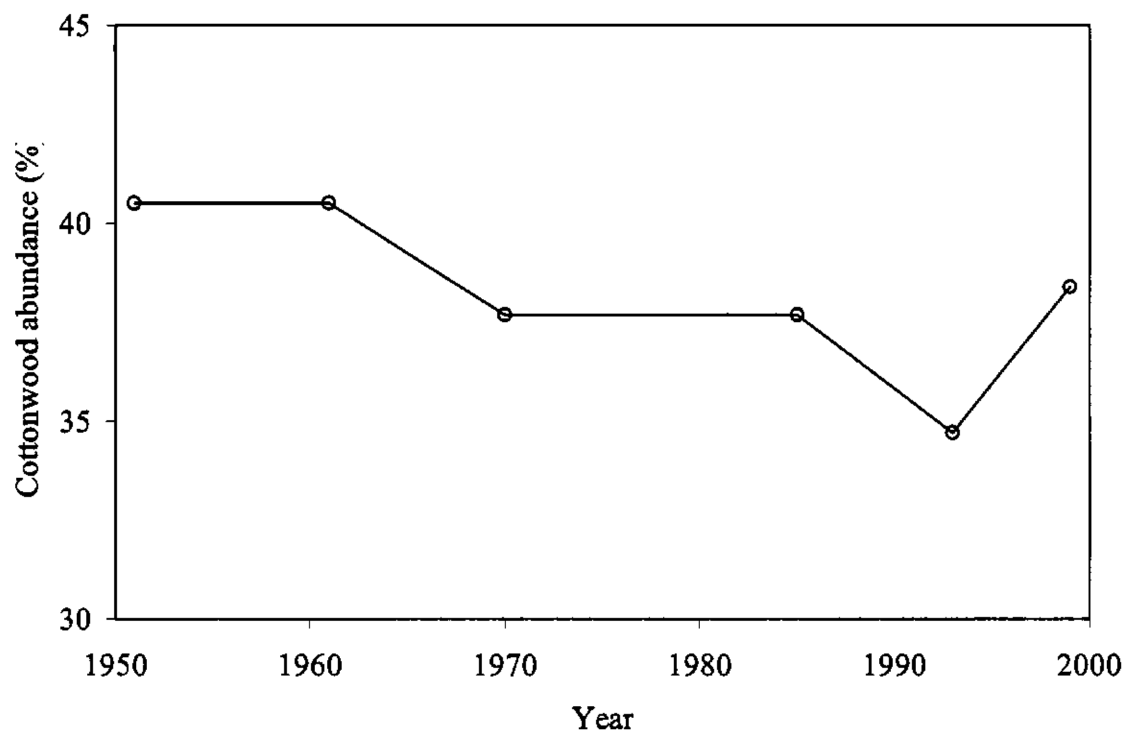

Figure 2-9: Results of aerial photo analysis determining percent lineal abundance of cottonwood trees along the Monarch Reach.

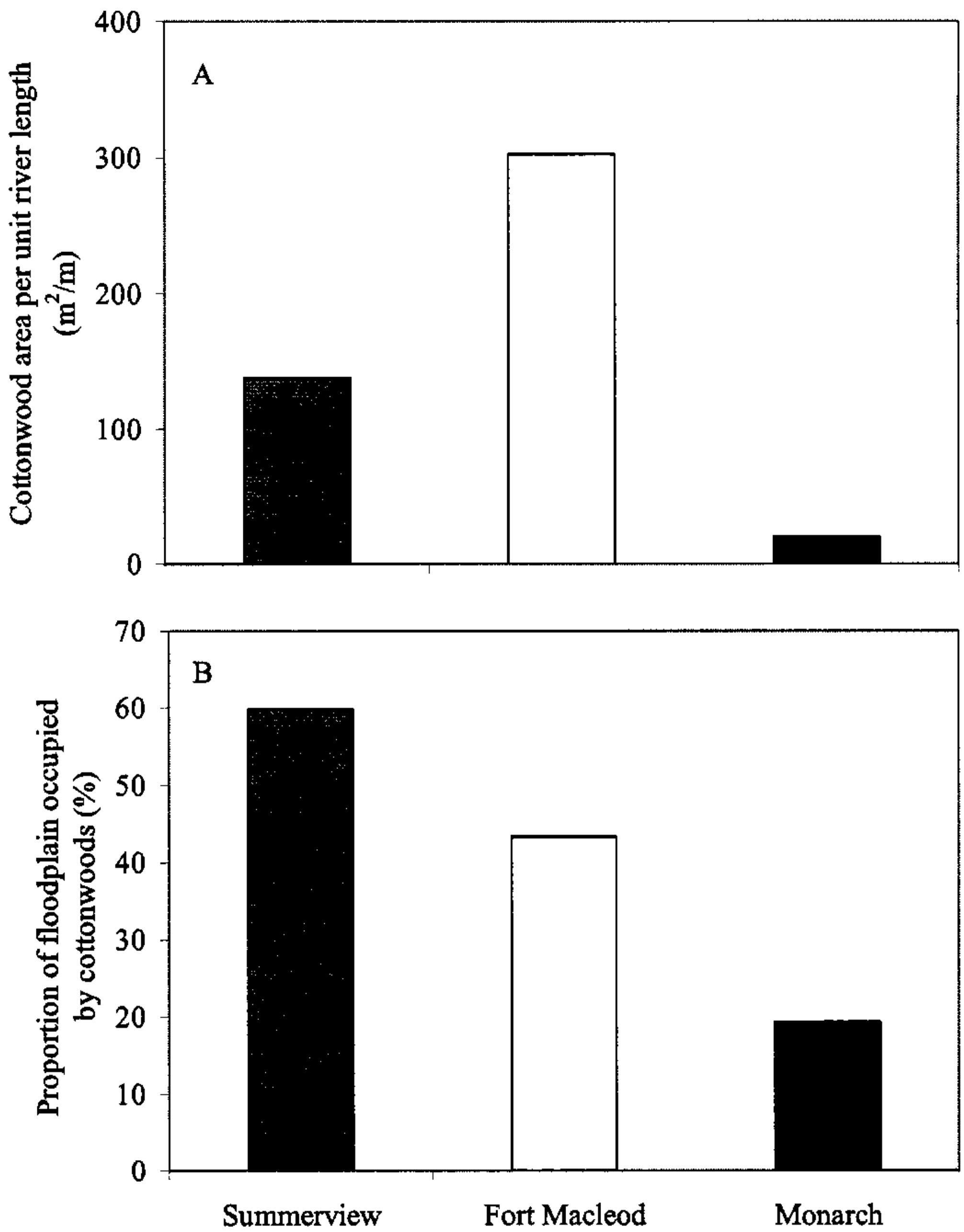

Figure 2-10: Cottonwood forest size measurements as (A) stand size per river length, and (B) percent of the floodplain occupied, across the three study reaches.

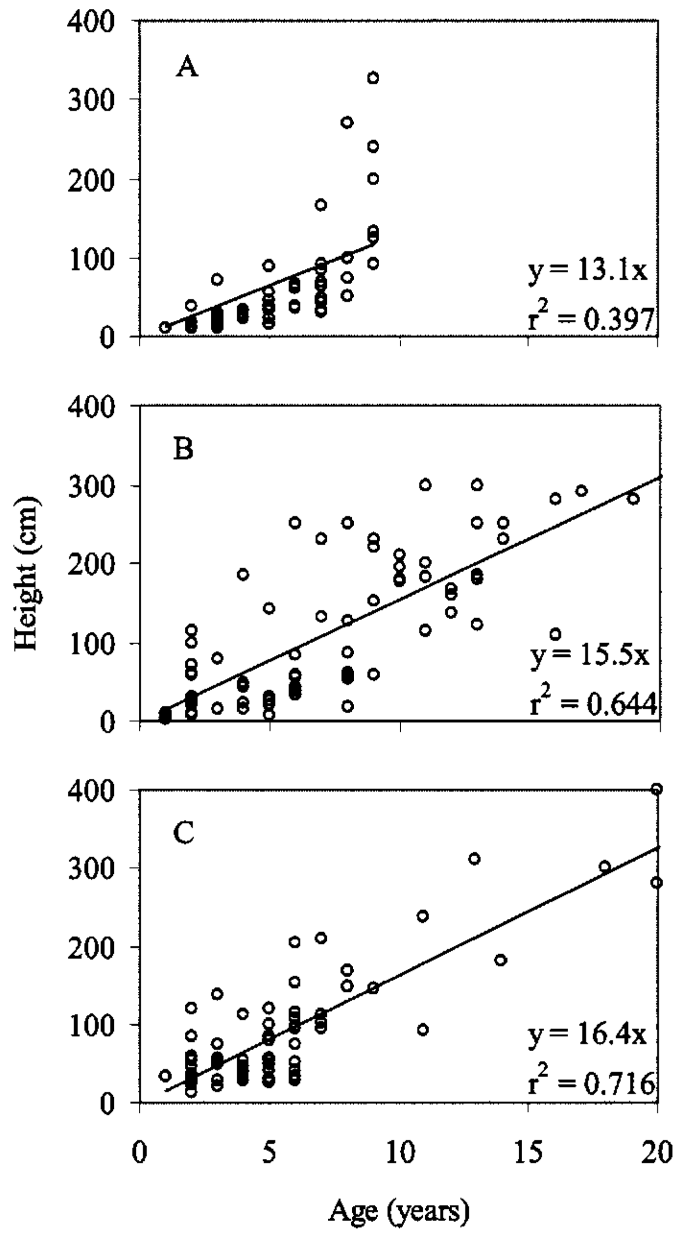

Figure 2-11: Regression analysis of height versus age of cottonwoods along the (A) Summerview, (B) Fort Macleod, and (C) Monarch reaches.

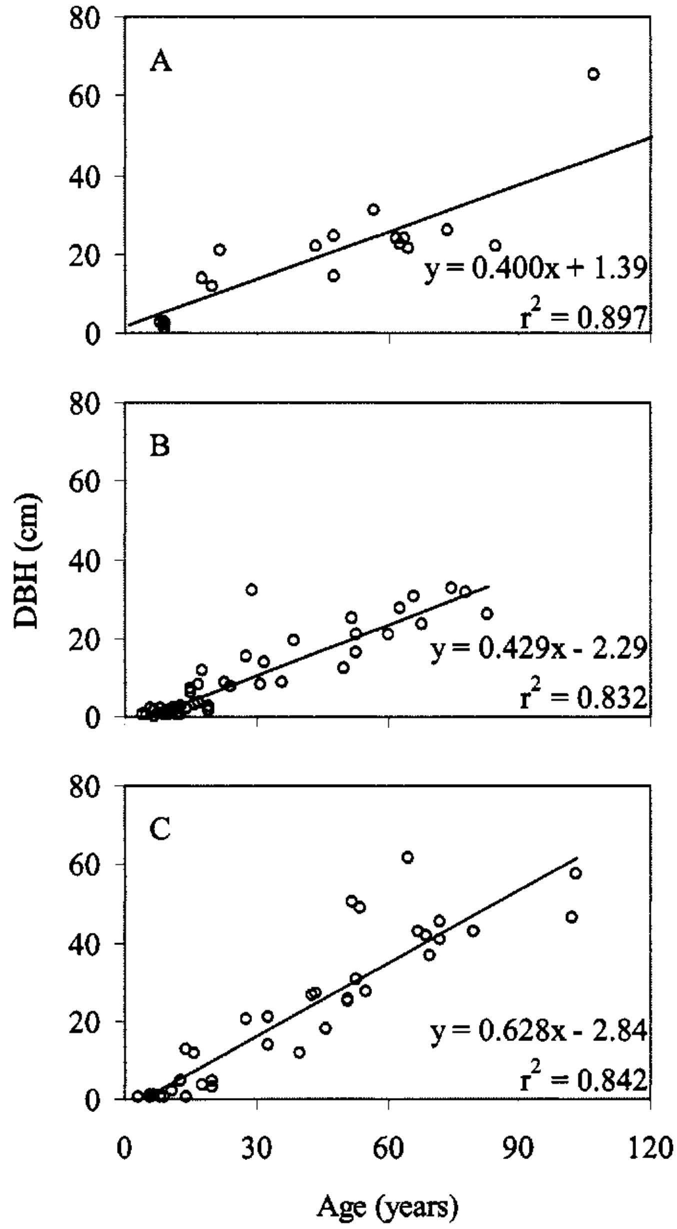

Figure 2-12: Regression analysis of diameter at breast height (DBH) versus age of cottonwood trees along the (A) Summerview, (B) Fort Macleod, and (C) Monarch reaches. There is an additional data point at Summerview (253 yrs, 100.8 cm) not shown.

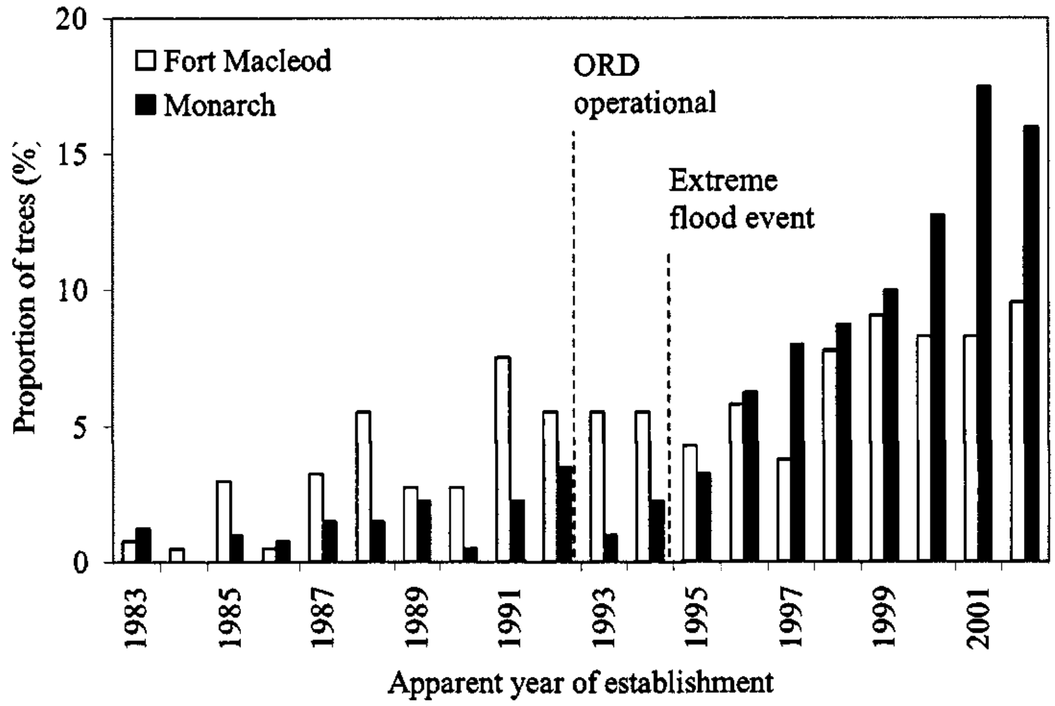

Figure 2-13: Cottonwood age structure (%) over one decade before and after the implementation of the Oldman River Dam (ORD) for the Fort Macleod and Monarch reaches.

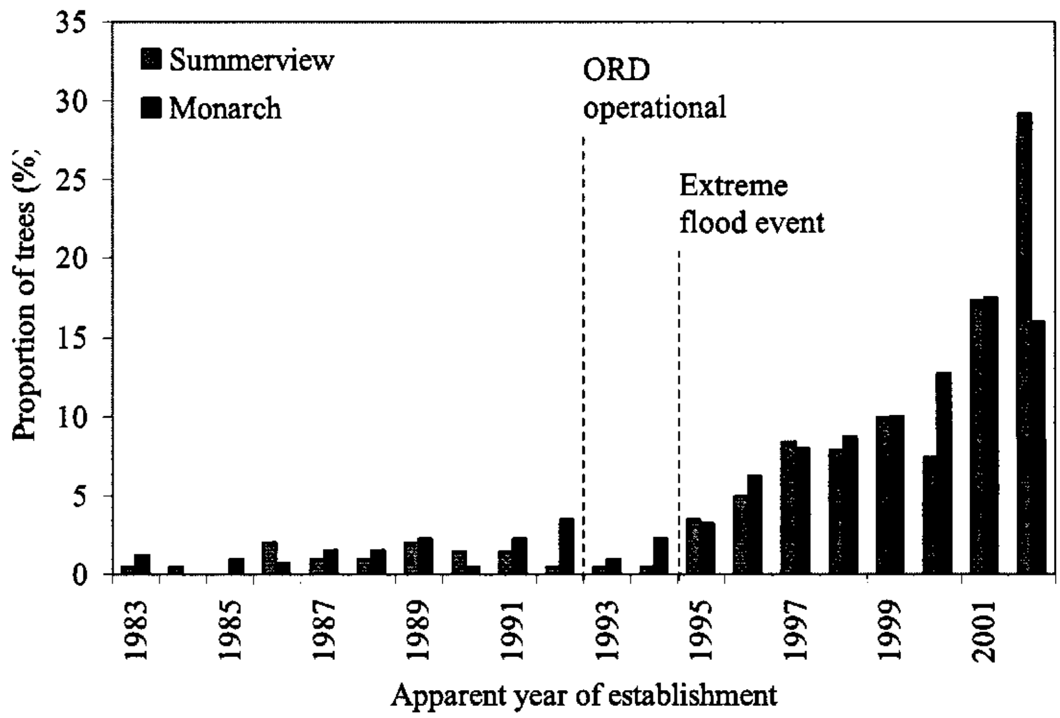

Figure 2-14 : Cottonwood age structure (%) over two decades before and after the implementation of the Oldman River Dam (ORD) for the Summerview and Monarch reaches.

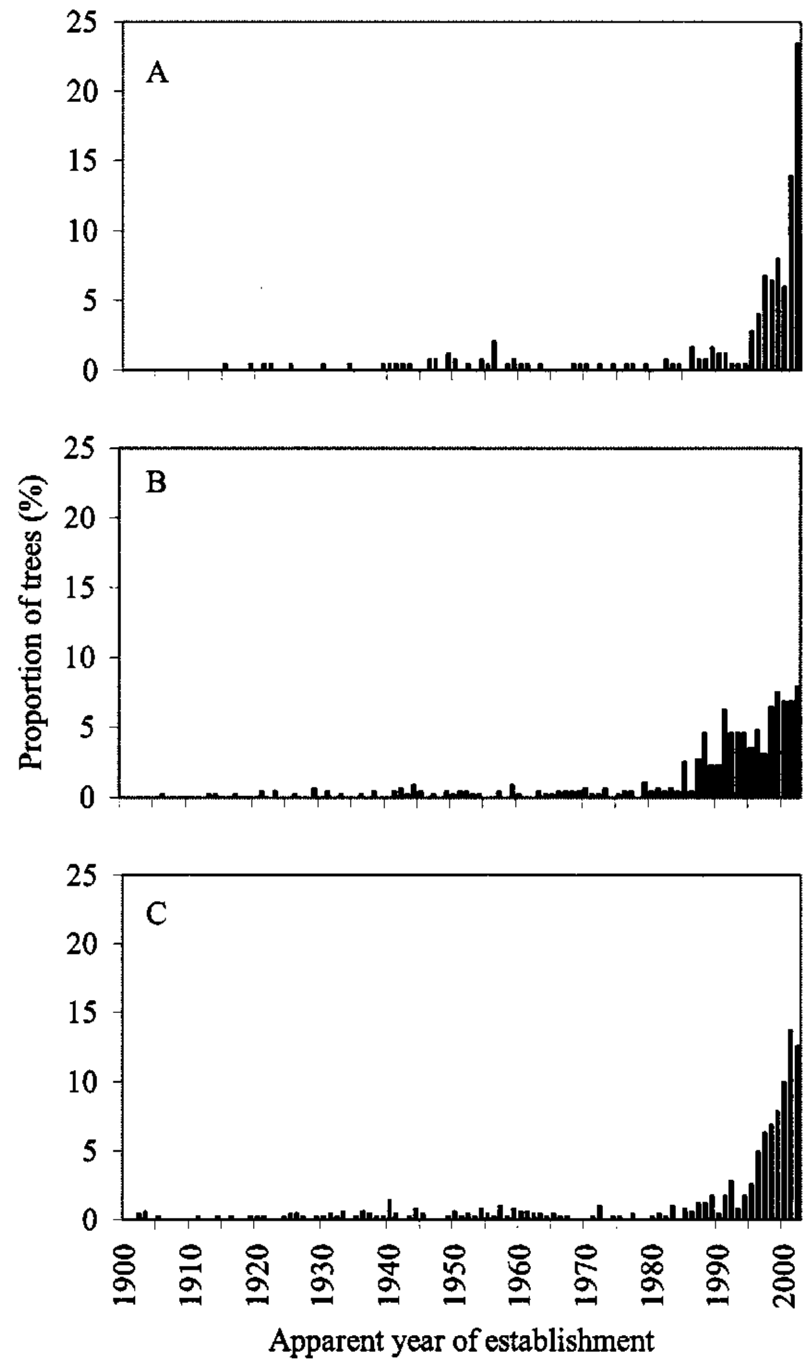

Figure 2-15: Age distribution of cottonwood trees along the (A) Summerview, (B) Fort Macleod, and (C) Monarch reaches. Not shown are individual trees estimated to have established in 1751, 1796, 1896, and 1897 along the Summerview Reach, and in 1811, 1873, 1874, 1895, and 1898 along the Monarch Reach.

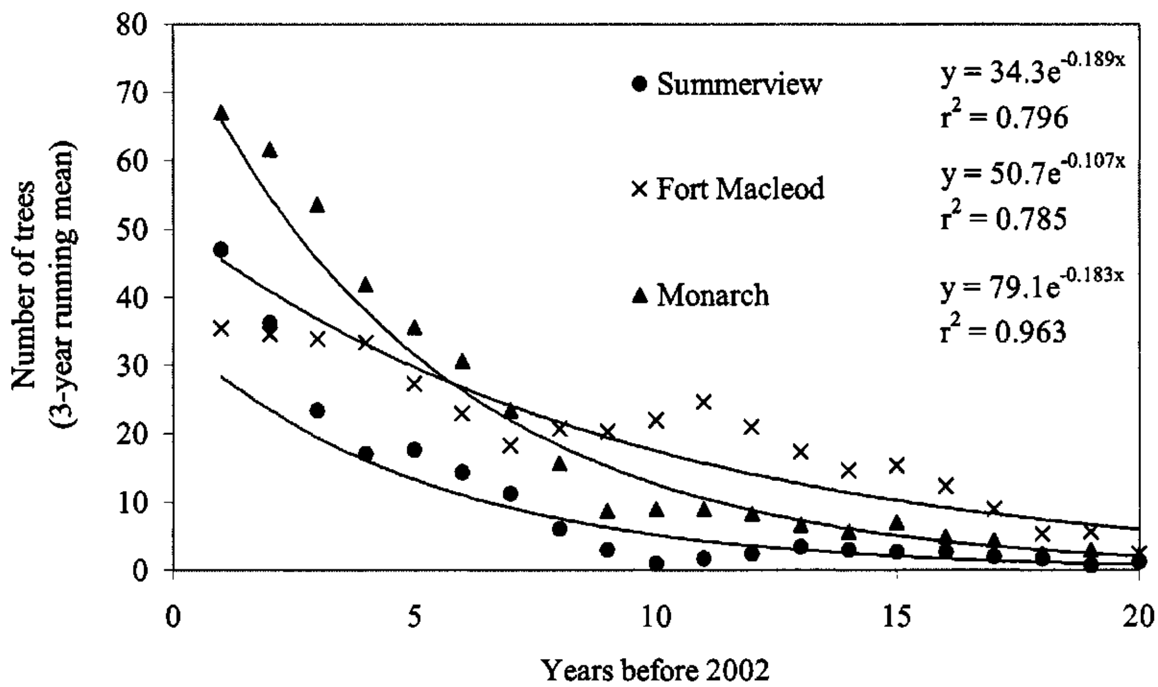

Figure 2-16: The exponential decay of cottonwood numbers along the three study reaches along the Oldman River over the last two decades. There has been a 17.2 % annual decrease in cottonwood numbers along the Summerview Reach, 10.1 % along the Fort Macleod Reach, and 16.7 % along the Monarch Reach.

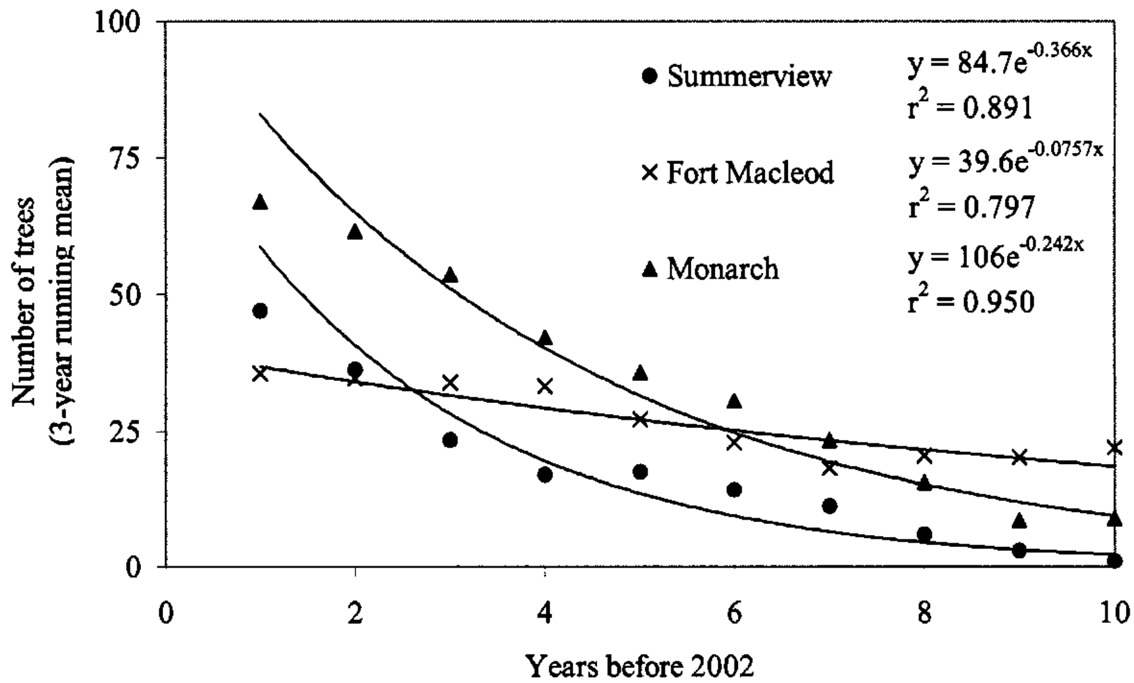

Figure 2-17: The exponential decay of cottonwood numbers along the three study reaches along the Oldman River over the last decade, the years since the Oldman River Dam became operational. There has been a 30.6 % annual decrease in cottonwood numbers along the Summerview Reach, 7.29 % along the Fort Macleod Reach, and 21.5 % along the Monarch Reach.

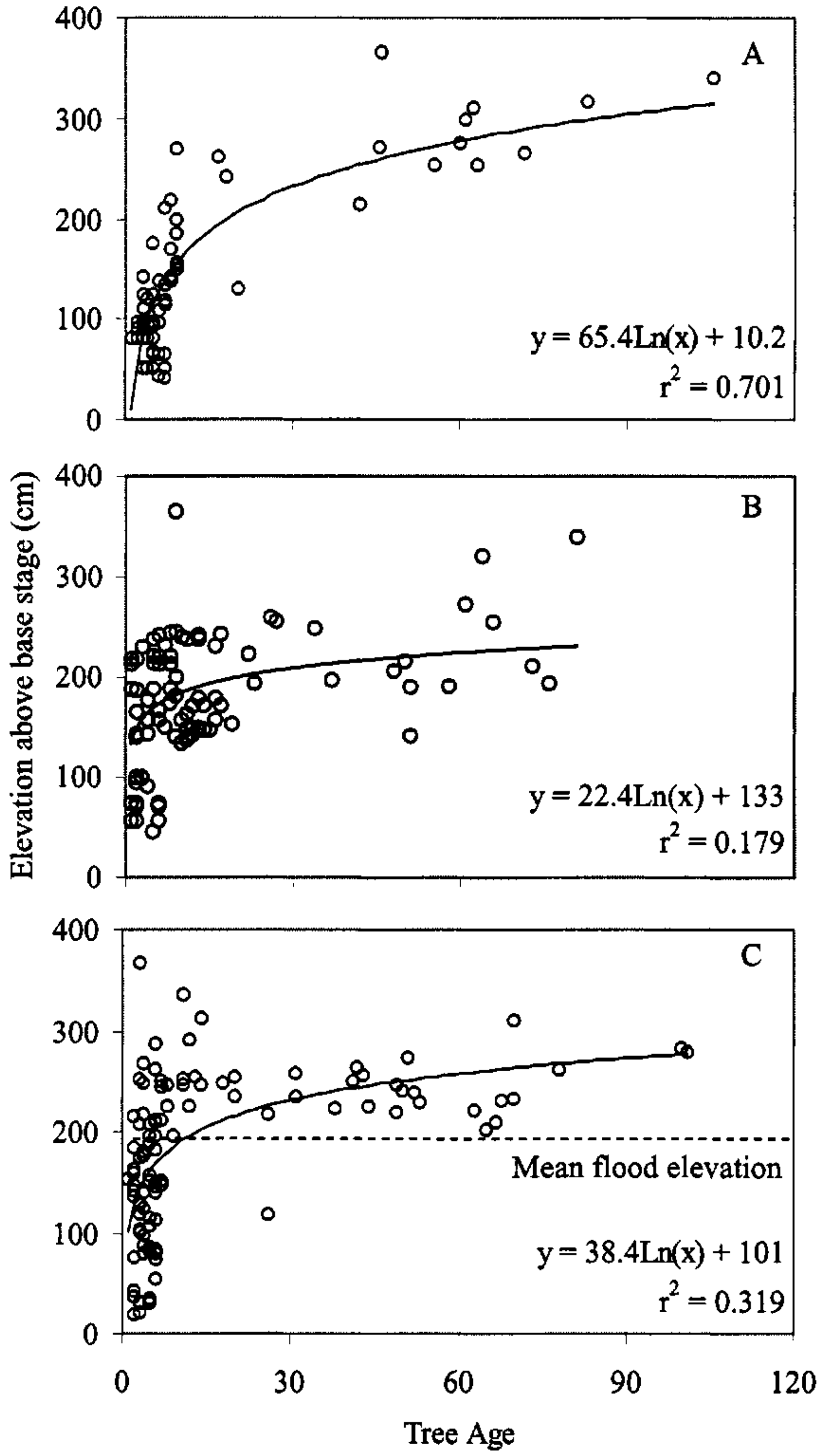

Figure 2-18: Cottonwood elevations above base flow along the (A) Summerview Reach, (B) Fort Macleod Reach, and (C) Monarch Reach along the Oldman River. Mean flood elevation along the Monarch Reach is based on remnant debris from the 1995 flood.

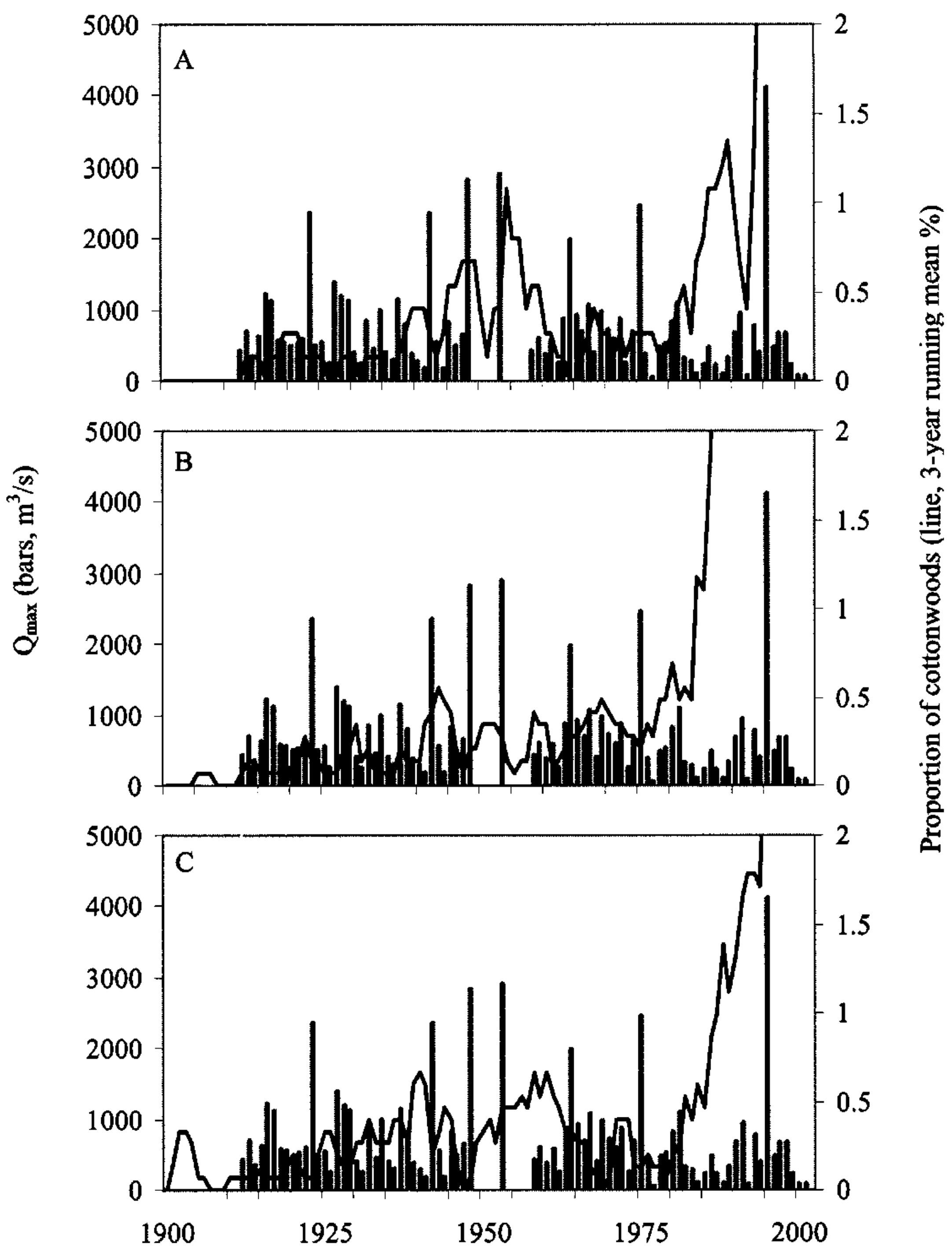

Figure 2-19: Cottonwood age structures of (A) Summerview, (B) Fort Macleod, and (C) Monarch reaches plotted against the annual maximum mean daily discharge (Q_{max}) of the Oldman River near Lethbridge (05AD007) to show recruitment peaks associated with flood years. Data gaps in the 1950s occurred due to the gauging station not being in operation. River regulation includes the Lethbridge Northern Irrigation District weir (1925) and the Oldman River Dam (1993).

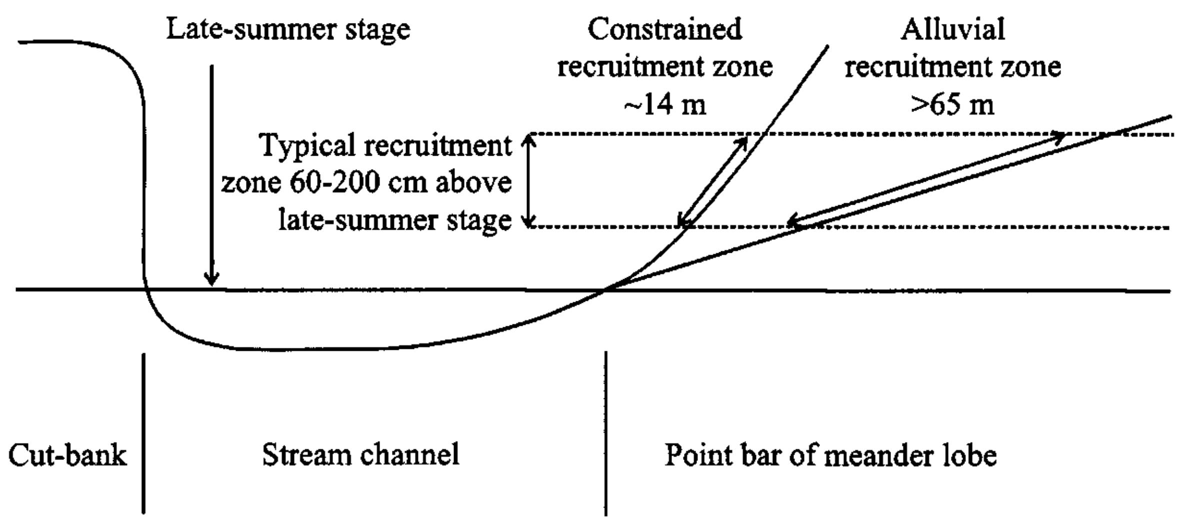

Figure 2-20: Cross section profile of the constrained and alluvial reaches showing influence of geomorphology on cottonwood recruitment zones (Modified from Mahoney and Rood 1998). Note the x- and y-axis vary in scale.

CHAPTER 3 COTTONWOOD GROWTH VARIES WITH GEOMORPHIC CONTEXT ALONG THE OLDMAN RIVER IN SOUTHERN ALBERTA

3.1 INTRODUCTION

In southern Alberta's semi-arid prairie ecoregion the principal native tree that inhabits the landscape are cottonwoods (*Populus* spp.). Cottonwoods are obligate phreatophytes in this dry environment and therefore exist only in riparian areas, at the interface between land and water. Here, cottonwoods depend on the riparian water table that is associated with adjacent rivers and streams (Cooper et al. 1999; Amlin and Rood 2003). Cottonwood trees are quite flood tolerant but are particularly sensitive to drought. They are therefore unable to survive in prairie regions away from perennial streams (Tyree et al. 1994; Rood et al. 2003a).

Water availability affects a number of morphological characteristics of cottonwoods. One of these is the size of water transporting xylem vessels. The construction of these vessels within cottonwoods coincides with available water. In the spring with abundant water, larger cells with bigger pit-membrane pores form. In the late-summer, limited water slows cell expansion and smaller pit-membranes are formed, thus diminishing vulnerability to xylem cavitation (Tyree and Sperry 1989). A practical measurement of vessel formation and water availability is radial trunk growth. Radial and basal area increments (a function of radial growth) are correlated with vessel size and density and these enable the characterization of a tree's water transport system (Schume et al. 2004).

Radial and basal area increments and branch elongation have been used to measure cottonwood responsiveness to water supply (Stromberg and Patten 1996; Dudek et al. 1998; Disalvo and Hart 2002). Some studies have found that branch elongation provides better correlations with water supply, or streamflow, than tree ring increments (Willms et al. 1998; Disalvo and Hart 2002). Others report that water deficits affect radial growth more than height growth (Kozlowski 1958). Regardless, a limitation of branch growth analysis is the short duration of record, usually only one or two decades, whereas tree rings can reflect annual differences in growth over the entire life of the tree.

This study was undertaken to compare cottonwood growth rates along sites with different geomorphic contexts along the Oldman River in southern Alberta. *Populus* growth has been intensely studied, primarily relating to fiber production in poplar plantations (Heilman and Stettler 1985; Ceulemans et al. 1992), but less attention has been given to the study of cottonwood growth patterns in native riparian settings.

Tree growth forms complex curves that can be broken down into a few distinct age-associated phases. These basic growth patterns can subsequently be dissected into fundamental parameters offering insight into the mechanics of growth (Kozlowski and Pallardy 1997). It was expected that cottonwood growth would be influenced by stand structure and density within native riparian stands. Since these are functions of the geomorphic context, it was also predicted that basic cottonwood growth parameters would vary across geomorphic contexts. That is, the physical nature of the floodplain influences aspects such as bank slope, sediment texture, channel form and migration rate.

Due to cottonwood dependency on the riparian water table, it was expected that variations in river discharge, and corresponding river stage, would affect cottonwood growth. Relationships between radial and basal area growth versus streamflow were assessed across years and sites to determine if the geomorphic context affects this connection. Previous work has shown strong relationships between streamflow and tree growth along wide, alluvial valleys but not along constrained valleys (Stromberg and Patten 1996). Contrary to these findings, it was predicted that cottonwoods along the constrained reach would be more sensitive to changes in the flow regime, and would show a stronger correlation with streamflow. This hypothesis is based on the recognition that riparian cottonwoods along constrained reaches are more responsive to hydrologic alterations with respect to recruitment and population structure (Willms 2005, Ch. 2). This responsiveness is due to the cottonwoods occurring at higher elevations on the stream bank along constrained reaches due to the hydrogeomorphic context (Willms 2005, Ch. 2).

An especially abrupt geomorphic transition along the Oldman River was used as the focus for the present study. At 'Rocky Coulee', the Oldman River valley abruptly changes from a wide, alluvial valley to a narrow, constrained valley, while the river maintains a similar flow regime. This provides an ideal study opportunity because the transition results in the dramatic change in geomorphic context without a change in hydrology.

3.2 MATERIALS AND METHODS

3.2.1 Study area

The Oldman River originates in the Rocky Mountains of southwestern Alberta. It flows easterly through the City of Lethbridge and is joined by a sequence of tributaries (Figure 3-1). The Oldman River Dam (ORD), approximately 160 river km upstream from Lethbridge (Buhrmann and Young 1982), was constructed in 1993 below the confluences of the Oldman, Crowsnest and Castle rivers.

Cottonwoods were investigated along three reaches of the Oldman River in this study (Figure 3-1). The Summerview Reach is located 3 km downstream from the ORD and extends for 3.5 km in river length. This reach was free-flowing prior to commissioning of the ORD. The channel is quite straight but has some pointbar formation with small cottonwood stands on them. This reach is considered 'moderately constrained' as the channel form is largely controlled by geology, but also partially from streamflow processes. The Fort Macleod Reach, approximately 61 km downstream of the ORD, is in a wide, alluvial valley. This river channel is dynamic with extensive meandering and point bar development and contains large cottonwood groves. The channel form is predominately controlled by streamflow processes, thus it is considered an 'alluvial' reach (Gordon et al. 2004). The Monarch Reach is approximately 95 km downstream of the ORD, and extends downstream from the Rocky Coulee transition to the town of Monarch, approximately 30 km west of Lethbridge. The river flows through a narrow, linear valley where the cottonwoods are restricted to small, narrow bands (Willms 2005). This reach is considered 'constrained' as the channel form is predominately controlled by geology. The Monarch and Fort Macleod reaches have experienced seasonal dewatering after 1925 when the Lethbridge Northern Irrigation District (LNID) weir started diverting water offstream for irrigation use.

Both the Monarch and Fort Macleod reaches are composed of *Populus balsamifera* L. (balsam poplar), *P. angustifolia* James (narrowleaf cottonwood), and *P. deltoides* Bartr. ex Marsh (plains cottonwood) (Eckenwalder 1996; Floate 2004). The Summerview Reach lacks plains cottonwood, but contains the other two species. These species are part of a globally unique hybrid swarm in southern Alberta (Rood et al. 1986; Floate 2004).

3.2.2 Sample collection

Increment cores from cottonwood tree trunks and discs (basal trunk cross sections) were collected along the three study reaches of the Oldman River. A total of 66 trees along the Summerview Reach, 109 trees along the Fort Macleod Reach, and 103 trees along the Monarch Reach were sampled from the three *Populus* species and their hybrids (Figure 3-2). Swedish increment borers (4.3 and 5.1 mm diameter) were used to extract cores from trees with a basal diameter of approximately 10 cm or greater. Cores were extracted approximately 30 cm above the ground surface to enable rotation of the increment borer. Discs were cut at ground level on saplings that were too small for extraction of increment cores.

3.2.3 Tree ring analyses

Cores were mounted onto grooved wooden planks and the cores and the discs were sanded with progressively finer sandpaper down to 320 grit (Stokes and Smiley 1968). Further surfacing was performed on some cores and discs with a razor blade to create a sharply cut and smooth surface. Samples with faint rings were treated with a lignin stain (80 % HCl: 20 % H_2O, saturated with phloroglucinol). An increment measuring machine with 0.002 mm precision (Velmex stage, Acu-Rite encoder from Velmex Inc., Bloomfield, New York; and MeasureJ2X software from VoorTech Consulting, Holderness, New Hampshire) and a dissecting microscope (typically set at 10 – 20X magnification) were used for analyses of the increment cores and discs.

Annual tree ring increments of the cottonwoods were graphed onto composite skeleton plots to allow for comparisons of growth patterns between individual trees to detect anomalies of missing or double rings (Stokes and Smiley 1968). Increment widths in some sections of the cores that had minor damage due to twisting or breaking of the core could also be corrected by matching high and low growth year patterns with those of neighboring trees. Cottonwoods often do not grow radially symmetrically and consequently the pith of the trees was sometimes missed when coring. A concentric circle ruler was used to estimate the distance from the last observable annual ring to the pith. The mean growth of the tree was then used to determine the number of missed rings.

Growth rates were standardized to reduce the genotypic and microsite variations. Standardization determined deviations from mean radial increment (RI) or basal area increment (BAI) of an individual, allowing for a more accurate comparison among trees. Standardized ring-widths were calculated in a similar manner reported by Fritts (1976). The standardized annual radial increment (SRI_a) equals the annual radial increment (RI_a) divided by the measured mean radial increment ($RI_{\bar{x}}$) over the lifespan of the tree or for some analyses, over a specified time or age period:

$$SRI_a = RI_a / RI_{\bar{x}}$$

When plotted, the SRI deviate around the mean, revealing above or below average growth years that are more readily comparable across trees or sites. This same method was applied to the standardization of BAI.

Data were then compiled only from those cores and discs in which increments could be interpreted with confidence. In total, 54 trees from the Summerview Reach, 95 trees from the Fort Macleod Reach, and 84 trees from the Monarch Reach were used in the analysis representing 84% of the total sampled with similar rejection rates across the three reaches (18%, 13%, 18%, respectively). Both RI and BAI were measured and converted into SRI and SBAI.

3.2.4 Reconstruction of Oldman River discharges

Hydrologic data were compiled from 'Hydat', Environment Canada's Surface Water and Sediment Database (GEG 2002) to reconstruct historical streamflows that were incomplete at some gauging stations. The gauging station (near Brocket 05AA024) located at the downstream end of the Summerview Reach on the Oldman River was damaged during a flood in 1995. Using the three upstream gauging stations of Castle River near Beaver Mines (05AA022), Crowsnest River near Frank (05AA008) and Oldman River near Waldron (05AA023), linear regression (r^2=0.977) was performed on the flow data from 1975, another major flood year to enable reconstruction of the missing monthly means for the Brocket gauge (Figure 3-3).

Reconstruction of the monthly mean discharge along the Oldman River near Fort Macleod involved the additions of Pincher Creek (05AA004) and Brocket discharges, minus the diversions made from the LNID weir (05AB016 and 05AB019). Reconstruction of the monthly mean discharge along the Oldman River near Monarch combined Willow Creek (05AB021) and Fort Macleod discharges.

3.2.5 Stand densities and sizes

Stand densities (stems >5 cm DBH/ha) were calculated for each site on each reach based on number of stems counted within a 4 m wide cross-sectional belt transect. Analysis of variance (ANOVA) was used to test for differences in stem densities between the three reaches. Stand sizes were calculated by digitizing air photos into ArcView 3.2 (ESRI, Redlands, California) and measuring cottonwood stand areas per unit of river length.

3.2.6 Growth patterns

Cottonwood increment data were organized for interpretation of growth over time, from seedling establishment to tree maturity. First year radial stem growth of seedlings and saplings was matched with the first year growth of mature trees, based on the interpretation of the cores and discs. Mean RI and BAI was then calculated for the cottonwood populations along all three reaches.

Growth rates were compared among the three reaches using the five most accurate, longest-lived trees for each reach. The use of multiple cores decreases the interaction of high-growth and low-growth years and reflects the average growth for the population. Analysis of covariance (ANCOVA) was used to test for differences in BAI among the three reaches. Juvenile (≤ 20 years) BAI and year of growth data were log transformed for normal distribution (Shapiro-Wilk $p=0.943$). Mature (> 20 years) BAI data were normally distributed (Shapiro-Wilk $p=0.624$). A Tukey test was subsequently used to detect differences in growth across the study reaches.

3.2.7 Growth versus streamflow regressions

Linear regression was used to investigate relationships between cottonwood annual growth and streamflow. To reduce the influence of accelerated juvenile growth on the annual means, only mature trees (> 20 years old) were used in this analysis (Summerview n = 9 [aged: 42, 46, 46, 55, 60, 72, 83, 105, 251 years], Fort Macleod n = 12 [aged: 26, 27, 29, 34, 36, 37, 48, 50, 51, 51, 76, 81 years], Monarch n = 8 [aged: 26, 27, 35, 38, 45, 58, 61, 75 years]). Mean RI, SRI, BAI and SBAI was calculated. As confidence in matching tree rings with exact years diminishes with time from the present, all regressions were limited to the period from 1980 to 2001, in which there was considerable confidence in tree ring interpretation.

Streamflows considered for the analyses included individual monthly means, annual mean discharge (January to December), growing season discharge (April to September), late-spring discharge (May to June), and late-summer discharge (August to September). The time period 1980 to 2001 covers a wide range of discharges, including some of the driest years on record and the largest flood on record.

3.2.8 Statistical analysis

JMP 5.0 (SAS Institute Inc., Cary, North Carolina) was used for all statistical calculations including regression analysis of streamflow and growth rates, ANOVA used for analyses of stand densities, and ANCOVA used for analyses of growth rates.

3.3 RESULTS

3.3.1 Stand density and size

There was a significant difference of cottonwood stand densities between the three study reaches (ANOVA: df=2, F=4.17, p=0.036) (Table B-6). The Monarch Reach had the lowest stem densities while the Summerview Reach had the highest, slightly higher than the Fort Macleod Reach (Figure 3-4). The forest size along the Fort Macleod Reach was by far the largest of the three measured being nearly 15-fold larger than the stand along the Monarch Reach and more than twice the size of the woodland along the Summerview Reach (Figure 3-5).

3.3.2 Cottonwood growth

Variation of cottonwood growth with age along all three study reaches along the Oldman River shared a similar pattern. Annual RI was small in the first few years of growth, increased rapidly to about the twentieth year of growth and then decreased thereafter (Figures 3-6A, 3-7A and 3-8A). Since BAI is a function of RI it reflects the combination of RI and the progressive expansion of the trunk area. At about twenty years, RI peaked and BAI reached a growth plateau. While RI decreased after the peak, BAI remained nearly constant (Figures 3-6B, 3-7B and 3-8B). Thus, with each additional year, a tree required less radial growth to produce the same basal area growth. This pattern is consistent across all three reaches, but there were major differences in the BAI of the post-20 year plateau.

Cottonwood BAI was tested for differences across the three reaches in both juvenile and mature growth rates. There was a trend towards differences in BAI of juvenile trees across the three reaches (ANCOVA: $F_{2,54}=3.11$, $p=0.0527$) but this possible difference was relatively slight (Table B-7). However, there were highly significant differences between BAI of mature trees across the three reaches (ANCOVA: $F_{2,57}=15.7$, $p<0.0001$) (Table B-8). The Tukey test found growth of the mature cottonwoods to be different between the alluvial Fort Macleod Reach and each of the two constrained reaches, but not between the two constrained reaches themselves.

Cumulative BAI (equivalent to cross sectional area) of the cottonwoods were similar rates across the three river reaches during the juvenile growth phase (Figure 3-9). It is around the 25^{th} growth year that the rate of growth along the alluvial, Fort Macleod Reach slowed and cumulative growth progressively fell away from that of trees on the constrained Summerview and Monarch reaches (Figure 3-9). Trees along the two constrained reaches had similar growth rates but growth was slightly slower along the Summerview Reach than the Monarch Reach.

3.3.3 Streamflow-growth analysis

Using linear regression, relationships were found between cottonwood tree growth and streamflow along the alluvial Fort Macleod Reach, but not along the constrained reaches. On the Monarch Reach, the most geomorphically constrained of the three, there was no significant correlation ($p<0.05$) between cottonwood RI, SRI, BAI, or SBAI and streamflow (Table B-11). Along the moderately constrained Summerview Reach only cottonwood BAI and September mean streamflow were apparently correlated (Table B-9). This correlation may reflect a chance occurrence as it is out of place with the rest of the data set.

Significant correlations ($p<0.05$) were found at the Fort Macleod Reach for both mean RI and mean SRI and streamflow (Table 3-1). RI and SRI were significantly positively correlated with mean streamflow during the months of May and June, during the growing season (April-September), the late-spring (May-June) (Figure 3-10), and annual streamflow with RI only. No significant correlation ($p<0.05$) was found between streamflow and BAI or SBI (Table B-10A, B).

3.4 DISCUSSION

3.4.1 Cottonwood growth

From this study, cottonwood growth curves can be illustrated as having four main features that relate to age of the tree and to environmental conditions in which the tree is growing: (I) the seedling is established and there is root system development; (II) seedlings with an established root system accelerate shoot growth; (III) a peak in radial and basal area growth rate is reached; and (IV) mature growth maintains the tree canopy, but further expansion is limited (Figure 3-11).

The cottonwood seedlings consistently grew very slowly in their first five years of growth across all three reaches (Figure 3-9). It is during this initial period after establishment that seedlings are at greatest risk of drought induced mortality as their root systems are being developed (Mahoney and Rood 1991; Cooper et al. 1999). Most of the growth resources are placed into root rather than shoot elongation as survival is dependent on the roots maintaining contact with moisture in the substrate. Above-ground growth is limited by water table declines (Kranjcec et al. 1998) and by competition as seedling densities can be up to hundreds or thousands per square metre (Stromberg et al. 1991; Virginillo et al. 1991; Johnson 1994). Regardless of the geomorphic context, all seedlings are under the same competition pressure. After a few years the roots become well developed and more resources can be allocated to above-ground growth.

Cottonwoods are capable of rapid growth once the root system has become well established in the water table. At approximately the fifth year of growth the juvenile trees began growing much faster along all three study reaches (Figure 3-6, 3-7, and 3-8). The trend showed a slight divergence in cumulative basal area increments between the study sites, but this difference was slight (Figure 3-9). This slight divergence is likely due to competition as increased seedling densities noticeably affects radial growth (Krinard and Johnson 1980). However, competition between seedlings during these early years would be relatively similar regardless of geomorphic context because cottonwood densities can be high in either a narrow or wide recruitment band (Kalischuk et al. 2001).

At about 20 years of age, the cottonwoods hit a radial growth peak that results in an associated plateau in basal area growth (Figure 3-6, 3-7, and 3-8). This is followed by a decrease in radial increment size resulting in fairly uniform basal area growth as the tree gets larger. This pattern is somewhat consistent with other species of trees (Poage and Tappeiner 2002). At this peak in growth the trees are well established and competition for resources will slow growth rates but probably not result in mortality.

Following the 20-year RI peak, the cross-sectional area of annual wood production is fairly uniform from year to year suggesting that tree canopy expansion has probably ceased or slowed down. Following this, the constant BAI will support a relatively constant leaf area as new leaves and branches replace ones that die. Competition between trees will therefore limit the physical space that the canopy can occupy (Hinckley et al. 1992). Radial growth in the mature trees thus supports maintenance of the canopy leaf area instead of canopy expansion.

While microsite variations influence growth rates and tree size because of differences in moisture and nutrient levels (Harner and Stanford 2003), stand densities often have a greater impact on tree growth than site productivity (Poage and Tappeiner 2002). The present study supports this interpretation. The Summerview Reach had the highest stand density resulting in slightly slower annual growth than the trees on the Monarch Reach. The Fort Macleod Reach also had a high stand density and by far the largest forest and this resulted in the slowest growth rate of the three reaches investigated in this study. Both the Monarch and Summerview reaches have smaller stands where there is less competition between mature trees as forest size is smaller and greater edge effects lead to increased radial growth (Krinard and Johnson 1980; Canham et al. 2004;

Pedersen and Howard 2004). Growth then becomes limited by abiotic and physiological constraints such as water availability and genetics (Hinckley et al. 1991; Hinckley et al. 1992).

3.4.2 Streamflow-growth analysis

The significant correlations between cottonwood growth and streamflow along the Oldman River occurred along the wide alluvial Fort Macleod Reach. Neither the constrained nor the partially constrained reaches revealed substantial relationships. Similar results have been found in other studies assessing cottonwood growth along wide alluvial versus confined reaches (Stromberg and Patten 1996). In the present study however, relationships between tree growth and streamflow were expected along the constrained reaches since the trees are established on alluvium. They were therefore expected to utilize groundwater that responds to changes in streamflow. Due to the constrained geomorphology, these reaches experience greater fluctuations in river stage than along the alluvial channel where flood waters can fan out across the broad and shallow floodplain. It was subsequently hypothesized that these trees would be under greater stress than trees along the alluvial reach. With larger fluctuations in river stage between high and low flows it was expected that cottonwood growth would be more responsive to the flow regime.

There are a few reasons why growth versus streamflow correlations were not found along the constrained reaches. It is possible that cottonwood growth along the constrained reaches is influenced by surface water and runoff to a greater degree than along the alluvial reach (Stromberg and Patten 1996). Another possible explanation is the trees' proximity to the channel edge; trees closer to the channel may be less limited by water than those further away and along the constrained reaches the trees were restricted to narrow bands close to the river. It is also possible that when trees closer to the channel edge experience high discharge needed for increased growth, the high discharge also inundates the trees reducing growth (Stromberg and Patten 1991). Another explanation is that the cottonwoods along the Fort Macleod Reach, although abundant, are under greater stress due to competition between individuals leading to greater sensitivity in streamflow changes.

The relationship found along the alluvial channel was between cottonwood radial growth and early-summer streamflows (Figures 3-10). Therefore it is during this period that there is the most water available to plants in the riparian area resulting in increased radial growth of cottonwoods. However, given that the only relationships between growth and streamflow were found along the alluvial reach, it is believed that competition between trees has lead to their sensitivity to changes in streamflow.

3.4.3 Conclusion

In this study trunk growth patterns of riparian cottonwoods were investigated and revealed a developmental growth pattern with a sequence of phases that involve different ecophysiological responses. Consequently, it is concluded that dendrochronological analyses of riparian cottonwoods must consider these phases if researchers intend to define the instream flow needs for cottonwood conservation or during field analyses to identify superior clones that may be suitable as parental genotypes for hybrid poplar breeding programs. It was also recognized that the geomorphic context as a landscape-scale physical parameter substantially influences growth pattern transitions and growth rates. In riparian zones the geomorphic context defines the forest structure. The grove size and density determines the extent of cottonwood competition which likely influences growth. Cottonwood growth is therefore appears to be indirectly determined by the local geomorphology. Wide alluvial valleys enable large and dense cottonwood forests with increased competition and decreased growth rates, whereas narrow valleys that constrain the river channel limit cottonwood occurrence to narrow bands of trees with reduced competition and increased growth. There is thus an intriguing contrast since the geomorphic context which is most favorable for riparian cottonwood forests produces competitive conditions that are least favorable for the growth rates of individual trees.

Table 3-1: Linear regression results from cottonwood radial increments (RI), standardized radial increments (SRI), basal area increments (BAI) and standardized basal area increments (SBAI) along the Fort Macleod Reach versus discharge of the Oldman River for the period 1980-2001.

	May	Jun	May-Jun	Apr-Sep	Annual
RI r^2	0.396	0.214	0.368	0.226	0.186
p	0.0017 **	0.03 *	0.0028 **	0.0252 *	0.0453 *
SRI r^2	0.290	0.198	0.305	0.18	0.142
p	0.0096 **	0.038 *	0.0077 **	0.049 *	0.0836
BAI r^2	0.000	0.0796	0.0366	0.0689	0.0721
p	0.997	0.203	0.394	0.238	0.227
SBAI r^2	0.000	0.0661	0.0299	0.0483	0.0476
p	0.994	0.248	0.441	0.326	0.329

* $p < 0.05$
** $p < 0.01$

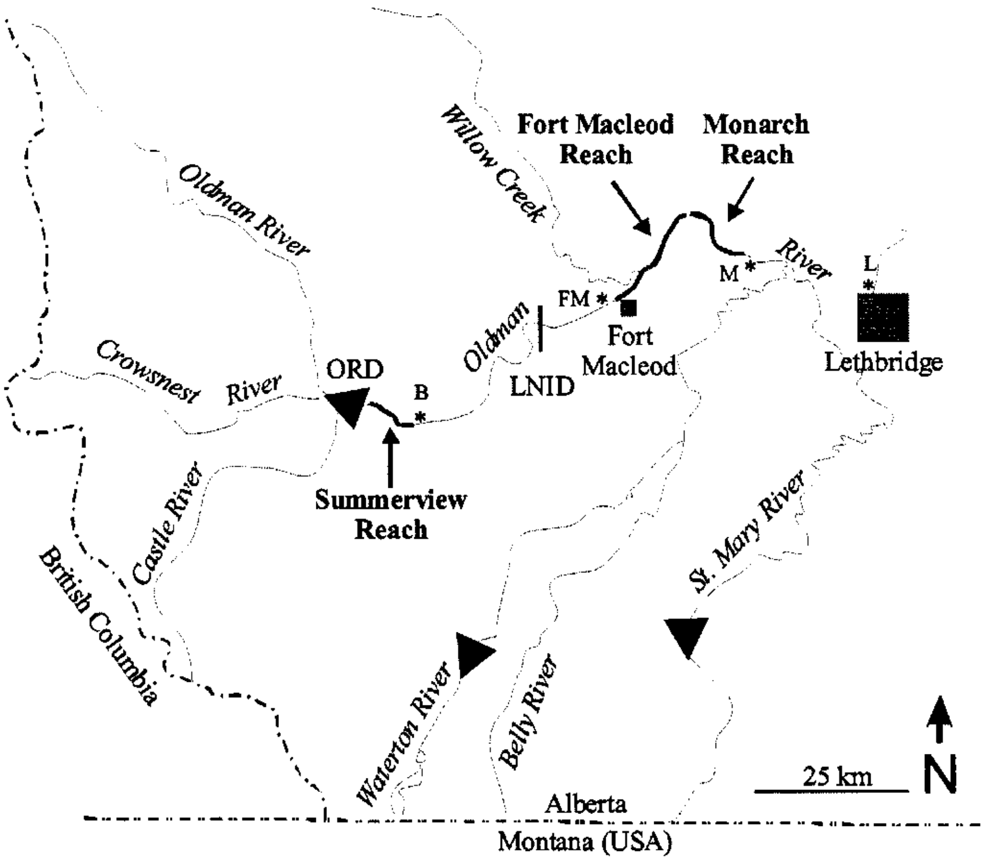

Figure 3-1: Map of the Oldman River and its tributaries in southern Alberta, Canada. The study reaches in bold are the Summerview Reach located just downstream of the Oldman River Dam (ORD), and the Fort Macleod and Monarch reaches located on either side of a geomorphic transition zone downstream of the Lethbridge Northern Irrigation District weir (LNID). Hydrometric gauging stations along the Oldman River are marked with an asterisk (*): Brocket (B), Fort Macleod (FM), Monarch (M), Lethbridge (L). Major dams are marked with triangles.

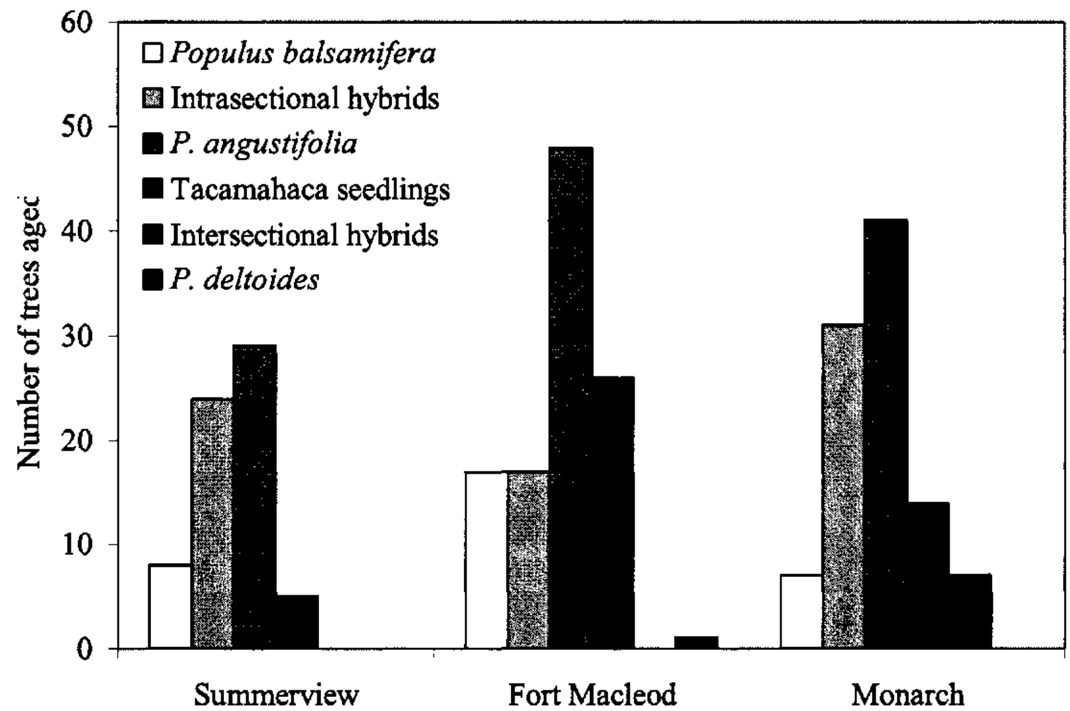

Figure 3-2: Number of trees aged along the three study reaches on the Oldman River. Section *Tacamahaca* contains *Populus balsamifera* and *P. angustifolia*, and section *Aigeiros* contains *P. deltoides*. The cottonwood species and hybrids are sequenced by elevational distribution with *P. balsamifera* occurring at the highest elevations, and *P. deltoides* at the lowest.

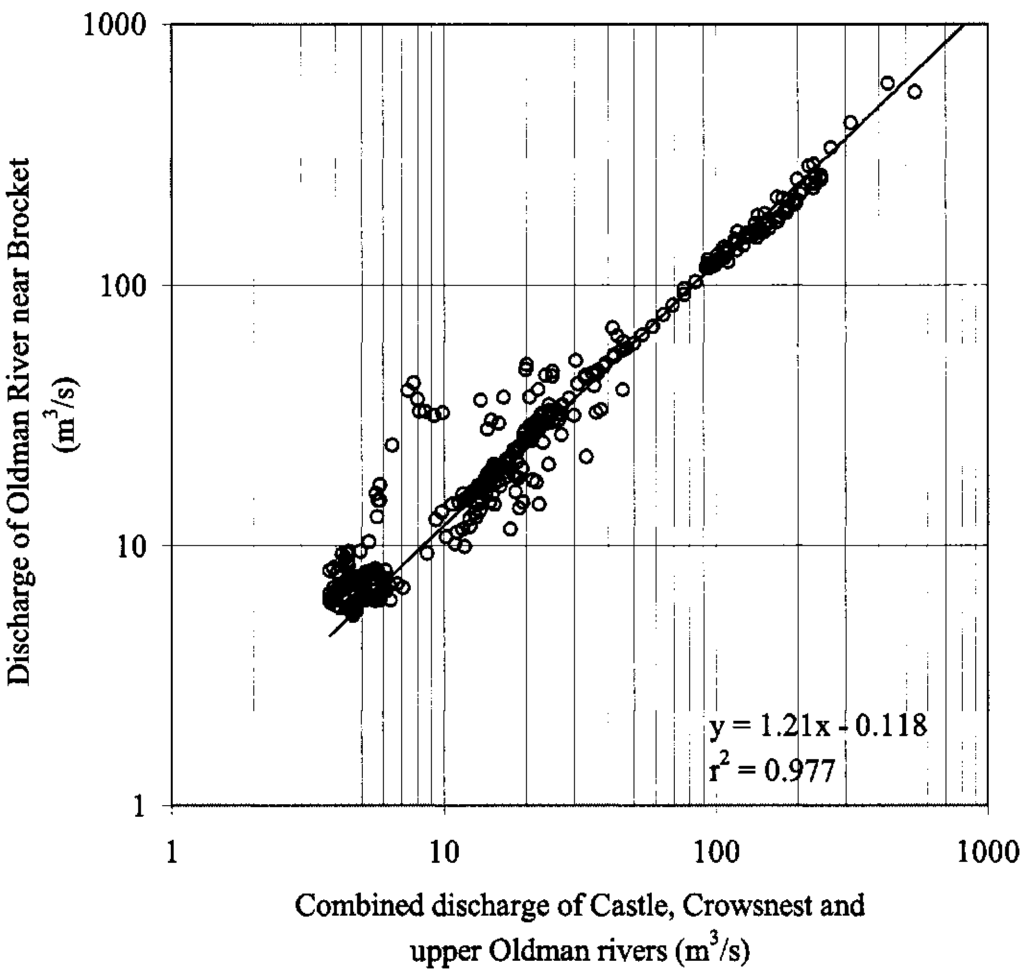

Figure 3-3 : Linear regression of 1975 daily flows for combined upstream discharges of the Castle, Crowsnest and upper Oldman rivers (05AA022, 05AA008, 05AA023) and the Oldman River near Brocket (05AA024) for reconstruction of missing discharges of the damaged gauging station near Brocket. One data point not shown at (870, 1220).

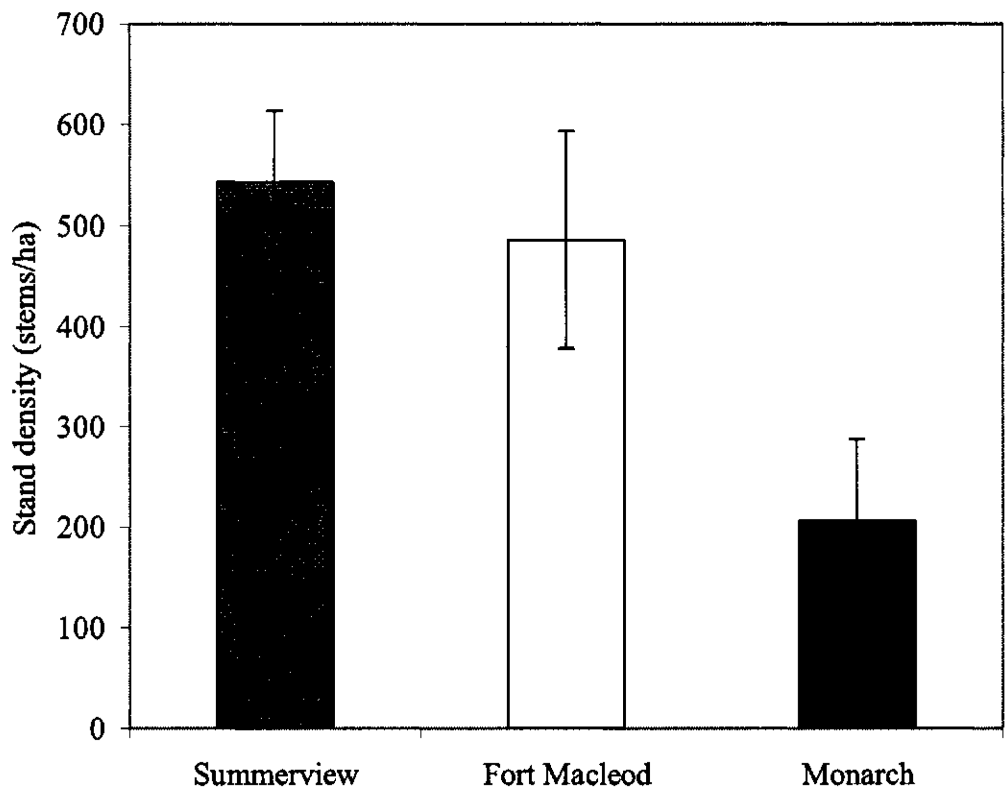

Figure 3-4: Stand densities of trees (>5 cm DBH) from the three study reaches along the Oldman River.

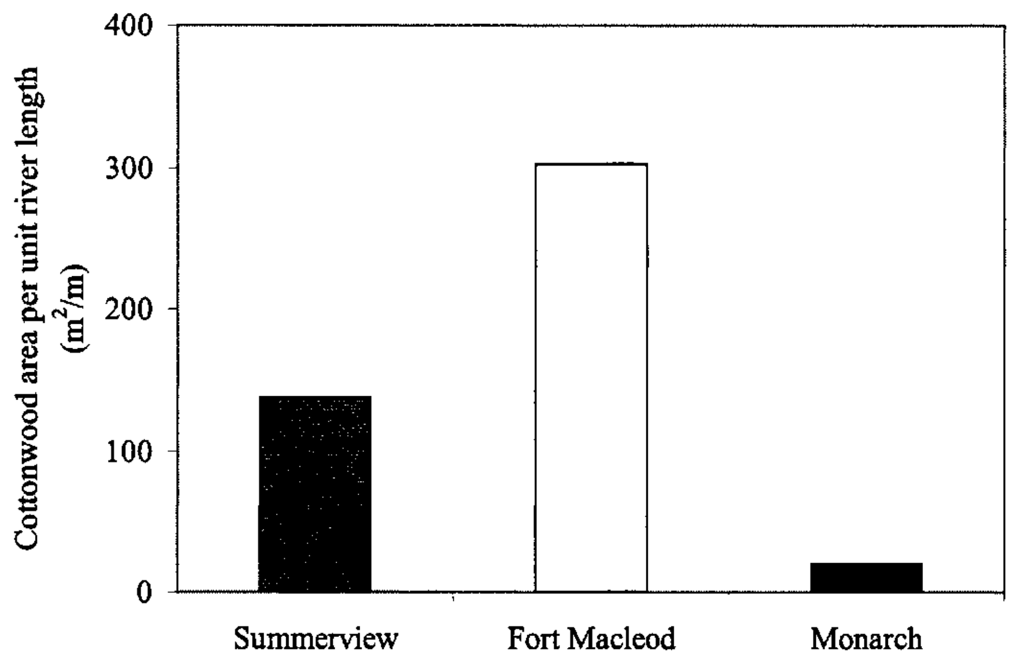

Figure 3-5: Cottonwood stand size based on river distance for each study reach along the Oldman River.

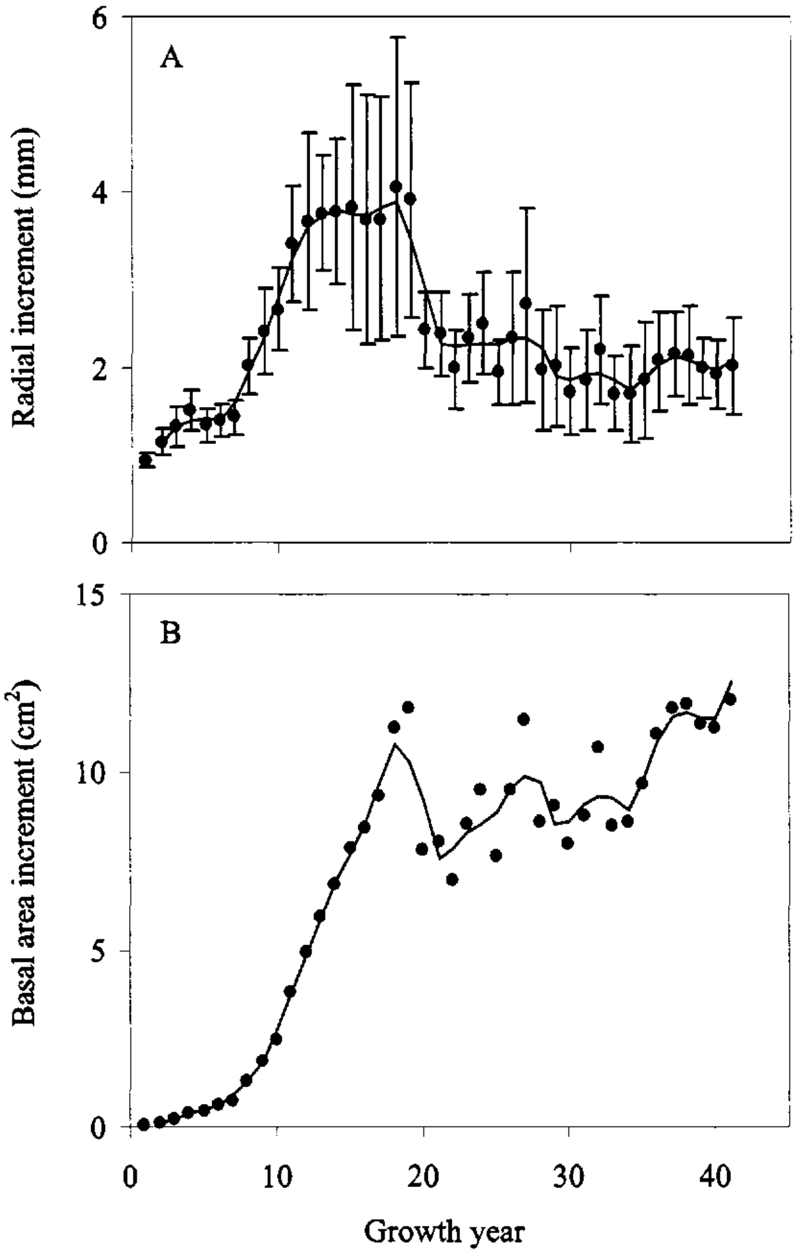

Figure 3-6: Cottonwood growth along the Summerview Reach of the Oldman River. Mean annual (A) radial increments with running three-year means and standard error bars, and (B) basal area increments with running three-year means. N differs with growth year, decreasing from 54 in year one to 6 in year 41.

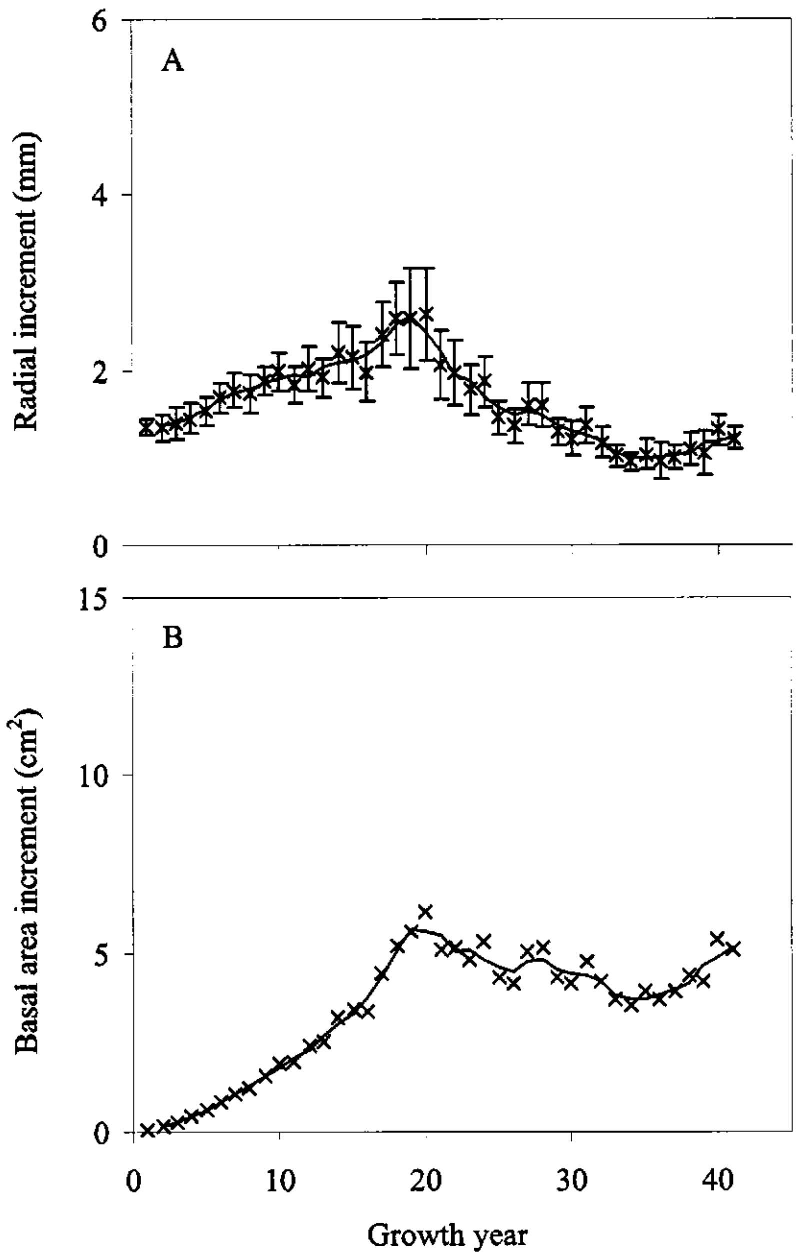

Figure 3-7: Cottonwood growth along the Fort Macleod Reach of the Oldman River. Mean annual (A) radial increments with running three-year means and standard error bars, and (B) basal area increments with running three-year means. N differs with growth year, decreasing from 95 in year one to 5 in year 41.

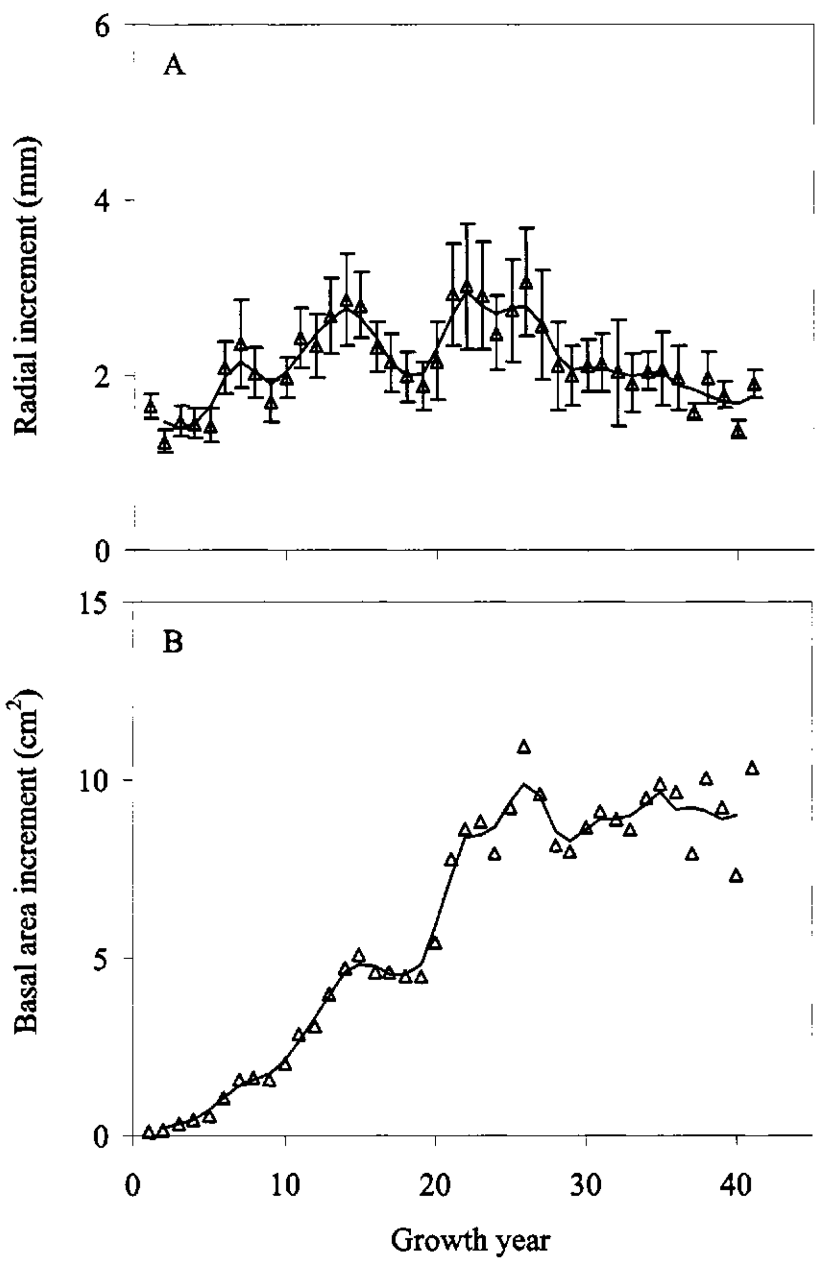

Figure 3-8: Cottonwood growth along the Monarch Reach of the Oldman River. Mean annual (A) radial increments with running three-year means and standard error bars, and (B) basal area increments with running three-year means. N differs with growth year decreasing from 84 in year one to 5 in year 41.

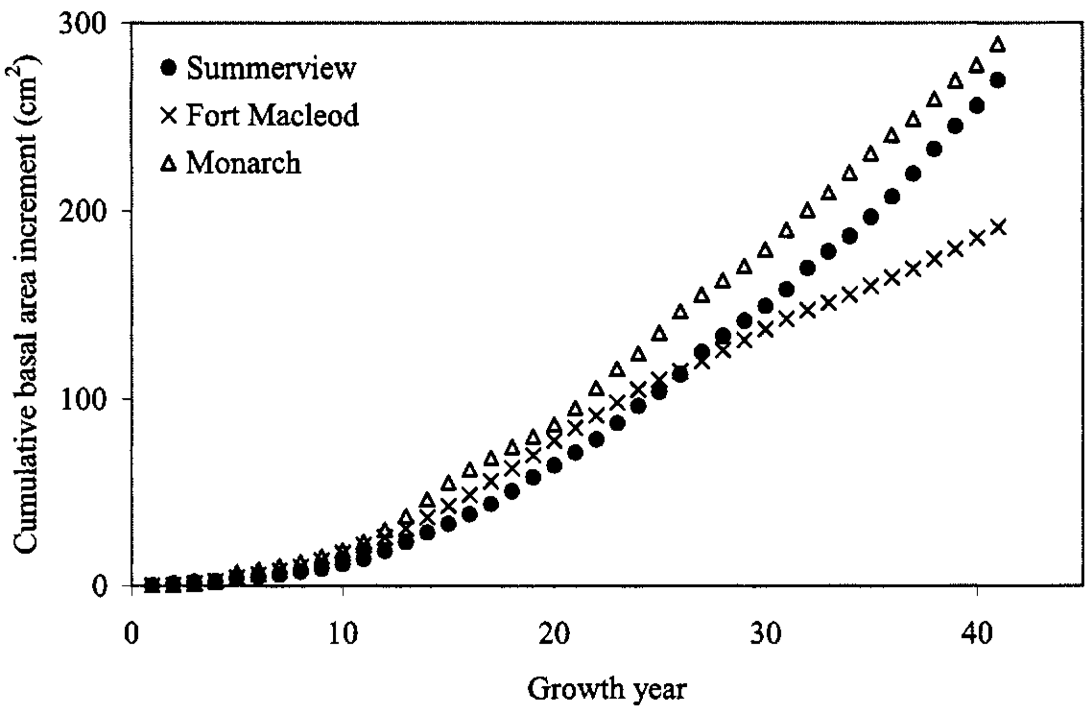

Figure 3-9: Mean cumulative basal area increment (stem cross-sectional area) for cottonwoods along the Oldman River. Each point has 5 data points.

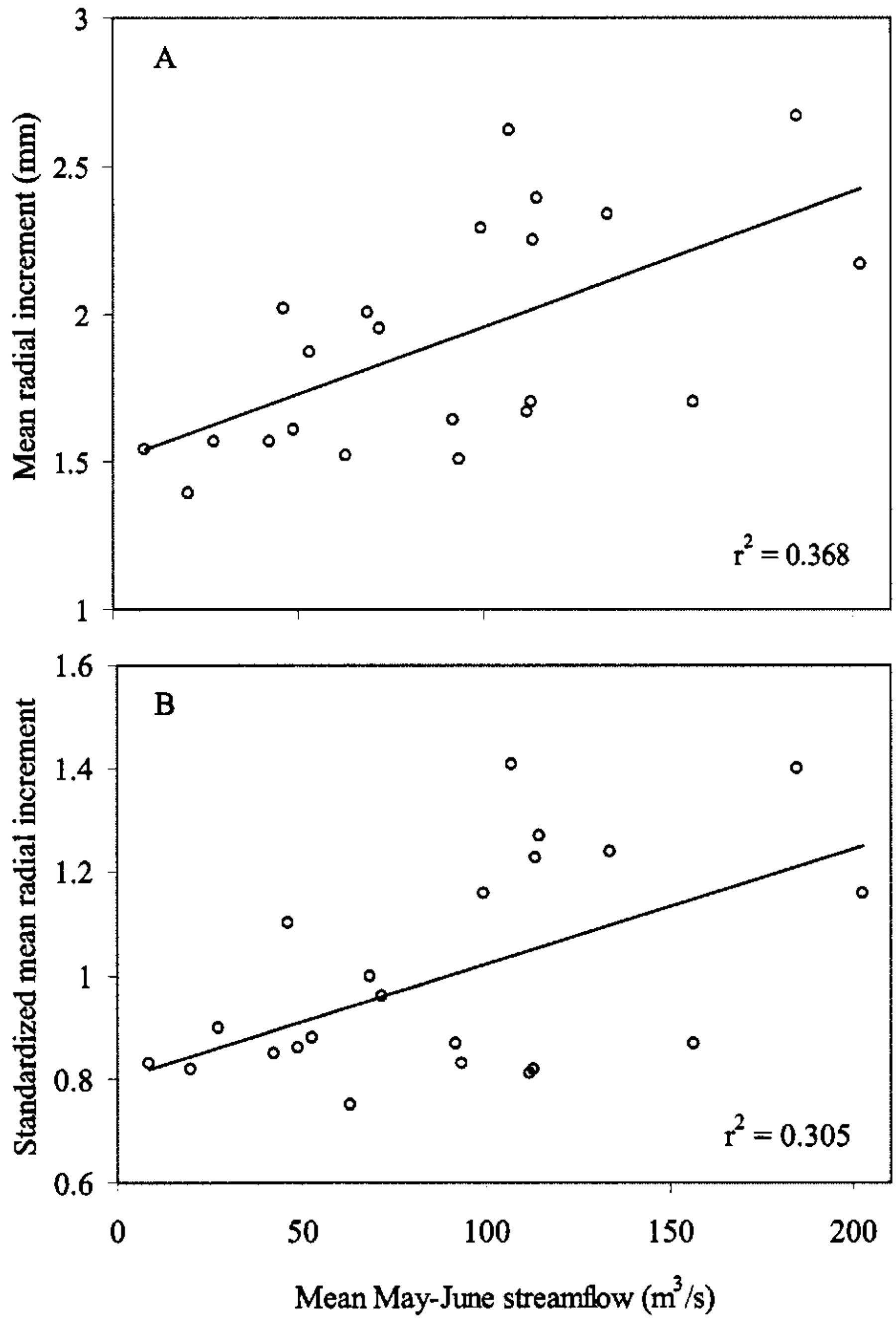

Figure 3-10 : Regressions analysis of mean May through June streamflow of the Oldman River near Fort Macleod with (A) mean radial increments, and (B) standardized mean radial increments from cottonwoods along the Fort Macleod Reach.

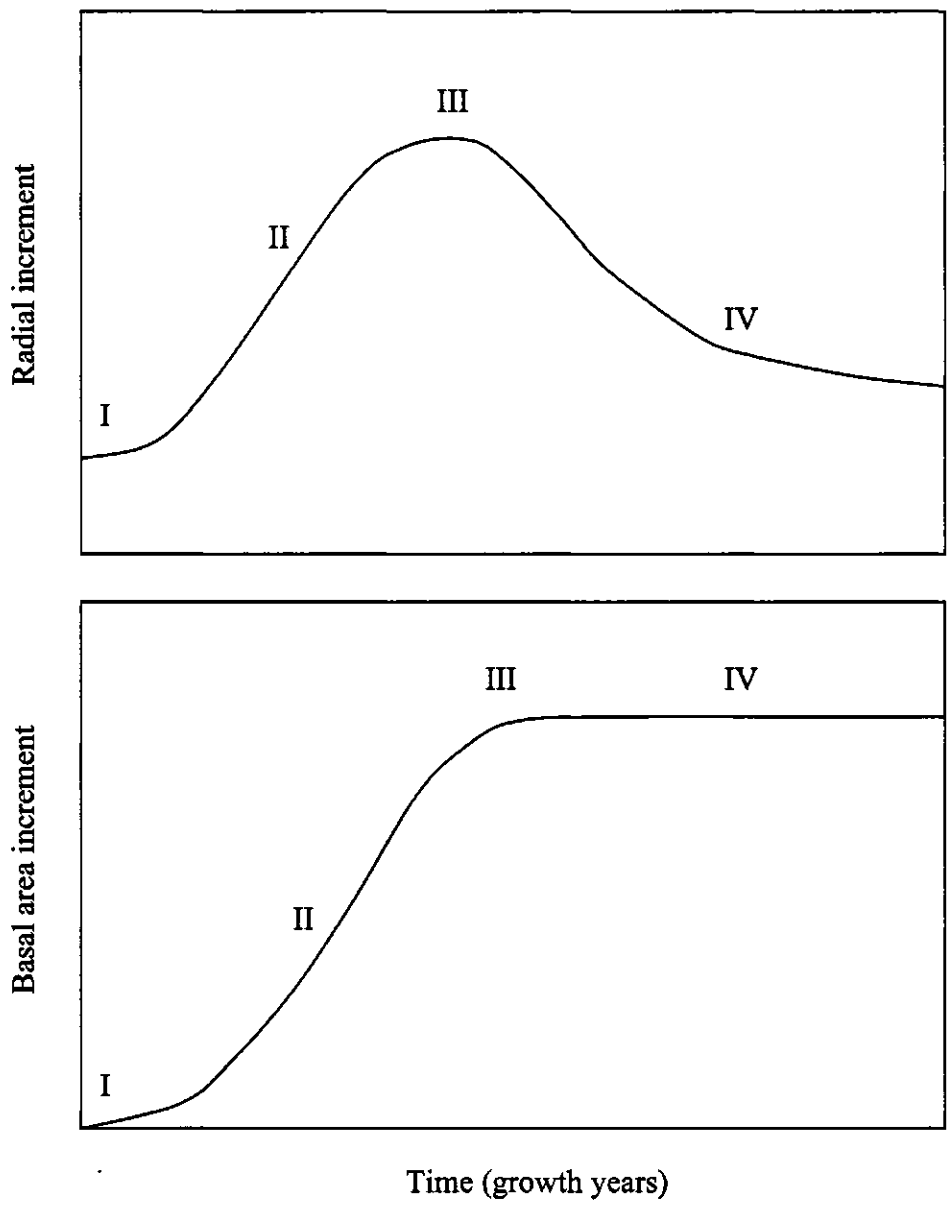

Figure 3-11: Generalized cottonwood growth curves showing the four stages of growth for both basal area increments and radial increments. I) seedling establishment and root elongation, II) accelerating juvenile shoot growth, III) peak growth and canopy expansion, and IV) mature growth for canopy maintenance.

CHAPTER 4 SUMMARY AND CONCLUSIONS

4.1 SUMMARY AND CONCLUSIONS

Cottonwood populations in western North American and around the world have suffered following river damming and diversion. It is only recently that the flow regime required for cottonwood reproduction and survival has been generally determined. The past two decades have seen great advances made in the areas of cottonwood ecology and physiology with respect to river regulation. There is still much more work needed however, and an area of research that is still relatively new involves the interaction of hydrology and fluvial geomorphology on cottonwood growth and reproduction.

The primary focus of this thesis is described in Chapter 2, the influence of geomorphic context on cottonwood recruitment along a regulated river that has been partially dewatered and subsequently seasonally rewatered. Chapter 3 presents an additional study that investigated the influence of geomorphic context and streamflow on cottonwood growth patterns. These complementary studies investigated two different aspects of the same cottonwood populations along the Oldman River in southern Alberta.

The cottonwood age structures analyzed in Chapter 2 reflect the impacts of flow regulation on cottonwood population processes. Recruitment rates were significantly different between the constrained floodplain in the Monarch Reach and the unconstrained alluvial floodplain in the Fort Macleod Reach when pre- and post-flood of 1995 were assessed. The Fort Macleod Reach had higher rates of recruitment in pre-flood years than the Monarch Reach suggesting that cottonwoods along alluvial reaches are more tolerant of the negative impacts of dewatering than those along constrained reaches. The flood and altered flow regime from the ORD resulted in proportionally greater recruitment along the constrained than the alluvial reach as the increased late-summer flows from ORD combined with the necessary recruitment conditions from the 1995 flood to provide favorable recruitment conditions. The alluvial reach supported steady cottonwood recruitment and did not experience recruitment fluctuations as large as along the constrained reach.

A comparison of the geomorphically similar Summerview and Monarch reaches did not reveal significant differences in recruitment rates relating to either the commissioning of the ORD, or the flood of 1995. Both reaches had low cottonwood numbers prior to ORD and high numbers after the flood of 1995. The large flood enabled cottonwood establishment high on the banks, and the increase in late-summer discharge allowed for greater survival on the Monarch Reach. Recruitment was similar along the Summerview Reach. It was expected that prior to the commissioning of the ORD recruitment rates would be higher along the Summerview than the Monarch Reach. However, due to the constrained context, scour from the flood of 1995 may have removed some of the seedlings and saplings that were previously established, thus resetting both reaches with open conditions for new recruitment to take place on.

Survival of seedlings varies with geomorphology. The constrained reaches have greater fluctuations in river stage with changes in discharge than broad alluvial reaches given a constant longitudinal gradient. Increased discharges along the unconstrained alluvial reach spread out across the shallow, flat floodplain, but along the constrained reaches river stage was forced upwards. The narrower and more constrained the river is by the valley, the greater the changes in stage with any given change in discharge

(Knighton 1998). The constrained reaches will also experience a greater decline in river stage with receding floodwaters potentially leaving newly established seedlings under more stressful conditions resulting in a relatively faster decline in water table than along alluvial reaches. Seedlings therefore have more severe conditions to overcome when establishing on the banks of a constrained channel. Because channel gradient was steeper along both constrained reaches, it is not known how discharge affected river stage. Ratings curves used were all developed at gauging stations located next to bridges and therefore may not provide accurate representations of reach characteristics. However, with increased gradient comes increased velocity and stream power which is more capable of bank and vegetation scour.

The greatest natural, physical impact to seedlings is scour from floods and ice (Bradley and Smith 1986; Smith and Pearce 2000). Cottonwood trees can handle inundation for extended periods but seedlings are easily scoured away (Smit 1988). Constrained river reaches are particularly prone to scour as the energy from the scouring event is restricted to a smaller cross-sectional area. This was evident when measuring cottonwood elevations along the three reaches. Seedlings were established at a wide range of elevations having not yet experienced a major scouring event, but trees greater than 10 years in age along the constrained reaches were only found at higher elevations. This lower limit of survival was the same as the surveyed debris line from the flood of 1995. The energy from flooding and ice breakup becomes dissipated across the floodplain on wider, alluvial reaches and so scour damage is less severe along the floodplain of the Fort Macleod Reach.

Growth rates differed between the alluvial and constrained reaches. It was subsequently concluded that competition between trees influenced radial growth. The slowest growth occurred along the alluvial reach with high stem density and the largest forest size. Edge effects that would increase growth rates are reduced by the size of the forest. Growth was greatest along the constrained reach with the narrowest, smallest stand that had a low density of trees and subsequently, reduced competition.

Streamflow and cottonwood radial growth were positively correlated on the Fort Macleod Reach for May, June, late-spring, growing season, and annual discharges. The late-spring period of May and June is the period of highest flows that typically occur along southern Alberta rivers (Mahoney and Rood 1998). Large flows during this time will raise the water table of the floodplain and provide additional water. Water availability promotes cottonwood growth, but their dependency on available water makes them particularly sensitive to drought stress (Mahoney and Rood 1992; Tyree et al. 1994). For conservation of poplars, it is not only the late-spring flows that are necessary for establishment of seedlings and growth, but also late-summer flows that are essential for long-term survival of seedlings and mature trees.

There was no significant correlation found between streamflow and cottonwood growth on either the Summerview or Monarch reach. Tree growth along these reaches might be influenced more by surface runoff than groundwater as was found along confined reaches in other areas (Stromberg and Patten 1996). Alternatively, any growth benefit to the trees along the confined reaches could be countered by inundation due to their proximity to the channel edge.

Surprisingly, significant relationships were only found between RI growth and streamflow. It was expected that BAI would provide better correlations since these measurements represent the amount of water conducting wood produced each year. It was therefore anticipated that BAI should provide a better measure of annual growth. Other studies relating growth to streamflow have also found significant associations with radial increments, but BAI was not previously analyzed (Stromberg and Patten 1991; Stromberg and Patten 1996).

This study demonstrated the influence that the geomorphic context has on cottonwood establishment, survival and growth. The study also investigated the interaction between geomorphic context and changes in flow regime relative to riparian cottonwood ecology. These results contribute to the understanding of riparian cottonwoods in a semi-arid region, and how river regulation can impact these trees. Consequently, future monitoring and study of cottonwoods should pay particular attention to the geomorphic context when interpreting results of cottonwood growth or population structure.

REFERENCES

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

Andersen, D.C. and D.J. Cooper. 2000. Plant-herbivore-hydroperiod interactions: effects of native mammals on floodplain tree recruitment. Ecological Applications 10: 1384-1399.

Auble, G.T. and M.L. Scott. 1998. Fluvial disturbance patches and cottonwood recruitment along the upper Missouri River, Montana. Wetlands 18: 546-556.

Bendix, J. and C.R. Hupp. 2000. Hydrological and geomorphological impacts on riparian plant communities. Hydrological Processes 14: 2977-2990.

Benn, P.C. and W.D. Erskine. 1994. Complex channel response to flow regulation: Cudgegong River below Windamere Dam, Australia. Applied Geography 14: 153-168.

Beschta, R.L. 1991. Stream habitat management for fish in the northwestern United States: the role of riparian vegetation. American Fisheries Society Symposium 10: 53-58.

Beschta, R.L. 2003. Cottonwoods, elk, and wolves in the Lamar Valley of Yellowstone National Park. Ecological Applications 13: 1295-1309.

Bessey, D.E. 1904. The number and weight of cottonwood seeds. Science 20: 118-119.

Braatne, J.H., S.B. Rood and P.E. Heilman. 1996. Life history, ecology and conservation of riparian cottonwoods in North America. In: R.F. Stettler, J. Bradshaw, H.D., P.E. Heilman and T.M. Hinckley (Editors), Biology of *Populus* and its implications for management and conservation. NRC Research Press, National Research Council of Canada, Ottawa, Ontario, Canada, pp. 57-85.

Bradley, C. 1993. Developing a conservation and management strategy for riparian forests in southern Alberta. Provincial Museum of Alberta No.19: 269-272.

Bradley, C.E. and D.G. Smith. 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. Canadian Journal of Botany 64: 1433-1442.

Brandt, S.A. 2000. Classification of geomorphical effects downstream of dams. Catena 40: 375-401.

Brayshaw, T.C. 1965a. Native poplars of southern Alberta and their hybrids. Department of Forestry, 1109, Ottawa, 40 pp.

Brayshaw, T.C. 1965b. The status of the black cottonwood (*Populus trichocarpa* Torrey and Gray). The Canadian Field-Naturalist 79: 91-95.

Buhrmann, H. and D. Young. 1982. Canoeing Chinook Country Rivers. Hans Buhrmann and David Young, Lethbridge, 154 pp.

Busch, D.E., N.L. Ingraham and S.D. Smith. 1992. Water uptake in woody riparian phreatophytes of the southwestern United States: a stable isotope study. Ecological Applications 2: 450-459.

Canham, C.D., P.T. LePage and K.D. Coates. 2004. A neighborhood analysis of canopy tree competition: effects of shading versus crowding. Canadian Journal of Forest Research 34: 778-787.

Ceulemans, R., G. Scarasciamugnozza, B.M. Wiard, J.H. Braatne, T.M. Hinckley, R.F. Stettler, J.G. Isebrands and P.E. Heilman. 1992. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation .1. Clonal comparisons of 4-year growth and phenology. Canadian Journal of Forest Research 22: 1937-1948.

Clipperton, G.K., C.W. Koning, A.G.H. Locke, J.M. Mahoney and B. Quazi. 2003. Instream flow needs determinations for the South Saskatchewan River Basin, Alberta, Canada. Alberta Environment, 271 pp.

Cooper, D.J., D.M. Merritt, D.C. Andersen and R.A. Chimner. 1999. Factors controlling the establishment of Fremont cottonwood seedlings on the upper Green River, USA. Regulated Rivers: Research & Management 15: 419-440.

Dewit, L. and D.M. Reid. 1992. Branch abscission in balsam poplar (*Populus balsamifera*): characterization of the phenomenon and the influence of the wind. International Journal of Plant Sciences 153: 556-564.

Disalvo, A.C. and S.C. Hart. 2002. Climatic and stream-flow controls on tree growth in a western montane riparian forest. Environmental Management 30: 678-691.

Dudek, D.M., J.R. McClenahen and W.J. Mitsch. 1998. Tree growth responses of *Populus deltoides* and *Juglans nigra* to streamflow and climate in a bottomland hardwood forest in central Ohio. American Midland Naturalist 140: 233-244.

Dynesius, M. and C. Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266: 753-762.

Eckenwalder, J.E. 1977. North American cottonwoods (*Populus*, Salicaceae) of sections Abaso and Aigeiros. Journal of the Arnold Arboretum 58: 193-208.

Eckenwalder, J.E. 1996. Systematics and evolution of *Populus*. In: R.F. Stettler, J. Bradshaw, H.D., P.E. Heilman and T.M. Hinckley (Editors), Biology of *Populus* and its Implications for Management and Conservation. NRC Research Press, Ottawa, Ontario, Canada, pp. 7-32.

Everitt, B.L. 1968. Use of the cottonwood in an investigation of the recent history of a flood plain. American Journal of Science 266: 417-439.

Farley, G.H., L.M. Ellis, J.N. Stuart and N.J. Scott. 1994. Avian species richness in different-aged stands of riparian forest along the Middle Rio-Grande, New-Mexico. Conservation Biology 8: 1098-1108.

Farrar, J.L. 1995. Trees in Canada. Fitzhenry & Whiteside Ltd., Markham, Ontario, and the Canadian Forest Service, Natural Resources Canada, Ottawa, ON., Markham, Ontario, 502 pp.

Fenner, P., W.W. Brady and D.R. Patton. 1984. Observations on seeds and seedlings of Fremont cottonwood. Journal of Desert Plants 6: 55-58.

Finch, D.M. and L.F. Ruggiero. 1993. Wildlife habitats and biological diversity in the Rocky Mountains and northern Great Plains. Natural Areas Journal 13: 191-203.

Floate, K.D. 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: 253-264.

Floate, K.D., G.D. Martinsen and T.G. Whitham. 1997. Cottonwood hybrid zones as centres of abundance for gall aphids in western North America: Importance of relative habitat size. Journal of Animal Ecology 66: 179-188.

Floate, K.D. and T.G. Whitham. 1993. The "Hybrid Bridge" hypothesis: Host shifting via plant hybrid swarms. The American Naturalist 141: 651-662.

Friedman, J.M., W.R. Osterkamp, M.L. Scott and G.T. Auble. 1998. Downstream effects of dams on channel geometry and bottomland vegetation: regional patterns in the Great Plains. Wetlands 18: 619-633.

Fritts, H.C. 1976. Tree Rings and Climate. Academic Press Inc., London, 567 pp.

Galloway, G. and J. Worrall. 1979. Cladoptosis - reproductive strategy in black cottonwood. Canadian Journal of Forest Research 9: 122-125.

Galuszka, D.A. and T.E. Kolb. 2002. Tree growth and regeneration response to climate and stream flow in a species-rich southwestern riparian forest. Western North American Naturalist 62: 266-279.

Geological Survey of Canada (GSC). 1967. Geologic Map 20 - 1967 Lethbridge, Alberta. Geological Survey of Canada, Ottawa.

Gom, L.A. and S.B. Rood. 1999a. The discrimination of cottonwood clones in a mature grove along the Oldman River in southern Alberta. Can. J. Bot. 77: 1084-1094.

Gom, L.A. and S.B. Rood. 1999b. Patterns of clonal occurrence in a mature cottonwood grove along the Oldman River, Alberta. Canadian Journal of Botany 77: 1095-1105.

Gordon, N.D., T.A. McMahon, B.L. Finlayson, C.J. Gippel and R.J. Nathan. 2004. Stream Hydrology: An introduction for ecologists. John Wiley & Sons, Chichester, 429 pp.

Government of Alberta. 2003. Water for Life, Alberta's strategy for sustainability: Facts and information on water in Alberta 2002, Edmonton, 28 pp.

Greenland Engineering Group (GEG). 2002. Surface Water and Sediment Data, Water Survey of Canada, Environment Canada.

Harner, M.J. and J.A. Stanford. 2003. Differences in cottonwood growth between a losing and a gaining reach of an alluvial floodplain. Ecology 84: 1453-1458.

Heilman, P.E. and R.F. Stettler. 1985. Genetic-variation and productivity of *Populus trichocarpa* and its hybrids .2. Biomass production in a 4-year plantation. Canadian Journal of Forest Research 15: 384-388.

Hinckley, T.M., J.H. Braatne, R. Cleulemans, P. Clum, J. Dunlap, D. Newman, B. Smit, G. Scarascia-Mugnozza and E. Van Volkenburgh. 1992. Growth dynamics and canopy structure. In: C.P. Mitchell, J.B. Ford-Robertson, T. Hinckley, and L. Sennerby-Forsse (Editor), Ecophysiology of Short Rotation Forest Crops. Elsevier Science Publishers, Ltd., London & New York, pp. 1-34.

Hinckley, T.M., H. Richter and P.J. Schulte. 1991. Water relations. In: A.S. Raghavendra (Editor), Physiology of Trees. John Wiley & Sons, Inc., pp. 137-155.

Horton, J.S., F.C. Mounts and J.M. Kraft. 1960. Seed germination and seedling establishment of phreatophyte species. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station Paper No. 48, 26 pp.

Hughes, F.M.R. and S.B. Rood. 2003. Allocation of river flows for restoration of floodplain forest ecosystems: A review of approaches and their applicability in Europe. Environmental Management 32: 12-33.

Hupp, C.R. and W.R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14: 277-295.

Jansson, R., C. Nilsson, M. Dynesius and E. Andersson. 2000. Effects of river regulation on river-margin vegetation: A comparison of eight boreal rivers. Ecological Applications 10: 203-224.

Johnson, W.C. 1992. Dams and riparian forests: case study from the upper Missouri River. Rivers 3: 229-242.

Johnson, W.C. 1994. Woodland expansion in the Platte River, Nebraska - Patterns and causes. Ecological Monographs 64: 45-84.

Johnson, W.C. 1998. Adjustment of riparian vegetation to river regulation in the great plains, USA. Wetlands 18: 608-618.

Johnson, W.C. 2000. Tree recruitment and survival in rivers: influence of hydrological processes. Hydrological Processes 14: 3051-3074.

Johnson, W.C., R.L. Burgess and W.R. Keammerer. 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. Ecological Monographs 46: 59-84.

Johnston, C.A. and R.J. Naiman. 1990. Browse selection by beaver: effects on riparian forest composition. Canadian Journal of Forest Research 20: 1036-1043.

Kalischuk, A.R., S.B. Rood and J.M. Mahoney. 2001. Environmental influences on seedling growth of cottonwood species following a major flood. Forest Ecology and Management 144: 75-89.

Kauffman, J.B. and W.C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. Journal of Range Management 37: 430-438.

Kellerhals, R., C.R. Neill and D.I. Bray. 1972. Hydraulic and Geomorphic Characteristics of Rivers in Alberta. Research Council of Alberta, River Engineering and Surface Hydrology Report 72-1, Edmonton, 52 pp.

Knighton, D. 1998. Fluvial Forms and Processes: A new perspective. Arnold, London, 383 pp.

Kondolf, G.M. 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels. Environmental management 21: 533-551.

Kozlowski, T.T. 1958. Water relations and growth of trees. Journal of Forestry 56: 498-502.

Kozlowski, T.T. and S.G. Pallardy. 1997. Physiology of woody plants. Academic Press, Inc, San Diego, 411 pp.

Kranjcec, J., J.M. Mahoney and S.B. Rood. 1998. The responses of three riparian cottonwood species to water table decline. Forest Ecology and Management 110: 77-87.

Krinard, R.M. and R.L. Johnson. 1980. Fifteen years of cottonwood plantation growth and yield. Southern Journal of Applied Forestry 4: 180-185.

Leopold, L.B. 1994. A View of the River. Harvard University Press, Cambridge, Massachusetts, 298 pp.

Mahoney, J.M., P. Koegler and S.B. Rood. 1990. The accuracy of tree ring analysis for estimating the age of riparian poplars. In: S.B. Rood and J.M. Mahoney (Editors), The Biology and Management of Southern Alberta's Cottonwoods, University of Lethbridge, pp. 25-30.

Mahoney, J.M. and S.B. Rood. 1991. A device for studying the influence of declining water-table on poplar growth and survival. Tree Physiology 8: 305-314.

Mahoney, J.M. and S.B. Rood. 1992. Response of a hybrid poplar to water table decline in different substrates. Forest Ecology and Management 54: 141-156.

Mahoney, J.M. and S.B. Rood. 1998. Streamflow requirements for cottonwood seedling recruitment - an integrative model. Wetlands 18: 634-645.

Martinsen, G.D. and T.G. Whitham. 1994. More birds nest in hybrid cottonwood trees. Wilson Bulletin 106: 474-481.

Moss, E.H. 1992. Flora of Alberta. University of Toronto Press, Toronto, 687 pp.

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

Nanson, G.C. and J.C. Croke. 1992. A genetic classification of floodplains. Geomorphology 4: 459-486.

Nilsson, C. 1992. Conservation management of riparian communities. In: L. Hansson (Editor), Ecological Principles of Nature Conservation. Elsevier Applied Science, London.

Nilsson, C. and K. Berggren. 2000. Alterations of riparian ecosystems caused by river regulation. Bioscience 50: 783-792.

Nilsson, C.a.M.S. 2002. Basic principles and ecological consequences of changing water regimes: riparian plant communities. Environmental Management 30: 468-480.

Patten, D.T. 1998. Riparian ecosystems of semi-arid North America: Diversity and human impacts. Wetlands 18: 498-512.

Pedersen, B.S. and J.L. Howard. 2004. The influence of canopy gaps on overstory tree and forest growth rates in a mature mixed-age, mixed-species forest. Forest Ecology and Management 196: 351-366.

Peterson, E.B., N.M. Peterson and D.S. McLennan. 1996. Black cottonwood and balsam poplar managers' handbook for British Columbia. B.C. Ministry of Forests, FRDA Report 250, Victoria, B.C., 116 pp.

Poage, N.J. and J.C. Tappeiner. 2002. Long-term patterns of diameter and basal area growth of old-growth Douglas-fir trees in western Oregon. Canadian Journal of Forest Research 32: 1232-1243.

Richter, B.D., J.V. Baumgartner, J. Powell and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10: 1163-1174.

Ripple, W.J. and R.L. Beschta. 2003. Wolf reintroduction, predation risk, and cottonwood recovery in Yellowstone National Park. Forest Ecology and Management 184: 299-313.

Rood, S., J. Campbell and T. Despins. 1986. Natural poplar hybrids from southern Alberta: I. Continuous variation for foliar characteristics. Canadian Journal of Botany 64: 1382-1388.

Rood, S. and S. Heinze-Milne. 1989. Abrupt downstream forest decline following river damming in southern Alberta. Canadian Journal of Botany 67: 1744-1749.

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

Rood, S.B., C.R. Gourley, E.M. Ammon, L.G. Heki, J.R. Klotz, M.L. Morrison, D. Mosley, G.G. Scoppettone, S. Swanson and P.L. Wagner. 2003b. Flows for floodplain forests: A successful riparian restoration. Bioscience 53: 647-656.

Rood, S.B., C. Hillman, T. Sanche and J.M. Mahoney. 1994. Clonal reproduction of riparian cottonwoods in southern Alberta. Canadian Journal of Botany 72: 1766-1774.

Rood, S.B., A.R. Kalischuk and J.M. Mahoney. 1998. Initial cottonwood seedling recruitment following the flood of the century of the Oldman River, Alberta, Canada. Wetlands 18: 557-570.

Rood, S.B., A.R. Kalischuk, M.L. Polzin and J.H. Braatne. 2003c. Branch propagation, not cladoptosis, permits dispersive, clonal reproduction of riparian cottonwoods. Forest Ecology and Management 186: 227-242.

Rood, S.B. and J.M. Mahoney. 1990. Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. Environmental Management 14: 451-464.

Rood, S.B. and J.M. Mahoney. 1995. River damming and riparian cottonwoods along the Marias River, Montana. Rivers 5: 195-207.

Rood, S.B. and J.M. Mahoney. 2000. Revised instream flow regulation enables cottonwood recruitment along the St. Mary River, Alberta, Canada. Rivers 7: 109-125.

Rood, S.B., J.M. Mahoney, D.E. Reid and L. Zilm. 1995. Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. Canadian Journal of Botany 73: 1250-1260.

Rood, S.B., K. Taboulchanas, C.E. Bradley and A.R. Kalischuk. 1999. Influence of flow regulation on channel dynamics and riparian cottonwoods along the Bow River, Alberta. Rivers 7: 33-48.

Rosgen, D. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado, 363 pp.

Rosgen, D.L. 1994. A Classification of Natural Rivers. Catena 22: 169-199.

Samuelson, G.M. and S.B. Rood. 2004. Differing influences of natural and artificial disturbances on riparian cottonwoods from prairie to mountain ecoregions in Alberta, Canada. Journal of Biogeography 31: 435-450.

Savoy, E. 1991. The importance of riparian forests to prairie birds: a case study - Dinosaur Provincial Park, Alberta. In: S.B. Rood and J.M. Mahoney (Editors), The Biology and Management of Southern Alberta's Cottonwoods. University of Lethbridge, University of Lethbridge, pp. 91-98.

Schier, G.A. and R.B. Campbell. 1976. Differences among *Populus* species in ability to form adventitious shoots and roots. Canadian Journal of Forest Research 6: 253-261.

Schume, H., M. Grabner and O. Eckmullner. 2004. The influence of an altered groundwater regime on vessel properties of hybrid poplar. Trees-Structure and Function 18: 184-194.

Scott, M.L., G.T. Auble and J.M. Friedman. 1997. Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. Ecological Applications 7: 677-690.

Scott, M.L., J.M. Friedman and G.T. Auble. 1996. Fluvial process and the establishment of bottomland trees. Geomorphology 14: 327-339.

Scott, M.L., P.B. Shafroth and G.T. Auble. 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management 23: 347-358.

Scott, M.L., S.K. Skagen and M.F. Merigliano. 2003. Relating geomorphic change and grazing to avian communities in riparian forests. Conservation Biology 17: 284-296.

Shields, F.D., A. Simon and L.J. Steffen. 2000. Reservoir effects on downstream river channel migration. Environmental Conservation 27: 54-66.

Smit, B.A. 1988. Selection of flood-resistant and susceptible seedlings of *Populus trichocarpa* Torr and Gray. Canadian Journal of Forest Research 18: 271-275.

Smith, D.G. and C.M. Pearce. 2000. River ice and its role in limiting woodland development on a sandy braid-plain, Milk River, Montana. Wetlands 20: 232-250.

Snyder, K. and D. Williams. 2000. Water sources used by riparian trees varies among streamtypes on the San Pedro River, Arizona. Agricultural and Forest Meteorolgy 105: 227-240.

Sparks, R.E. 1995. Need for ecosystem management of large rivers and their floodplains. BioScience 45: 168-182.

Stalker, A.M. and R.W. Barendregt. 1993. The Origin of the Valleys of Lethbridge. In: R.W. Barendregt, M.C. Wilson and F.J. Jankunis (Editors), The Paliser Triangle: A region in space and time. The University of Lethbridge, Lethbridge, pp. 153-164.

Stettler, R.F., L. Zsuffa and R. Wu. 1996. The role of hybridization in the genetic manipulation of *Populus*. In: R.F. Stettler, H.D. Bradshaw Jr., P.E. Heilman and T.M. Hinckley (Editors), Biology of *Populus* and its Implications for Management and Conservation. NRC Research Press, Ottawa, Ontario, Canada, pp. 87-112.

Stokes, M.A. and T.L. Smiley. 1968. An Introduction to Tree-Ring Dating. The University of Chicago Press, Chicago, 73 pp.

Stromberg, J.C. and D.T. Patten. 1991. Instream flow requirements for cottonwoods at Bishop Creek, Inyo County, California. Rivers 2: 1-11.

Stromberg, J.C. and D.T. Patten. 1996. Instream flow and cottonwood growth in the eastern Sierra Nevada of California, USA. Regulated Rivers-Research & Management 12: 1-12.

Stromberg, J.C., D.T. Patten and B.D. Richter. 1991. Flood flows and dynamics of Sonoran riparian forests. Rivers 2: 221-235.

Tyree, M.T., K.J. Kolb, S.B. Rood and S. Patino. 1994. Vulnerability to drought-induced cavitation of riparian cottonwoods in Alberta - a possible factor in the decline of the ecosystem. Tree Physiology 14: 455-466.

Tyree, M.T. and J.S. Sperry. 1989. Vulnerability of xylem to cavitation and embolism. Annual Review of Plant Physiology and Plant Molecular Biology 40: 19-38.

Virginillo, M., J.M. Mahoney and S.B. Rood. 1991. Establishment and survival of Poplar seedlings along the Oldman River, Southern Alberta. In: S.B. Rood and J.M. Mahoney (Editors), The Biology and Management of Southern Alberta's Cottonwoods, University of Lethbridge, pp. 55-61.

Wallace, J.B., S.L. Eggert, J.L. Meyer and J.R. Webster. 1997. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. Science 277: 102-104.

Waltz, A.M. and T.G. Whitham. 1997. Plant development affects arthropod communities: Opposing impacts of species removal. Ecology 78: 2133-2144.

Whitham, T.G. 1989. Plant hybrid zones as sinks for pests. Science 244: 1490-1493.

Williams, G.P. and M.G. Wolman. 1984. Downstream effects of dams on alluvial rivers. US Department of the Interior, USGS Professional Paper 1286, Washington, 64 pp.

Willms, C.R. 2004. Impacts of the Oldman River Dam on downstream riparian cottonwood forests, Follow-up Environmental Impact Assessment of the Oldman River Dam. Piikani Environmental Services, Brocket, 108 pp.

Willms, C.R. 2005. The influence of geomorphology and flow regulation on riparian cottonwoods, M.Sc. thesis, University of Lethbridge, Lethbridge, 140 pp.

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

World Commission on Dams (WCD). 2000. Dams and Development: A New Framework for Decision-Making. Earthscan Publications, London, UK, 404 pp.

APPENDIX A

HYDROLOGY OF THE OLDMAN RIVER

A hydrologic analysis was performed for the Oldman River to assess changes in the flow regime resulting from operations of the Lethbridge Northern Irrigation District (LNID) weir and the Oldman River Dam (ORD) using methods described by Richter et al. (1996).

Oldman River

The Oldman River is a perennial stream channel originating in the Rocky Mountains of southwestern Alberta. Peak annual stream flows usually occur in May and June in response to melting of the winter snow pack and/or spring rain events (Figure A-1). The median date for maximum mean daily discharge is June 7.

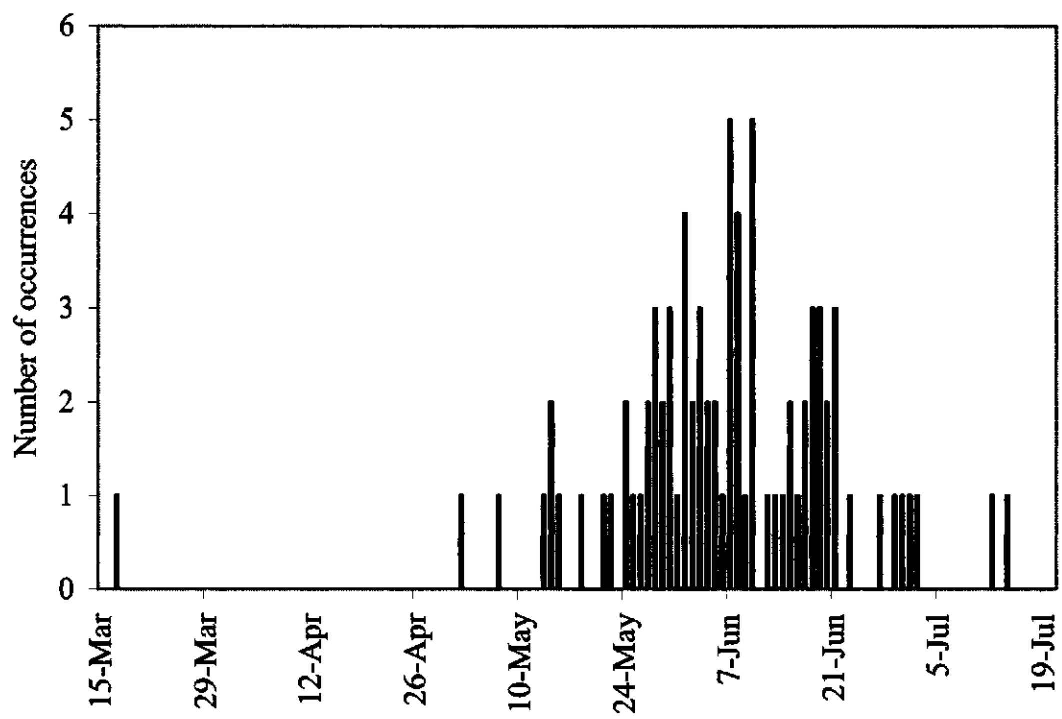

Figure A-1: Date and number of occurrences of maximum mean daily discharge between 1912 and 2001 along the Oldman River near Lethbridge (05AD007).

Lethbridge Northern Irrigation District (LNID) weir

Construction of the LNID weir was completed in fall of 1922 with diversion commencing in May 1923. On June 1, 1923 a greater than a 1-in-100 year flood (based on log Pearson Type III analysis at Fort Macleod gauge) damaged the weir infrastructure and prevented further diversions until the summer of 1925. Diversion data was compiled for the record period of 1925 until 2001 for the analysis in this study.

Diverted flow from the Oldman River generally occurs from April through October with a peak mean monthly discharge of 13.6 m^3/s occurring in July (Figure A-2). Mean maximum daily discharge was 20.2 m^3/s (sd = 7.77) but varied from 43.5 m^3/s (1990) to 8.18 m^3/s (1966).

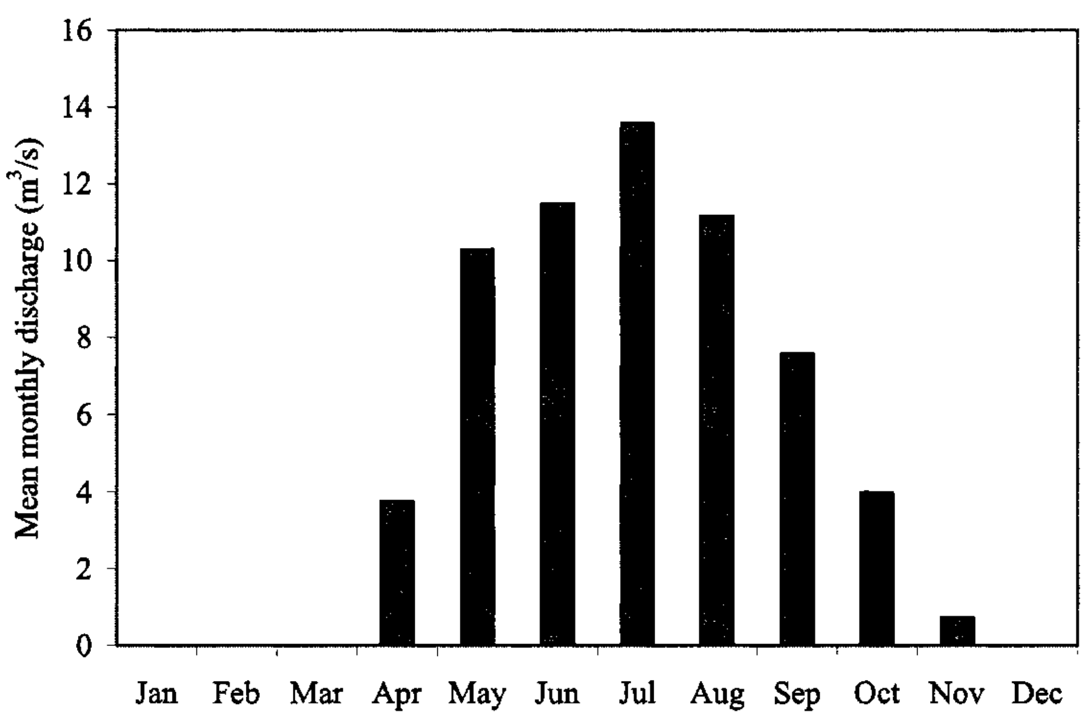

Figure A-2: Mean monthly diversion of discharge from the Oldman River by the Lethbridge Northern Irrigation District weir for the record period 1925-2001.

Large quantities of water that are diverted from the Oldman River in the early-summer do not pose as serious an impact upon the flow regime as there is a correspondingly high discharge of the river during this time. In the late-summer when flows are naturally low diverted flows will have a greater impact upon the river (Figure A-3). On a monthly basis, August mean flows were the most negatively impacted by the diversions made at the LNID weir (Table A-1). The diversion canal currently has a capacity of 45 m^3/s although it is rare for such high flows to be diverted. With the capacity to divert the whole river during periods of low flow, regulations ensured a minimum of approximately 1 m^3/s (30 cubic feet per second) to pass downstream prior to commissioning of the ORD (J. Mahoney pers. comm.). There were times that the weir did allow only the required minimum flow downstream (Figure A-4).

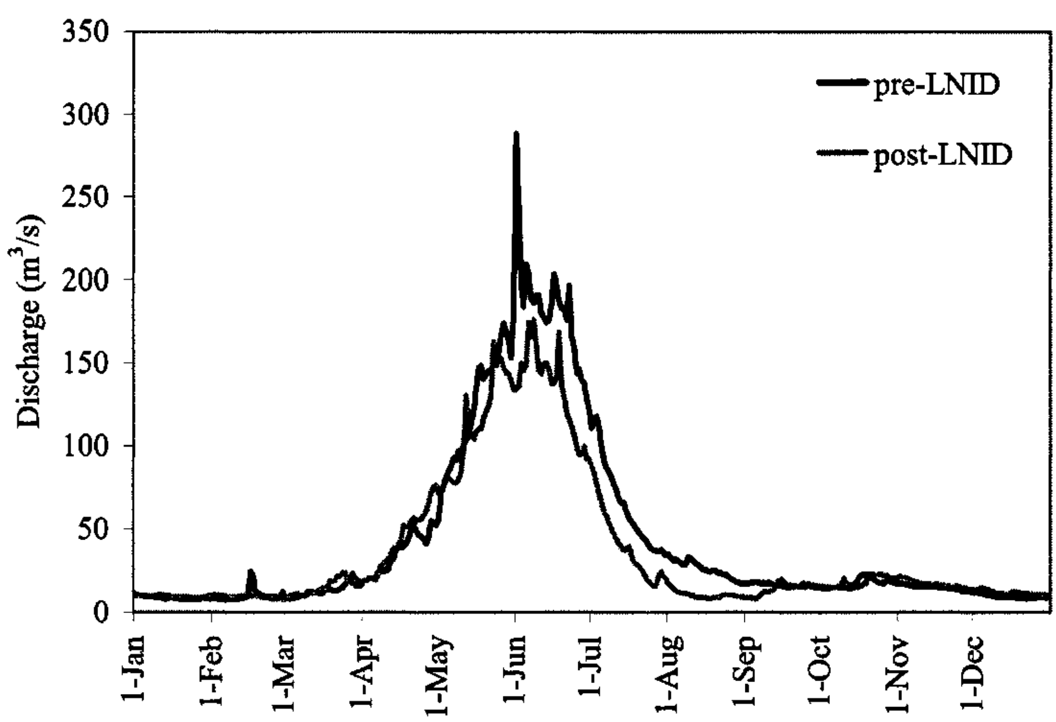

Figure A-3: A comparison of the average hydrographs of the Oldman River near Fort Macleod for the pre- and post-impact periods by the Lethbridge Northern Irrigation District (LNID) weir (1925).

Table A-1: Changes to the flow regime of the Oldman River at Fort Macleod (05AB007) due to diversions of the Lethbridge Northern Irrigation District (LNID) weir (1925).

	Discharge (m^3/s)		Deviation	Percent of
	Pre-LNID	**Post-LNID**	**magnitude**	**pre-LNID**
Monthly magnitude				
January	8.9	9.7	0.8	9
February	10.1	9.5	-0.5	-5
March	13	15.2	2.3	17
April	36.2	43.2	7	19
May	123.9	112.8	-11.1	-9
June	181.4	133	-48.4	-27
July	64.7	40.4	-24.3	-38
August	26.2	10.6	-15.6	-60
September	16.5	14.2	-2.3	-14
October	17.4	18.8	1.4	8
November	15	16.8	1.9	12
December	9.6	11.9	2.3	24
Magnitude and duration of annual extremes				
1-day minimum	5.21	2.64	-2.6	-49
3-day minimum	5.45	2.82	-2.6	-48
7-day minimum	5.73	2.99	-2.7	-48
1-day maximum	429	329	-99.9	-23
3-day maximum	379	254	-124.6	-33
7-day maximum	318	208	-110.6	-35

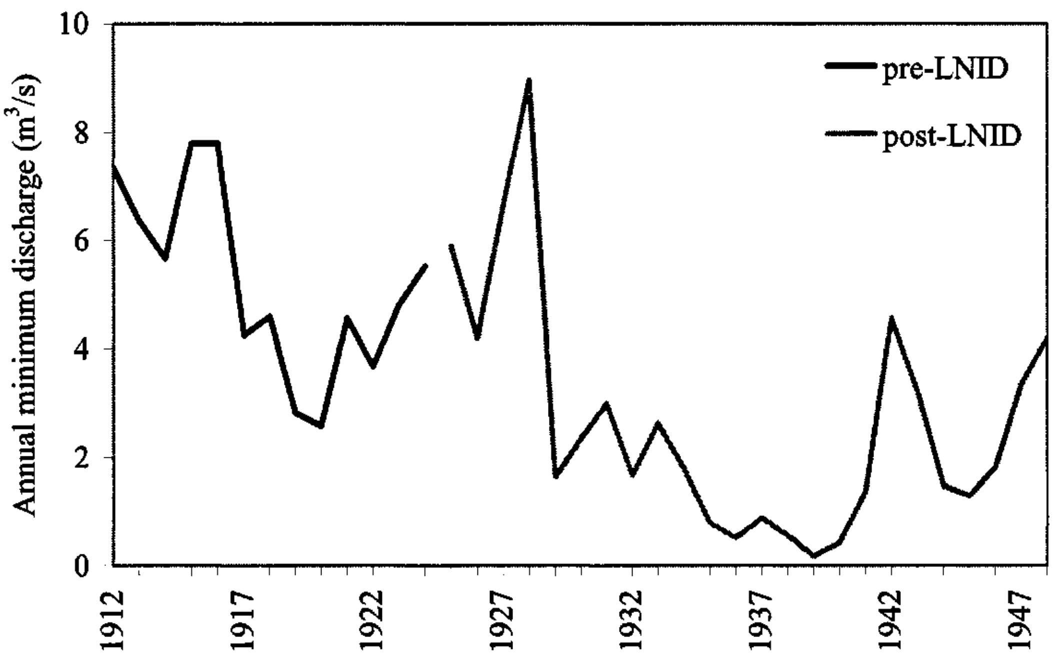

Figure A-4: A comparison of annual minimum discharges of the Oldman River near Fort Macleod for pre- and post-impact periods by the LNID weir (1925).

With the expansion of irrigation, the LNID weir has diverted progressively more water from the Oldman River over time. Between 1978 – 88 there was a major rehabilitation and upgrading of the headworks canal system. Linear regression shows that total diversion made by the weir has increased over the record period by 57% (Figure A-5) and that recent mean annual and maximum withdrawals have been at unprecedented levels (Figure A-5 and A-6).

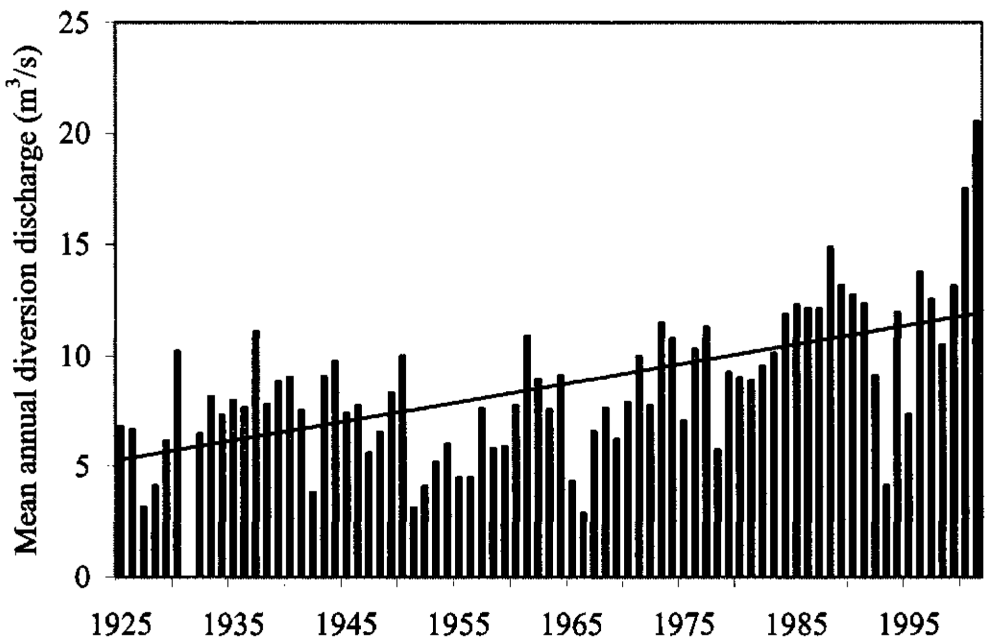

Figure A-5: Mean annual diversion from the LNID weir. Line of best fit ($r^2 = 0.342$) shows general increase in diversion over time.

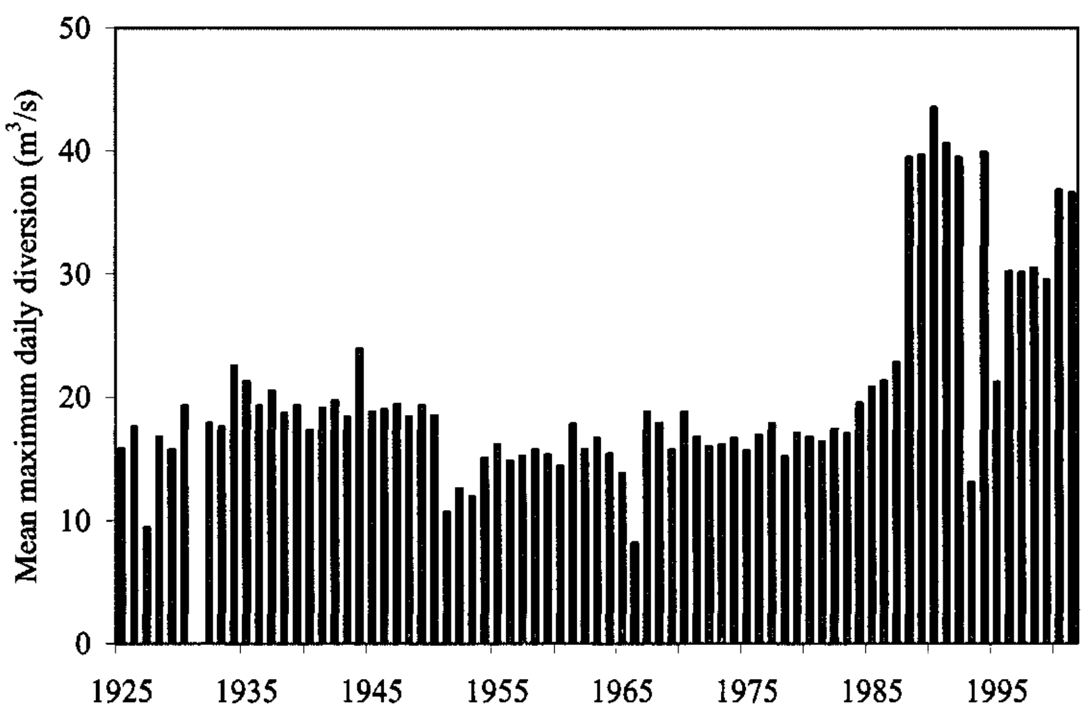

Figure A-6: Mean maximum daily diversion of the Lethbridge Northern Irrigation District weir.

Oldman River Dam (ORD)

The operations strategy of the ORD implemented in 1993 attempted to return a more natural flow regime to the river downstream of the LNID weir. Peak flows in the spring and early summer were stored in the ORD reservoir and then released in the late summer to compensate for the water withdrawals by the LNID weir (Figure A-7). This resulted in below normal discharge during the early-summer, and above average discharge in the late-summer (Table A-7). Minimum discharge immediately below the ORD was higher than natural (Figure A-8), and discharge downstream of the LNID weir returned to near pre-weir conditions. Mean discharges for August and September over the pre-weir, post-weir and post-dam periods were 25.3, 12.7, and 23.2 m^3/s, respectively.

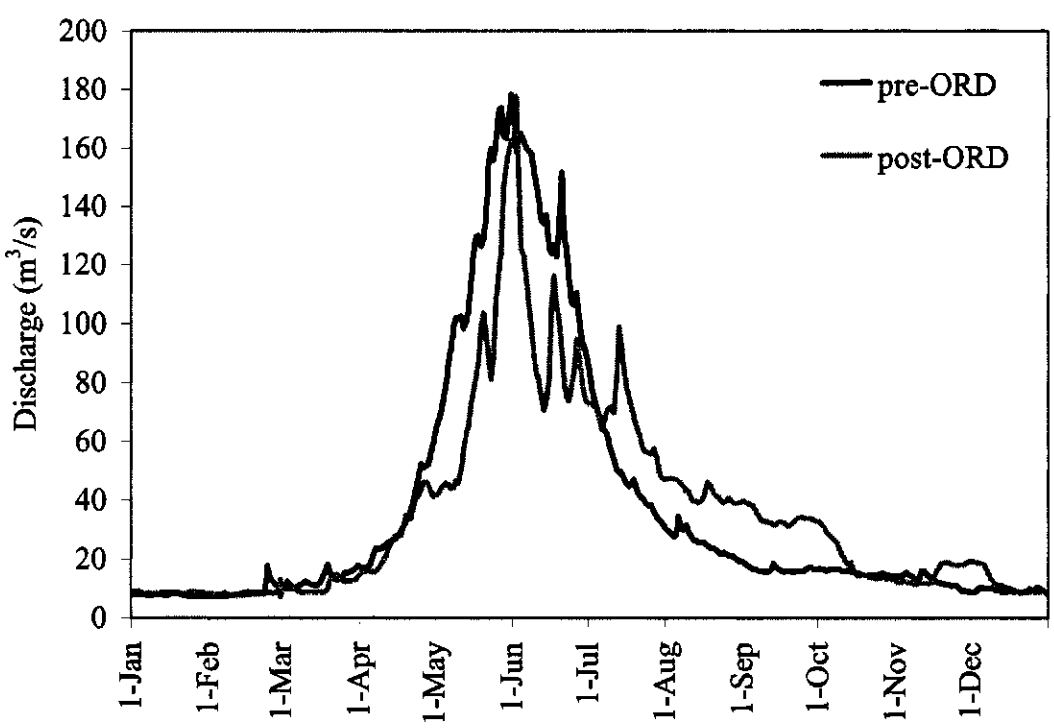

Figure A-7: A comparison of the hydrographs for the pre- and post-impact periods by the Oldman River Dam (ORD) (1993).

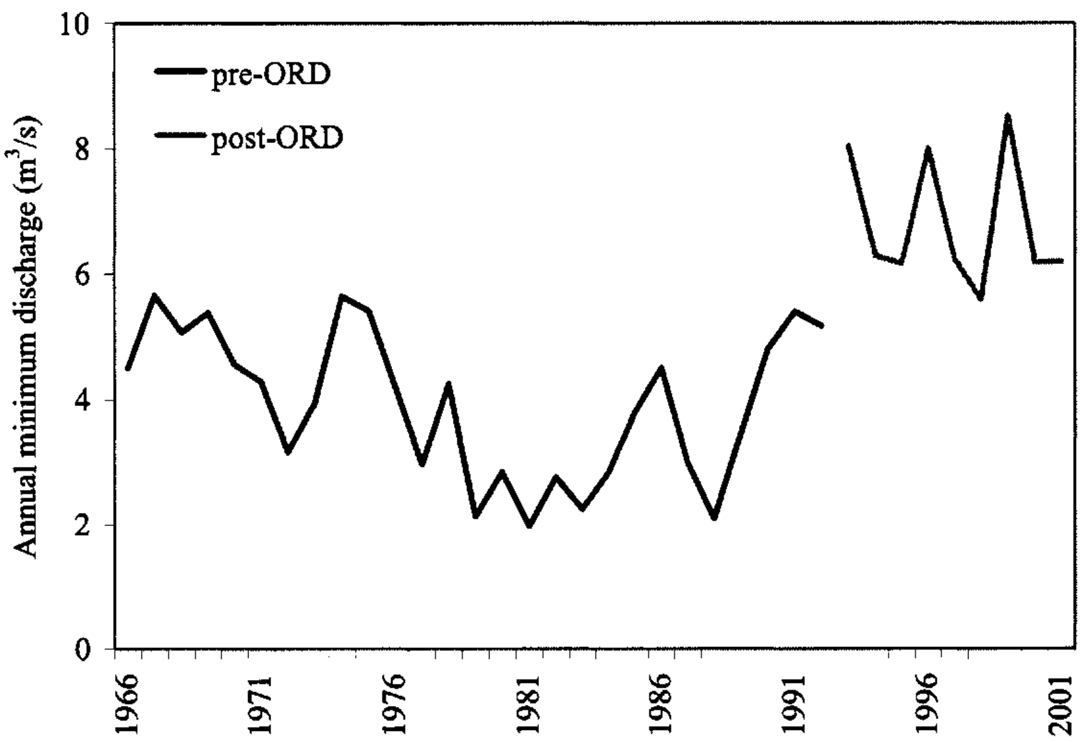

Figure A-8: A comparison of annual minimum discharges of the Oldman River near Brocket for the pre- and post-impact periods by the Oldman River Dam (ORD) (1993).

Table A-2: Changes to the flow regime of the Oldman River at Brocket (05AA024) due to the Oldman River Dam (ORD).

	Discharge (m^3/s)		**Deviation**	**Percent of**
	Pre-ORD	**Post-ORD**	**magnitude**	**pre-ORD**
Monthly magnitude				
January	7.9	8.5	0.6	8
February	8.9	8.1	-0.8	-9
March	12.8	10.4	-2.4	-19
April	32.6	28.7	-3.9	-12
May	122.2	81.5	-40.7	-33
June	133.4	98	-35.4	-27
July	50.5	67.4	16.9	33
August	25.4	42.4	17.1	67
September	16.5	34	17.5	106
October	15.4	19	3.6	24
November	12.5	14.9	2.4	19
December	9.3	11.8	2.5	27
Magnitude and duration of annual extremes				
1-day minimum	3.93	6.81	2.9	73
3-day minimum	4.14	6.85	2.7	65
7-day minimum	4.52	6.99	2.5	55
1-day maximum	319	233	-86.2	-27
3-day maximum	275	219	-56.8	-20
7-day maximum	238	195	-42.6	-18

Table A-3: Mean monthly diversions made by the LNID weir in m^3/s.

Station ID	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
05AB016	1925				0.683	8.93	9.23	13.8	9.62	4.12	0.932			6.79
05AB016	1926				0.636	4.52	13.1	12.3	9.13	5.4	1.51			6.66
05AB016	1927				0.432	1.58	1.74	5.53	4.14	4.35	4.08	0.004		3.13
05AB016	1928					4.53	10.4	1.24	3.63	2.95	6.06			4.1
05AB016	1929				0.024	2.68	4.29	9.54	10.1	8.42	7.85	0.045		6.15
05AB016	1930				4.54	10.7	14.6	18.4	12.4	7.97	2.74			10.2
05AB016	1931													
05AB016	1932					8.61	2.51	12.4	12.8	5.14	3.39			6.47
05AB016	1933				0.591	3.47	14.5	15.3	14.4	5.27	3.4			8.17
05AB016	1934				0.771	14.1	6.59	7.11	11.2	8	3.3			7.33
05AB016	1935					4.54	10.5	17.8	11.8	6.41	4.73			8.01
05AB016	1936					8.83	11.2	14.2	7.58	6.67	5.12			7.67
05AB016	1937					17.9	15.4	16.1	13.5	8.49	5.67			11.1
05AB016	1938					7.27	12.8	15.1	9.39	5.53	4.62			7.83
05AB016	1939				0.709	16.7	8.41	9.38	11.7	10	4.82			8.85
05AB016	1940					10.5	15.2	15.1	11.9	7.99	2.62			9.05
05AB016	1941				0.24	13.3	7.62	15.1	7.86	5.38	2.75			7.51
05AB016	1942				4.75	7.62	0.32	1.78	5.65	2.45	3.94			3.8
05AB016	1943					10.2	12	17	11.6	6.77	5.66	0.133		9.08
05AB016	1944				5.13	22.6	11.1	13.9	7.74	4.79	2.87			9.77
05AB016	1945				4.22	11.4	4.32	7.49	11.6	9.3	3.54			7.43
05AB016	1946					13.1	7.01	11.1	13.6	6.18	2.93			7.75
05AB016	1947					4.43	2.76	14.3	11.4	2.52	3.32			5.58
05AB016	1948					5.43	4.14	9.57	8.37	10.5	7.71			6.55
05AB016	1949				1.94	10.9	7.17	15.1	8.32	8.31	6.22	0.368		8.32
05AB016	1950				0.603	14.3	14.4	13	12.3	9.05	6.3			10
05AB016	1951					3.46	3.71	3.14	5.74	3.14	2.42			3.1
05AB016	1952					6.25	4.52	4.26	6.5	3.81	3.15			4.09
05AB016	1953					6.73	1.9	4.17	10.3	8.54	4.4			5.17
05AB016	1954					4.34	13.1	11.8	9.21	2.08	1.46			6
05AB016	1955				0.312	2.87	7.73	3.52	7.91	6.13	2.73			4.45

05AB016	1956					5.03	11.7	3.5	4.92	3.46	2.72			4.46
05AB016	1957					10.5	9.28	10.9	10.4	7.94	4.13			7.62
05AB016	1958					8.38	9.12	6.51	6.35	5.47	4.64			5.79
05AB016	1959				0.084	9.03	9.13	7.8	9.13	3.47	2.38			5.88
05AB016	1960					6.54	9.04	13.5	11.7	7.61	5.72			7.76
05AB016	1961				6.76	7.5	15.7	16.4	11.9	9.52	8.47			10.9
05AB016	1962				0.522	7.09	13.8	14.3	10.8	8.36	7.49	2.05		8.94
05AB016	1963				7.36	9.96	12.9	2.16	7.23	8.3	5.32			7.58
05AB016	1964					5.24	14.1	13.2	12.6	11.4	7.2	2.25		9.11
05AB016	1965					6.76	4.43	3.04	10	3.32	2.26			4.28
05AB016	1966					2.78	3.55	3.07	4.28	3.3	2.85			2.84
05AB016	1967					0.471	3.85	12.6	15.4	8.68	4.86			6.57
05AB016	1968				2.05	11.4	12	12.9	10.9	2.18	1.9			7.65
05AB016	1969					3.6	11.7	3.12	12.9	8.89	3.32			6.21
05AB016	1970				1.31	12.7	8.87	12.5	10.3	5.54	3.99			7.92
05AB016	1971				8.62	14.7	7.86	14.7	13.1	6.98	3.79			10
05AB016	1972					6.06	13.7	14.4	12.5	5.02	2.55			7.77
05AB016	1973				8.41	13.9	14.3	15.4	11.4	9.08	7.66	0.211		11.5
05AB016	1974				1.32	11	9.11	15.3	16.3	14.4	7.75			10.8
05AB016	1975					4.44	7.26	10.2	14.2	9.1	4.14			7.07
05AB016	1976				2.35	11.5	15.3	15.8	13.1	8.55	5.51			10.3
05AB016	1977				8.3	15.3	16.7	12	11.9	11.2	3.76			11.3
05AB016	1978					0	10.9	14	10.5	2.6	2.01			5.73
05AB016	1979					4.9	16.4	16.3	13.5	9.39	4.25			9.25
05AB016	1980				6.37	10.9	7.47	16.1	11	6.32	4.55			9
05AB016	1981				5.94	7.67	7.47	15.6	10.9	8.31	6.04			8.87
05AB016	1982				1.69	11.3	13.6	15.4	14.6	9.96	0.003			9.52
05AB016	1983				5.9	10.9	15.7	16.5	13.2	7.74	0.364			10.1
05AB016	1984				8.76	18.8	18.9	18.3	10.4	6.92	0.904			11.9
05AB016	1985				9.29	16.2	18.9	16.6	12.7	9.91	2.28			12.3
05AB019	1986				9.01	16.5	20.1	20.2	11.6	6.85	0.824			12.15
05AB019	1987				5.15	21.3	22.3	18.8	10.5	4.93	1.93			12.13
05AB019	1988				11.4	30.6	25.6	16.6	8.29	6.23	5.34			14.87
05AB019	1989				8.82	21.5	13.4	32.6	11.2	2.98	1.88			13.20
05AB019	1990				1.76	9.93	15.5	34.1	14.5	9.14	4.25			12.74

05AB019	1991				3.7	10.7	25	13.6	11.7	10.6	11.1			12.34
05AB019	1992				4.69	30	16.5	4.06	3.69	3.33	1.61			9.13
05AB019	1993				0.649	7.68	7.22	4.84	3.82	2.67	1.92			4.11
05AB019	1994				1.42	9.21	12.4	27.8	14.6	14.7	3.48			11.94
05AB019	1995				5.86	5.73	6.36	11.7	10	8.65	3.1			7.34
05AB019	1996				0.505	7.03	25.1	27.6	22.1	11.5	2.38			13.75
05AB019	1997				1.44	11	13.3	27.1	13.5	15.6	5.76			12.53
05AB019	1998				4.01	17.8	5.85	7.61	15	18.6	4.66			10.50
05AB019	1999				6.84	9.4	17.9	24.9	15.8	14.3	2.83			13.14
05AB019	2000				2.04	24.7	26.3	33.8	19.5	13.4	2.99			17.53
05AB019	2001				2.63	21.8	24.7	35	31.4	23.2	4.87			20.51
	Mean	0	0	0	3.761271	10.27922	11.48079	13.565	11.14079	7.569211	3.973382	0.723	0	

Table A-4: Total monthly diversions made by the LNID weir in dam^3.

Station ID	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total
05AB016	1925				1770.3	23918.1	23924.2	36961.9	25766.2	10679.0	2496.3			125516.0
05AB016	1926				1648.5	12106.4	33955.2	32944.3	24453.8	13996.8	4044.4			123149.4
05AB016	1927				1119.7	4231.9	4510.1	14811.6	11088.6	11275.2	10927.9	10.4		57975.3
05AB016	1928					12133.2	26956.8	3321.2	9722.6	7646.4	16231.1			76011.3
05AB016	1929				62.2	7178.1	11119.7	25551.9	27051.8	21824.6	21025.4	116.6		113930.5
05AB016	1930				11767.7	28658.9	37843.2	49282.6	33212.2	20658.2	7338.8			188761.5
05AB016	1931													
05AB016	1932					23061.0	6505.9	33212.2	34283.5	13322.9	9079.8			119465.3
05AB016	1933				1531.9	9294.0	37584.0	40979.5	38569.0	13659.8	9106.6			150724.8
05AB016	1934				1998.4	37765.4	17081.3	19043.4	29998.1	20736.0	8838.7			135461.4
05AB016	1935					12159.9	27216.0	47675.5	31605.1	16614.7	12668.8			147940.1
05AB016	1936					23650.3	29030.4	38033.3	20302.3	17288.6	13713.4			142018.3
05AB016	1937					47943.4	39916.8	43122.2	36158.4	22006.1	15186.5			204333.4
05AB016	1938					19472.0	33177.6	40443.8	25150.2	14333.8	12374.2			144951.6
05AB016	1939				1837.7	44729.3	21798.7	25123.4	31337.3	25920.0	12909.9			163656.3
05AB016	1940					28123.2	39398.4	40443.8	31873.0	20710.1	7017.4			167565.9
05AB016	1941				622.1	35622.7	19751.0	40443.8	21052.2	13945.0	7365.6			138802.5
05AB016	1942				12312.0	20409.4	829.4	4767.6	15133.0	6350.4	10552.9			70354.7
05AB016	1943					27319.7	31104.0	45532.8	31069.4	17547.8	15159.7	344.7		168078.2
05AB016	1944				13297.0	60531.8	28771.2	37229.8	20730.8	12415.7	7687.0			180663.3
05AB016	1945				10938.2	30533.8	11197.4	20061.2	31069.4	24105.6	9481.5			137387.2
05AB016	1946					35087.0	18169.9	29730.2	36426.2	16018.6	7847.7			143279.7
05AB016	1947					11865.3	7153.9	38301.1	30533.8	6531.8	8892.3			103278.2
05AB016	1948					14543.7	10730.9	25632.3	22418.2	27216.0	20650.5			121191.6
05AB016	1949				5028.5	29194.6	18584.6	40443.8	22284.3	21539.5	16659.6	953.9		154688.8
05AB016	1950				1563.0	38301.1	37324.8	34819.2	32944.3	23457.6	16873.9			185283.9
05AB016	1951					9267.3	9616.3	8410.2	15374.0	8138.9	6481.7			57288.4
05AB016	1952					16740.0	11715.8	11410.0	17409.6	9875.5	8437.0			75587.9
05AB016	1953					18025.6	4924.8	11168.9	27587.5	22135.7	11785.0			95627.5
05AB016	1954					11624.3	33955.2	31605.1	24668.1	5391.4	3910.5			111154.5
05AB016	1955				808.7	7687.0	20036.2	9428.0	21186.1	15889.0	7312.0			82347.0

05AB016	1956		13472.4	30326.4	9374.4	13177.7	8968.3	7285.2		82604.4
05AB016	1957		28123.2	24053.8	29194.6	27855.4	20580.5	11061.8		140869.2
05AB016	1958		22445.0	23639.0	17436.4	17007.8	14178.2	12427.8		107134.3
05AB016	1959	217.7	24186.0	23665.0	20891.5	24453.8	8994.2	6374.6		108782.8
05AB016	1960		17516.7	23431.7	36158.4	31337.3	19725.1	15320.4		143489.7
05AB016	1961	17521.9	20088.0	40694.4	43925.8	31873.0	24675.8	22686.0		201464.9
05AB016	1962	1353.0	18989.9	35769.6	38301.1	28926.7	21669.1	20061.2	5313.6	170384.3
05AB016	1963	19077.1	26676.9	33436.8	5785.3	19364.8	21513.6	14249.1		140103.6
05AB016	1964		14034.8	36547.2	35354.9	33747.8	29548.8	19284.5	5832.0	174350.0
05AB016	1965		18106.0	11482.6	8142.3	26784.0	8605.4	6053.2		79173.5
05AB016	1966		7446.0	9201.6	8222.7	11463.6	8553.6	7633.4		52520.8
05AB016	1967		1261.5	9979.2	33747.8	41247.4	22498.6	13017.0		121751.5
05AB016	1968	5313.6	30533.8	31104.0	34551.4	29194.6	5650.6	5089.0		141436.8
05AB016	1969		9642.2	30326.4	8356.6	34551.4	23042.9	8892.3		114811.8
05AB016	1970	3395.5	34015.7	22991.0	33480.0	27587.5	14359.7	10686.8		146516.3
05AB016	1971	22343.0	39372.5	20373.1	39372.5	35087.0	18092.2	10151.1		184791.5
05AB016	1972		16231.1	35510.4	38569.0	33480.0	13011.8	6829.9		143632.2
05AB016	1973	21798.7	37229.8	37065.6	41247.4	30533.8	23535.4	20516.5	546.9	212474.0
05AB016	1974	3421.4	29462.4	23613.1	40979.5	43657.9	37324.8	20757.6		199216.8
05AB016	1975		11892.1	18817.9	27319.7	38033.3	23587.2	11088.6		130738.8
05AB016	1976	6091.2	30801.6	39657.6	42318.7	35087.0	22161.6	14758.0		190875.7
05AB016	1977	21513.6	40979.5	43286.4	32140.8	31873.0	29030.4	10070.8		208894.5
05AB016	1978			28252.8	37497.6	28123.2	6739.2	5383.6		105996.4
05AB016	1979		13124.2	42508.8	43657.9	36158.4	24338.9	11383.2		171171.4
05AB016	1980	16511.0	29194.6	19362.2	43122.2	29462.4	16381.4	12186.7		166220.6
05AB016	1981	15396.5	20543.3	19362.2	41783.0	29194.6	21539.5	16177.5		163996.7
05AB016	1982	4380.5	30265.9	35251.2	41247.4	39104.6	25816.3	8.0		176074.0
05AB016	1983	15292.8	29194.6	40694.4	44193.6	35354.9	20062.1	974.9		185767.3
05AB016	1984	22705.9	50353.9	48988.8	49014.7	27855.4	17936.6	2421.3		219276.6
05AB016	1985	24079.7	43390.1	48988.8	44461.4	34015.7	25686.7	6106.8		226729.2
05AB019	1986	23353.9	44193.6	52099.2	54103.7	31069.4	17755.2	2207.0		224782.0
05AB019	1987	13348.8	57049.9	57801.6	50353.9	28123.2	12778.6	5169.3		224625.3
05AB019	1988	29548.8	81959.0	66355.2	44461.4	22203.9	16148.2	14302.7		274979.2
05AB019	1989	22861.4	57585.6	34732.8	87315.8	29998.1	7724.2	5035.4		245253.3
05AB019	1990	4561.9	26596.5	40176.0	91333.4	38836.8	23690.9	11383.2		236578.8

05AB019	1991				9590.4	28658.9	64800.0	36426.2	31337.3	27475.2	29730.2			228018.2
05AB019	1992				12156.5	80352.0	42768.0	10874.3	9883.3	8631.4	4312.2			168977.7
05AB019	1993				1682.2	20570.1	18714.2	12963.5	10231.5	6920.6	5142.5			76224.7
05AB019	1994				3680.6	24668.1	32140.8	74459.5	39104.6	38102.4	9320.8			221476.9
05AB019	1995				15189.1	15347.2	16485.1	31337.3	26784.0	22420.8	8303.0			135866.6
05AB019	1996				1309.0	18829.2	65059.2	73923.8	59192.6	29808.0	6374.6			254496.4
05AB019	1997				3732.5	29462.4	34473.6	72584.6	36158.4	40435.2	15427.6			232274.3
05AB019	1998				10393.9	47675.5	15163.2	20382.6	40176.0	48211.2	12481.3			194483.8
05AB019	1999				17729.3	25177.0	46396.8	66692.2	42318.7	37065.6	7579.9			242959.4
05AB019	2000				5287.7	66156.5	68169.6	90529.9	52228.8	34732.8	8008.4			325113.7
05AB019	2001				6817.0	58389.1	64022.4	93744.0	84101.8	60134.4	13043.8			380252.4

Table A-5: Mean monthly flows for the Oldman River near Fort Macleod in m^3/s. Flows for 1910-48 are from gauging station Fort Macleod (05AB007), 1949-65 Monarch (05AD019) – Willow Creek (05AB021), 1966-85 Brocket (05AA024) + Pincher Creek (05AA004) – LNID (05AB016), 1986-2001 Brocket (05AA024) + Pincher Creek (05AA004) – LNID (05AB019)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1910								13.0	17.7	29.9			
1911				50.4	168.0	237.0	55.9	58.9	115.0	36.5	38.9	18.2	
1912	11.2	10.7	24.0	46.3	106.0	108.0	84.9	34.4	20.7	19.7	20.2	12.0	41.6
1913	8.7	8.0	10.9	73.9	148.0	174.0	51.3	32.8	21.6	21.9	18.9	11.7	48.5
1914	8.0	6.7	11.4	44.6	116.0	104.0	42.8	21.7	19.1	47.3	36.2	14.3	39.5
1915	12.1	9.7	13.3	48.5	185.0	174.0	93.6	46.6	26.9	31.8	25.2	15.5	57.1
1916	9.6	37.2	30.6	45.2	103.0	326.0	143.0	35.9	25.8	17.8	15.9	9.2	66.4
1917	7.8	7.1	7.6	24.2	172.0	247.0	79.6	24.7	15.1	11.2	9.6	7.3	51.1
1918	14.6	8.0	16.1	33.1	86.0	126.0	32.5	18.9	15.6	14.9	11.3	8.8	32.2
1919	8.6	5.1	8.6	35.4	114.0	75.6	25.3	13.1	8.5	9.8	9.1	7.1	26.8
1920	6.1	7.3	12.6	29.5	129.0	175.0	91.1	22.9	13.1	14.0	10.4	7.4	43.2
1921	8.1	9.2	10.6	32.7	121.0	132.0	39.6	14.9	10.5	12.1	8.2	7.9	33.9
1922	6.8	5.3	6.0	18.8	127.0	143.0	42.3	15.7	9.0	8.4	8.2	5.1	33.0
1923	6.5	5.9	7.7	23.1	118.0	446.0	79.6	32.4	16.0	6.5	11.2	8.1	63.2
1924	7.3	10.6	9.4	15.1	84.6	128.0	35.9	25.9	12.2	10.5	10.4	10.3	30.0
1925	11.3	10.2	31.3	78.1	136.0	101.0	22.9	8.3	12.3	19.2	14.9	15.3	38.5
1926	9.9	9.1	8.1	33.4	37.6	37.3	16.5	4.7	47.3	59.3	25.3	15.6	25.4
1927	9.6	8.3	11.0	44.7	173.0	299.0	109.0	46.3	86.4	59.2	31.6	20.7	75.1
1928	24.2	18.2	38.3	50.8	177.0	151.0	140.0	32.1	23.1	34.3	20.0	13.2	60.3
1929	8.3	7.5	21.9	22.5	122.0	193.0	27.5	5.4	3.9	4.0	8.2	7.1	35.9
1930	6.2	14.2	13.2	61.8	109.0	114.0	22.2	3.2	3.5	7.7	8.3	6.2	30.8
1931	6.9	5.8	7.3	10.2	43.7								
1932									5.5	6.8			
1933	6.8	4.5	6.8	21.2			42.1	8.9			34.5	21.0	
1934	17.0	20.6	28.1	115.0	150.0	118.0	26.7	2.5	2.9			13.2	
1935	14.3	19.1	12.1	30.6	88.8	99.9	23.0	2.6	1.9	3.2	8.4	6.4	25.8
1936	5.5	4.0	12.3	39.5	84.4	57.6	2.5	0.8	0.8	2.0	6.9	5.5	18.5
1937	4.3	4.7	6.7	18.3	65.1	125.0	23.2	1.8	1.1	7.4	24.1	10.6	24.3
1938	8.0	7.7	10.3	54.3	185.0	154.0	42.5	9.6	4.4	6.4	13.5	8.4	42.2

1939	7.0	5.3	14.7	32.9	54.2	95.6	26.0	1.5	1.4	10.1	14.7	11.9	22.9
1940	7.0	6.6	15.6	29.7	89.8	40.7	8.1	2.9	15.8	25.7	17.7	12.1	22.7
1941	9.2	7.6	11.2	26.4	34.3	38.9	10.2	1.7	13.2	23.2	16.6	26.1	18.3
1942	16.7	8.4	8.1	30.9	215.0	243.0	92.0	33.8	32.3	19.9	14.6	10.5	60.6
1943	8.2	9.8	28.3	89.3	102.0	132.0	53.5	6.0	4.1	3.4	7.0	5.2	37.4
1944	5.2	5.3	5.7	5.6	15.3	29.8	9.3	2.1	2.1	3.9	6.7	6.2	8.1
1945	5.7	5.0	7.0	3.4	86.9	192.0	49.4	3.9	3.9	10.1	13.4	9.4	32.5
1946	8.1	6.7	10.3	35.4	94.6	121.0	38.1	3.3	15.2	19.6	19.4	14.7	32.2
1947	12.4	22.0	29.0	73.2	173.0	117.0	26.7	10.2	22.6	50.7	30.8	11.5	48.4
1948	10.9	8.3	13.0	86.3	244.0	333.0	78.6	41.6	7.8	11.3	12.9	7.0	71.2
1949	6.0	5.4	7.5	42.2	103.7	81.5	13.7	3.9	2.8	6.6	13.7	11.4	24.9
1950	6.6	10.1	15.1	46.6	143.4	192.8	67.5	11.5	3.4	9.6	20.5	19.9	45.6
1951	11.9	14.7	33.9	81.4	289.9	289.6	169.3	56.4	135.1	91.7	47.6	28.2	104.1
1952	21.0	21.5	39.1	120.9	119.8	100.7	53.4	27.1	15.5	11.0	11.5	9.3	45.9
1953	9.4	10.5	20.9	51.8	205.1	584.1	111.2	24.9	11.7	10.9	14.2	8.7	88.6
1954	5.5	13.8	13.7	43.4	214.7	190.2	92.3	27.0	34.8	37.5	26.7	18.5	59.8
1955	7.5	7.7	8.5	60.6	167.8	204.2	111.2	20.6	8.6	20.3	26.9	10.2	54.5
1956	8.9	7.2	14.2	44.2	179.1	135.1	79.2	20.6	10.2	9.3	11.2	10.1	44.1
1957	7.1	9.9	28.1	29.2	202.8	121.9	17.3	2.2	1.8	8.7	17.3	8.9	37.9
1958	7.2	7.2	13.4	50.7	170.2	105.9	79.2	22.5	11.1	6.4	8.7	9.6	41.0
1959	10.7	8.7	27.0	38.1	172.6	203.4	66.5	14.2	25.7	28.9	26.0	17.8	53.3
1960	7.9	17.2	41.6	61.8	118.6	103.3	24.2	7.1	1.4	2.4	9.5	7.9	33.6
1961	8.7	8.8	9.2	12.4	163.8	143.9	15.5	3.7	2.5	16.2	19.0	6.8	34.2
1962	9.4	15.7	23.7	83.7	88.2	91.1	20.8	3.5	2.9	2.5	8.5	10.2	30.0
1963	7.8	19.8	12.7	7.9	65.4	128.8	174.3	16.2	3.9	5.4	9.5	11.2	38.6
1964	6.6	6.0	12.1	22.4	183.8	243.4	51.0	5.8	5.0	10.4	10.7	5.8	46.9
1965	5.7	11.8	14.5	56.8	111.7	226.8	99.0	20.6	31.6	29.3	21.1	14.4	53.6
1966	8.7	9.2	32.4	43.4	129.2	141.5	50.8	18.3	11.3	9.1	8.9	6.1	39.1
1967	8.0	8.3	13.3	17.8	220.5	309.3	63.6	5.4	2.2	5.0	10.9	6.0	55.9
1968	5.8	9.5	11.9	14.5	92.7	123.6	38.3	12.3	26.1	31.3	19.9	12.6	33.2
1969	12.6	11.2	15.0	76.2	129.9	162.3	83.4	6.5	4.3	9.3	11.4	7.2	44.1
1970	5.1	5.8	7.1	10.7	119.6	145.1	25.0	3.4	5.5	6.4	8.2	5.7	29.0
1971	5.1	11.2	9.3	23.4	159.9	151.0	37.7	6.3	6.4	9.8	10.0	8.0	36.5
1972	6.9	6.5	37.3	51.2	243.3	246.5	73.5	30.3	20.9	20.8	12.7	7.5	63.1
1973	11.2	10.1	12.0	11.8	82.6	79.3	14.6	2.2	1.5	1.8	7.5	7.1	20.1

1974	9.7	9.5	15.7	48.4	159.7	240.4	57.0	15.1	3.1	3.9	10.1	8.0	48.4
1975	6.9	6.1	7.2	23.1	132.0	278.3	91.0	19.3	10.4	14.5	19.5	20.6	52.4
1976	11.2	11.2	13.9	38.7	134.3	66.0	33.4	78.8	17.8	9.6	10.2	7.5	36.1
1977	5.8	7.2	6.3	13.2	30.2	18.1	0.6	1.7	4.5	8.3	7.6	7.6	9.3
1978	6.2	5.2	28.4	31.4	140.9	133.6	68.3	18.6	18.7	13.7	9.7	8.7	40.3
1979	6.9	6.6	16.9	27.2	130.0	86.7	14.4	2.1	1.0	3.9	4.5	7.9	25.7
1980	4.2	5.6	6.9	42.7	116.1	98.0	10.8	5.1	11.7	10.2	12.2	19.4	28.6
1981	14.6	13.1	13.6	28.3	215.2	153.9	55.4	16.3	5.5	5.7	8.1	7.1	44.7
1982	3.9	5.2	7.6	14.8	75.4	123.1	36.6	0.9	2.0	13.3	8.0	7.7	24.9
1983	6.7	9.2	9.7	18.6	75.5	61.9	24.6	1.8	0.8	7.2	9.6	5.5	19.2
1984	8.8	7.5	6.4	10.0	32.7	65.5	11.4	1.9	2.6	10.6	8.4	5.4	14.3
1985	4.8	4.3	6.7	17.1	73.5	52.3	1.8	1.0	26.8	39.7	29.3	14.3	22.6
1986	9.6	29.2	40.1	49.4	130.2	95.0	8.0	1.6	9.3	28.3	15.1	11.3	35.6
1987	10.1	8.1	14.6	50.7	83.7	22.6	21.7	19.6	11.9	8.5	7.8	5.7	22.1
1988	4.1	4.4	6.7	15.9	42.9	42.0	1.4	2.5	1.7	4.7	9.3	7.3	11.9
1989	4.8	4.1	7.1	23.2	81.6	105.4	6.1	6.4	19.0	15.1	31.8	18.3	26.9
1990	13.1	10.0	11.2	52.5	159.0	154.6	33.0	16.1	4.2	12.9	27.2	10.2	42.0
1991	9.6	13.1	12.1	35.5	69.9	153.6	100.2	74.3	16.4	12.1	10.4	10.1	43.1
1992	8.9	8.7	8.7	8.2	8.8	8.0	18.6	12.2	12.4	12.3	9.6	8.2	10.4
1993	8.6	9.0	10.3	12.3	54.9	129.0	159.7	72.9	57.0	33.3	16.4	14.9	48.2
1994	11.3	8.9	19.0	41.9	94.9	49.0	15.4	18.8	17.5	14.2	9.1	7.7	25.6
1995	7.0	6.6	7.1	16.5	94.2								10.9
1996				81.2	103.8	122.5	44.0	22.0	19.3	17.8	10.4	9.1	35.8
1997	8.4	9.4	19.8	26.0	112.8	116.0	23.6	20.6	17.7	13.6	11.4	7.1	32.2
1998	6.4	6.6	7.1	15.8	100.0	167.8	38.6	16.3	17.4	16.2	13.0	10.7	34.7
1999	8.9	8.9	9.1	19.9	38.7	53.7	37.7	23.0	11.2	10.1	40.3	30.0	24.3
2000	10.0	8.1	9.3	20.1	35.2	19.3	18.7	19.1	12.1	10.6	9.3	7.5	14.9
2001	7.6	7.1	6.6	11.4	20.5	19.8	22.5	15.2	10.2	11.0	9.3	7.4	12.4

APPENDIX B

STATISTICS

Table B-1: Results from chi-square (χ^2) test of independence assessing the age structures of the Fort Macleod (OFM) and Monarch (OM) reaches. A twenty-year time period was used to test both pre- and post-Oldman River Dam (ORD) periods.

		Number of years OFM>OM	Number of years OM>OFM	Totals
Pre-ORD (1983-92)	Observed	8	2	10
	Expected	5	5	10
Post-ORD (1993-2002)	Observed	3	7	10
	Expected	5	5	10

Null hypothesis: The ORD will have no impact on cottonwood recruitment allowing for equal numbers of trees along both study reaches during the pre- and post-ORD time periods.

$\chi^2 = \Sigma$ ([Observed – Expected]^2 / Expected)
$\alpha = 0.05$

Pre-ORD
$\chi^2 = 3.6$, df = 1, critical χ^2 value = 3.84

Since 3.6 < 3.84, accept the null hypothesis (p = 0.0578).

Post-ORD
$\chi^2 = 1.6$, df = 1, critical χ^2 value = 3.84

Since 1.6 < 3.84, cannot reject the null hypothesis (p = 0.206).

Conclusion: There is no significant difference between the age structures along the two reaches in either pre- or post-ORD periods. Therefore, ORD did not affect recruitment along one reach more than the other.

Table B-2: Results from chi-square (χ^2) test of independence assessing the age structures of the Fort Macleod (OFM) and Monarch (OM) reaches. A twenty-year time period was used to test both pre- and post-flood of 1995 periods.

		Number of years OFM>OM	Number of years OM>OFM	Totals
Pre-flood '95 (1983-94)	Observed	10	2	12
	Expected	6	6	12
Post-flood '95 (1995-2002)	Observed	1	7	8
	Expected	4	4	8

Null hypothesis: The 1995 flood will have no impact on cottonwood recruitment allowing for equal numbers of trees along both study reaches during the pre- and post-flood time periods.

$\chi^2 = \Sigma$ ([Observed – Expected]^2 / Expected)
$\alpha = 0.05$

Pre-flood
$\chi^2 = 8$, df = 1, critical χ^2 value = 3.84

Since 8 > 3.84, reject the null hypothesis (p = 0.00468).

Post-flood
$\chi^2 = 4.5$, df = 1, critical χ^2 value = 3.84

Since 4.5 > 3.84, reject the null hypothesis (p = 0.0339).

Conclusion: There is a significant difference between the age structures along the two reaches in both pre- and post-flood periods. Therefore, the flood of 1995 did affect recruitment along one reach more then the other.

Table B-3: Results from chi-square (χ^2) test of independence assessing the age structures of the Summerview (OS) and Monarch (OM) reaches. A twenty-year time period was used to test both pre- and post-Oldman River Dam (ORD) periods.

		Number of years OS>OM	Number of years OM>OS	Totals
Pre-ORD (1983-92)	Observed	3	7	10
	Expected	5	5	10
Post-ORD (1993-2002)	Observed	3	7	10
	Expected	5	5	10

Null hypothesis: The ORD will have no impact on cottonwood recruitment allowing for equal numbers of trees along both study reaches during the pre- and post-ORD time periods.

$\chi^2 = \Sigma$ ([Observed – Expected]^2 / Expected)
$\alpha = 0.05$

Pre-ORD
$\chi^2 = 1.6$, df = 1, critical χ^2 value = 3.84

Since 1.6 < 3.84, accept the null hypothesis (p = 0.206).

Post-ORD
$\chi^2 = 1.6$, df = 1, critical χ^2 value = 3.84

Since 1.6 < 3.84, cannot reject the null hypothesis (p = 0.206).

Conclusion: There is no significant difference between the age structures along the two reaches in either pre- or post-ORD periods. Therefore, ORD did not affect recruitment along one reach more than the other.

Table B-4: Results from chi-square (χ^2) test of independence assessing the age structures of the Summerview (OS) and Monarch (OM) reaches. A twenty-year time period was used to test both pre- and post-flood of 1995 periods.

		Number of years OS>OM	Number of years OM>OS	Totals
Pre-flood '95 (1983-94)	Observed	3	9	12
	Expected	6	6	12
Post-flood '95 (1995-2002)	Observed	3	5	8
	Expected	4	4	8

Null hypothesis: The 1995 flood will have no impact on cottonwood recruitment allowing for equal numbers of trees along both study reaches during the pre- and post-flood time periods.

$\chi^2 = \Sigma$ ([Observed – Expected]^2 / Expected)
$\alpha = 0.05$

Pre-flood
$\chi^2 = 3$, df = 1, critical χ^2 value = 3.84

Since $3 < 3.84$, reject the null hypothesis ($p = 0.0833$).

Post-flood
$\chi^2 = 0.5$, df = 1, critical χ^2 value = 3.84

Since $0.5 < 3.84$, reject the null hypothesis ($p = 0.480$).

Conclusion: There is no significant difference between the age structures along the two reaches in both pre- and post-flood periods. Therefore, the flood of 1995 did not affect recruitment along one reach more then the other.

Table B-5: Using an ANOVA to detect differences in surface elevations of cottonwood trees across reaches and ages.

ANOVA Single Factor

Null hypothesis: Elevations of trees will be the same across both ages and reaches.

Source of variation	degrees of freedom	sum of squares	F ratio	P value
Reach	1	1286.36	0.3897	0.5331
Age class	5	425438.84	25.7742	<0.0001
Reach and age class	12	130784.49	3.3014	0.0002

Decision: Reject the null hypothesis for variation between age classes and between age classes across reaches.

Conclusion: There is a difference in elevation of trees with regards to ages along a reach, and age classes between the three reaches.

Table B-6: Using analysis of variance (ANOVA) to detect differences in cottonwood stand densities across reaches.

ANOVA Single Factor

Null hypothesis: Stand densities will be the same across the reaches.

Source of variation	degrees of freedom	sum of squares	F ratio	P value
Reach	2	407396	4.17	0.0363

Decision: Reject the null hypothesis for variation between reaches.

Conclusion: There is a difference in stand densities between the three reaches.

Table B-7: Analysis of covariance (ANCOVA) performed on the differences in cottonwood basal area growth rates of juvenile tree growth across three study reaches along the Oldman River.

Shapiro-Wilk Goodness-of-Fit Test:

$p < 0.0001$, as the data is non-parametric it was transformed with the equation:

$$\log(\text{juvenile BAI } (cm^2))$$

Transformation resulted in $p = 0.943$, so the data is now parametric and normally distributed.

ANCOVA:

Null hypothesis: There is no difference between the lines of best fit from the regressions of juvenile basal area growth across the three reaches.

Result: $F_{2, 54} = 3.11$, $p = 0.0527$

Decision: Since $p > 0.05$, cannot reject the null hypothesis for lack of difference in growth rates.

Conclusion: There is no significant difference in basal area growth rates of juvenile trees across the three study reaches along the Oldman River.

Table B-8: Analysis of covariance (ANCOVA) performed on the differences in cottonwood basal area growth rates of mature trees across three study reaches along the Oldman River.

Shapiro-Wilk Goodness-of-Fit Test:

$p = 0.624$, so the data is parametric and normally distributed.

ANCOVA:

Null hypothesis: There is no difference between the lines of best fit from the regressions of mature basal area growth across the three reaches.

Result: $F_{2,57} = 15.7$, $p < 0.0001$

Decision: Since $p < 0.0001$, reject the null hypothesis for lack of difference in growth rates.

Conclusion: There is a highly significant difference in basal area growth rates of mature trees across the three study reaches along the Oldman River.

Table B-9: Linear regression results from cottonwood radial increments (RI), standardized radial increments (SRI), basal area increments (BAI) and standardized basal area increments (SBAI) along the Summerview Reach versus discharge of the Oldman River for the period 1980-2001.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Apr-Sep	May-Jun	Aug-Sept
RI																
r^2	0.066	0.0494	0.0169	0.0053	0.122	0.0012	0.0543	0.0971	0.0003	0.0136	0.0608	0.0001	0.0002	0.0011	0.0361	0.0483
p-value	0.249	0.32	0.564	0.747	0.111	0.879	0.297	0.158	0.936	0.606	0.269	0.965	0.947	0.882	0.397	0.326
SRI																
r^2	0.0164	0.0305	0.0025	0.0583	0.101	0.0119	0.0065	0.0155	0.0161	0.0075	0.0344	0.0161	0.0171	0.0291	0.0518	0.0011
p-value	0.57	0.437	0.825	0.279	0.15	0.629	0.72	0.581	0.574	0.702	0.408	0.574	0.562	0.448	0.308	0.886
BAI																
r^2	0.0352	0.0271	0.0053	0.0062	0.0752	0.0341	0.0297	0.0398	0.0447	0.0000	0.0031	0.0066	0.009	0.0145	0.0679	0.0024
p-value	0.403	0.464	0.747	0.728	0.217	0.411	0.443	0.373	0.345	0.988	0.807	0.72	0.675	0.594	0.242	0.83
SBAI									**							
r^2	0.0044	0.0192	0.0003	0.0041	0.0032	0.0108	0.0264	0.0785	0.302	0.0012	0.0000	0.0406	0.031	0.0345	0.0022	0.174
p-value	0.768	0.538	0.938	0.778	0.803	0.645	0.47	0.207	0.008	0.877	0.993	0.368	0.433	0.408	0.836	0.0531

* $p < 0.05$
** $p < 0.01$

Table B-10: Linear regression results from cottonwood radial increments (RI), standardized radial increments (SRI), basal area increments (BAI) and standardized basal area increments (SBAI) along the Fort Macleod Reach versus discharge of the Oldman River for the period 1980-2001.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Apr-Sep	May-Jun	Aug-Sept
RI					**	*							*	*	**	
r^2	0.0119	0.0018	0.0080	0.0708	0.396	0.214	0.0084	0.0078	0.0252	0.0657	0.0218	0.0154	0.186	0.226	0.368	0.0158
p-value	0.629	0.852	0.692	0.231	0.0017	0.03	0.685	0.695	0.480	0.249	0.512	0.582	0.0453	0.0252	0.0028	0.577
SRI					**	*								*	**	
r^2	0.0069	0.0011	0.0002	0.0377	0.290	0.198	0.0070	0.0098	0.0202	0.0893	0.0129	0.0335	0.142	0.18	0.305	0.0159
p-value	0.712	0.884	0.953	0.387	0.0096	0.038	0.712	0.662	0.528	0.177	0.615	0.415	0.0836	0.049	0.0077	0.576
BAI																
r^2	0.0571	0.000	0.0044	0.0126	0.000	0.0796	0.0406	0.0705	0.0407	0.0031	0.0214	0.0591	0.0721	0.0689	0.0366	0.0702
p-value	0.284	0.998	0.77	0.619	0.997	0.203	0.369	0.2325	0.368	0.806	0.516	0.275	0.227	0.238	0.394	0.233
SBAI																
r^2	0.0433	0.001	0.000	0.0023	0.000	0.0661	0.0299	0.0434	0.0193	0.0167	0.0145	0.0591	0.0476	0.0483	0.0299	0.040
p-value	0.353	0.887	0.976	0.832	0.994	0.248	0.442	0.352	0.537	0.567	0.594	0.276	0.329	0.326	0.441	0.372

* $p < 0.05$
** $p < 0.01$

Table B-11: Linear regression results from cottonwood radial increments (RI), standardized radial increments (SRI), basal area increments (BAI) and standardized basal area increments (SBAI) along the Monarch Reach versus discharge of the Oldman River for the period 1980-2001.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Apr-Sep	May-Jun	Aug-Sept
RI																
r^2	0.0002	0.102	0.0757	0.0559	0.0114	0.0376	0.0024	0.0002	0.0082	0.127	0.0000	0.029	0.0039	0.0117	0.0325	0.0009
p-value	0.946	0.147	0.215	0.29	0.636	0.387	0.829	0.952	0.688	0.103	0.986	0.449	0.782	0.632	0.422	0.897
SRI																
r^2	0.0054	0.105	0.0692	0.0323	0.0548	0.0538	0.0000	0.0061	0.0187	0.13	0.0026	0.0384	0.0087	0.0209	0.0692	0.0119
p-value	0.745	0.143	0.237	0.424	0.294	0.301	0.998	0.73	0.544	0.100	0.822	0.382	0.679	0.521	0.237	0.629
BAI																
r^2	0.0005	0.0604	0.06	0.0655	0.0143	0.0008	0.0003	0.0018	0.0023	0.0718	0.007	0.0218	0.005	0.0025	0.0012	0.0001
p-value	0.923	0.271	0.272	0.25	0.597	0.902	0.944	0.85	0.831	0.228	0.712	0.512	0.755	0.827	0.879	0.973
SBAI																
r^2	0.0015	0.0443	0.0224	0.0373	0.0055	0.0208	0.0079	0.0133	0.0017	0.0406	0.0076	0.0509	0.0025	0.0044	0.0042	0.0086
p-value	0.863	0.347	0.507	0.389	0.743	0.522	0.694	0.61	0.857	0.369	0.7	0.313	0.824	0.768	0.774	0.681

* $p < 0.05$
** $p < 0.01$