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RESEARCH ARTICLE

River regulation and riparian woodlands: Cottonwood conservation with an environmental flow regime along the Waterton River, Alberta

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Abstract

Following water withdrawal, riparian cottonwoods have declined downstream from some dams in western North America. Analyses of aerial photographs and field observations in the 1980s suggested that the black and narrowleaf cottonwoods (*Populus trichocarpa* and *Populus angustifolia*) along the Waterton River, Alberta, were declining due to drought stress following the 1964 damming and diversion. This raised concern for the riverine ecosystems and in 1991, "functional flows" commenced with 2 changes: (a) the minimum flow was increased from 0.9 to 2.3 m^3/s (mean discharge 21.9 m^3/s) and (b) flow ramping provided gradual stage recession after the spring peak. This provided an environmental flow regime that was delivered for 2 decades and this study investigated the consequent river flow patterns and riparian woodlands upstream and downstream from the Waterton Dam. Analyses of aerial photographs from 1951 to 2009 assessed 4 flow management intervals: (a) the free-flowing predam condition, (b) the initial dammed interval to the mid-1970s, (c) a drought interval in the 1980s, and (d) with the environmental flow regime after 1991. Analyses revealed woodland reduction from 1961 to 1985 due to losses through bank erosion with major floods and apparent decline due to low flows following a regional drought and water withdrawal for irrigation. With the subsequent environmental flow regime, there was apparent woodland recovery, despite drought in 2000 and 2001. This study demonstrated that the correspondence between river flow patterns and the extent of riparian woodlands and the benefit from the environmental flow regime that probably reduced drought stress and mortality.

KEYWORDS

floods, functional flows, hydrology, instream flow, *Populus*

1 | INTRODUCTION

Cottonwoods, river valley poplars (*Populus* spp.), provide important environmental contributions in western North America and around the Northern Hemisphere. They are ecological pioneer species that colonize newly disturbed sites and line river valleys creating rich and biodiverse riparian woodland corridors (Brayshaw, 1965; Scott, Friedman, & Auble, 1996). These provide important habitat for birds, mammals, and invertebrate communities (Knopf, Johnson, Rich, Samson, & Szaro, 1988; Swift, Larson, & DeGraaf, 1984; Whitham et al., 1999), litter and shade that benefit the aquatic food web and fish, contribute parental genotypes for fast growing hybrid poplars, and provide valued aesthetic and recreation areas for human use (Heilman, Peabody, DeBell, & Strand, 1972; Jackson, Carpenter, Dahm, McKnight, & Naiman, 2001). Cottonwoods provide the foundation for riparian forests and the associated ecosystem services (Ward, Tockner, & Schiemer, 1999) thus encouraging their conservation and restoration.

In some regions of western North America, riparian cottonwoods have declined following river damming and water withdrawal (Bradley & Smith, 1986; Rood & Heinze-Milne, 1989). The cottonwoods are often phreatophytic, with deep roots to access the alluvial groundwater (Cooper, Merritt, Andersen, & Chimner, 1999; Rood, Bigelow, & Hall, 2011). As a consequence, when river flows are reduced and the water table declines, the riparian cottonwoods are stressed (Amlin & Rood, 2002; Scott, Shafroth, & Auble, 1999).

The Waterton River is one of three "southern tributaries" within the Oldman River Basin along with the Belly River and the St. Mary River (Figure 1). These rivers originate in the Rocky Mountains of the Waterton-Glacier International Park and flow northeast through the montane and foothill ecoregions to the prairies, where cottonwoods provide the only native trees. The Waterton and St. Mary Rivers were dammed in 1964 and 1951, respectively, whereas the Belly River is less extensively regulated. Commencing around 1900, a canal system from the three rivers was developed to support Canada's largest irrigation complex and due to the severe reduction in instream flows cottonwoods along the lower St. Mary River collapsed over the latter decades of the twentieth century (Rood & Heinze-Milne, 1989; Rood, Mahoney, Reid, & Zilm, 1995; Rood & Mahoney, 2000). There was subsequent concern for the other tributaries and this study was undertaken to investigate correspondences between instream flows and riparian woodlands along the Waterton River.

Mapping in the 1880s indicated that the Waterton River valley naturally supported abundant riparian forests, in contrast to scattered groves along the lower St. Mary River (Dawson & McConnell, 1884). On the basis of the aerial photographs from 1961 versus 1981, Rood and Heinze-Milne (1989) reported severe reduction in the lineal extent of cottonwoods downstream of the St. Mary Dam (−48%) and apparently moderate decline downstream from the Waterton Dam (−23%). Subsequently, Rood et al. (1995) reported a progressive decline in the areal abundance of riparian cottonwoods along the St. Mary River between 1951 and 1985 (−61%) but slight change along the lower Waterton River. However, field observations through the late 1980s indicated that those cottonwood groves were in poor health (Figure 2). with substantial branch and crown die-back that follows drought stress (Rood, Patiño, & Coombs, 2000; Scott et al., 1999). There were apparent gaps in the population structure, with mature trees but a deficiency of juveniles that are required for population replenishment, and seedlings were apparently sparse. These patterns suggested drought-induced woodland decline.

Subsequent studies of the historic hydrology suggested that Waterton River regulation altered two flow components that contributed to the woodland decline: (a) insufficient late summer instream flows that imposed drought stress on new or established cottonwoods and (b) abrupt river stage decline in early summer, which interrupts the connection between the absorbing root systems and the alluvial groundwater (Rood et al., 1995; Scott et al., 1999). In association with implementation of the Oldman River Dam in the early 1990s (Rood, Kalischuk, & Mahoney, 1998), regional water managers altered operational regimes for the Waterton and St. Mary dams because these also contribute to instream flows along the lower reaches of the Oldman River. The management changes delivered "functional flow" components that involved: (a) increasing the minimum instream flow through the growth season and (b) flow ramping, gradual flow recession after the spring peak (Rood & Mahoney, 2000; Rood et al., 2016). These were intended to conserve or restore the riparian and aquatic

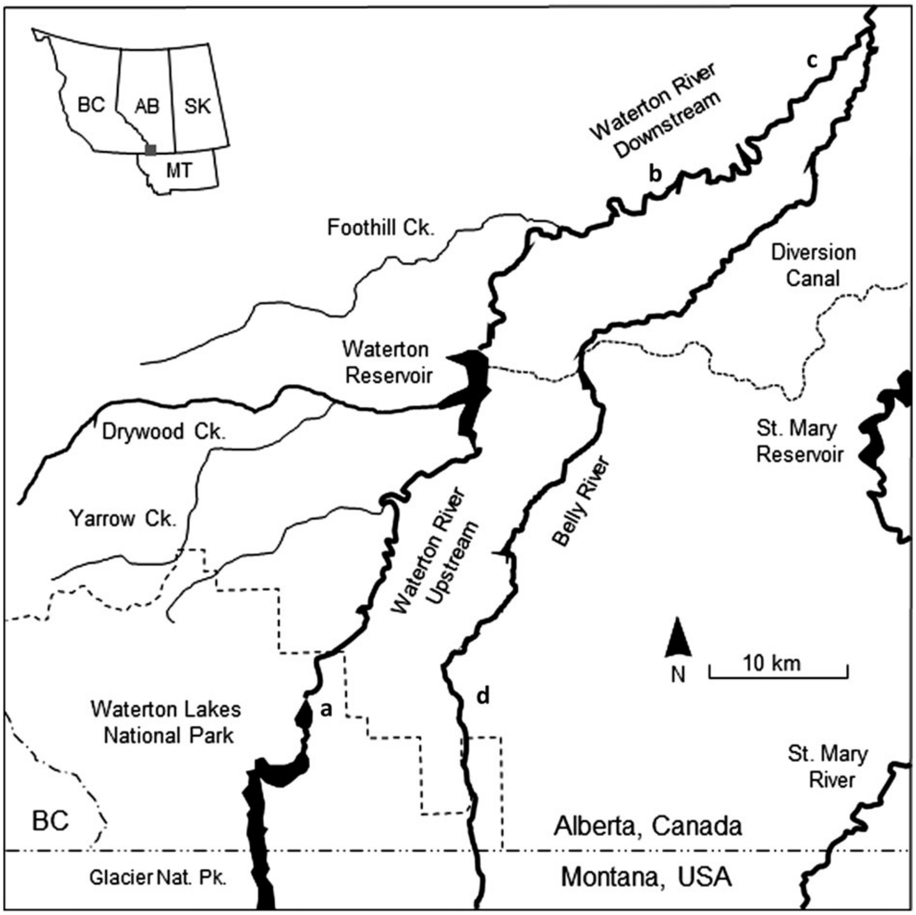

FIGURE 1 The Waterton River study area with major tributaries and gauging stations: Waterton River (a) near Waterton Park, (b) near Glenwood, (c) near Standoff, and (d) Belly River near Mountain View

FIGURE 2 A typical, representative riparian cottonwood grove along the Waterton River downstream from the Waterton Dam with the 1980s drought (July 1989, S. Rood). [Colour figure can be viewed at wileyonlinelibrary.com]

ecosystems (Shafroth, Auble, Stromberg, & Patten, 1998) while continuing to supply irrigation water from the storage reservoirs.

This study extends from prior research that investigated the historic hydrology and riparian woodlands along the Waterton River system (Berg, Samuelson, Willms, Pearce, & Rood, 2007; Rood & Heinze-Milne, 1989; Rood et al., 1995; Samuelson & Rood, 2004). It investigated the conditions and changes of the riparian woodlands and possible correspondence with different patterns of river flow regulation. It particularly investigated conditions following the environmental flow regime, anticipating some benefit to the riparian cottonwood population. The study findings would contribute to the understanding of the instream flow needs for riparian woodlands and the implementation of functional flows for riparian restoration.

2 | METHODS

2.1 | Study area

The Waterton River originates from snowmelt and rainfall runoff within Waterton Glacier International Park (Figure 1). From these Rocky Mountain headwaters, the river flows through the Waterton Lakes sequence and then 100 km to its confluence with the Belly River. The free-flowing upstream reach extends 32 km through foothills with aspen parkland, to the Waterton Reservoir. This involves a confined valley where riparian woodlands are limited to narrow bands along the river. The 8-km long Waterton Reservoir impounds the Waterton River and Drywood Creek (Figure 1), which contributes about 22% of the annual flow and more substantially to floods, with ~30% of the 1995 peak. The alluvial downstream reach extends for 60 km and displays a broader floodplain except in two short canyons (Foster, 2016).

2.2 | Historic hydrology

The Waterton River discharges (*Q*) were accessed from the Water Survey of Canada's HYDAT records (wateroffice.ec.gc.ca). Data were analysed for the daily mean *Q* (Q_{daily}), maximum *Q* (Q_{max}), monthly means (Q_{Jul}, etc.), and mean *Q* through the cottonwood growth season from May to October ($Q_{May-Oct}$). Four dam management intervals were compared: *predam* (before 1963), *dammed* (or *postdam*, 1964 to 1976), dammed and *drought* (1977 to 1990) and *environmental flows* (1991 to 2014).

A 106-year series was developed by coordinating data from four gauging stations (Figure 1). The station near Waterton Park (05AD003, drainage area 612 km^2) just downstream from Waterton Lakes commenced in 1908 without winter values, and year-round records followed from 1912. A gap from 1931 to 1947 was infilled through interpolation with linear regression with the adjacent free-flowing Belly River near Mountain View (05AD005; 1911–2012), with strong correspondences for Q_{daily} (r^2 = 0.920), Q_{max} (r^2 = 0.871), Q_{months} (r^2 = 0.965), and $Q_{May-Oct}$ (r^2 = 0.921).

Downstream from the Waterton Dam, the station near Standoff (05AD008) commenced seasonal data in 1916, lapsed between 1931 and 1934, and continued until 1966. A replacement station was established in 1966 near Glenwood (05AD028) and continues. The two stations differ slightly in drainage area (1631 vs. 1730 km^2) but with no intervening tributaries. The 1966 overlap provided very close correspondence (r^2 = 0.978) and *Q* from these two stations were combined. To infill the 1930s gap, regressions were undertaken between the predam Standoff station and the upstream *Q*: Q_{daily} (r^2 = 0.896), Q_{max} (r^2 = 0.656), Q_{months} (r^2 = 0.956), and $Q_{May-Oct}$ (r^2 = 0.861). Daily *Q* were also considered for the Waterton-Belly canal gauge (05AD027) that commenced in 1968 and records diversion from the Waterton Reservoir (Foster, 2016).

To investigate correspondence with weather, precipitation values were obtained from Environment Canada for the Waterton Park Gate (Climate ID #3056214) and the more complete time series for Lethbridge, Alberta (#3033890) for 1908 to 1960 and from Alberta Agriculture and Forestry's AgroClimatic Information Service for 1961 to 2013.Correlations were investigated between various interannual series (Foster, 2016) and results are presented for seasonal precipitation (April through September to incorporate a delay prior to the contribution to Q), $Q_{May-Oct}$ and the average annual Pacific Decadal Oscillation index (PDO, http://jisao.washington.edu/pdo/PDO.latest).

The 1991 *Water Allocation Regulation* more than doubled the minimum instream flow requirement downstream from the Waterton Dam, from 0.93 to 2.27 m^3/s (Rood & Vandersteen, 2010). To investigate compliance, the yearly days with *Q* below 2.27 m^3/s were tabulated for the growth season. As a comparative reference for the free-flowing and regulated reaches, "base flows" were assessed as the typical low flow for ice-free periods for the upstream (4.56 m^3/s) and downstream (6.78 m^3/s) reaches prior to damming, and the occurrences of lower flows were also tabulated.

Statistical analyses with SPSS 21 (IBM Corp., Somers, NY) included Pearson product correlations (*r*) and coefficients of determination (r^2) to determine correspondences between the various interannual time series and also for 5-year moving averages to provide data smoothing.

2.3 | Temporal patterns of riparian woodlands

The riparian forests along the Waterton River include two *Populus* section *Tacamahaca* species, black cottonwoods, *Populus trichocarpa* Torr. & Gray ex. Hook, and narrowleaf cottonwoods, *Populus angustifolia* James; and their native, intermediate hybrids (Berg et al., 2007; Floate, 2004). To assess the abundances of these riparian woodlands, stereoscopic pairs of aerial photographs were obtained from the Air Photo Distribution service of Alberta Environment and Parks (Edmonton, AB) for 1951 (1:40,000), 1961 (1:31,680), 1985 (1:30,000), 1999 (1:30,000), and 2009 (1:30,000; color, others were grey scale). These provided two photograph series in the pre-dam interval, one in the dammed interval, one shortly after the drought, and the final series following 18 years of environmental flows.

Images were digitally scanned, imported into ArcMap 10 (ESRI, Redlands, CA; 2010) and georectified using an orthorectified base layer, with at least 10 distributed control points, producing an overall root mean square error of <5 m after quadratic transformations (Bolstad & Smith, 1992). Images were cropped with a footprint of 15% to enable comparable interpretation, and mosaicked for each series.

The river valley was divided into 4-km segments, with slight variation to accommodate geomorphic, vegetation, or land-use transitions, producing seven upstream segments and 14 downstream from the Waterton Reservoir. The aerial photograph segments were viewed stereoscopically with up to 3-fold magnification and polygons with apparently similar cottonwood forest densities were digitized in ArcMap at a scale of 1:5,000. Woodland density classifications were assigned, initially with six categories (Foster, 2016), and these were collapsed to produce a 3-point scale: 1—sparse woodland, 2—open canopy, and 3—closed canopy. The wooded polygon areas were multiplied by the associated density values and accumulated to provide the woodland area index. Changes (Δ) in this index were then determined across the sequential aerial photographs.

The comparisons revealed substantial cottonwood forest removal through river channel erosion, as well as with artificial floodplain clearing, and these two impacts were also indexed and tabulated. The key results are presented here and additional tabulations are in Foster (2016).

Following the analyses of historic hydrology and the woodland mapping, we sought to coordinate the two temporal patterns and considered correspondences between changes in hydrologic patterns and woodland distributions, particularly across the different flow management intervals and with flood events and woodland erosion.

3 | RESULTS

3.1 | Historic hydrology

3.1.1 | Free-flowing upstream reach

The free-flowing upstream reach of the Waterton River drains the relatively pristine Waterton Glacier International Park and consequently reflects regional climate patterns. The study emphasized the growth season discharge ($Q_{May-Oct}$), which provides the primary flow contribution since winter flows are consistently very low (Rood, Samuelson, Weber, & Wywrot, 2005). Over the past century, the $Q_{May-Oct}$ along the upstream reach of the Waterton River has been variable, with multiple year intervals with higher (e.g., around 1950) or lower flows (late 1930s, around 1985; Figure 3b). A 15-year drought included the 1930s and was followed by an extended interval of higher flows in the predam interval when the first two aerial photographs were taken. A second prolonged drought occurred in the 1980s, followed by some flow recovery towards the end of the study interval.

There was only slight correlation between the upstream $Q_{May-Oct}$, and the growth season precipitation at Lethbridge ($n = 102$, $r^2 = 0.082$, $p = .004$; Figure 3). Conversely, very strong association was observed with the PDO ($r^2 = 0.522$, $p < 0.001$; Figure 3). This correspondence was closer with the major, multiple-year low or high flow sequences, and apparently lower in the past two decades. There was no correlation between the PDO and Lethbridge precipitation ($r^2 = 0.007$, $p = .418$).

3.1.2 | Regulated downstream reach

Prior to damming, the downstream flows largely tracked those along the upstream reach (Figure 3), with some differentiation reflecting inflows from the east-slope tributary creeks (Figure 1). After damming, the downstream flows declined, with major reduction especially during the drought intervals. This would reflect reduced inflows with the drought and increased water withdrawal for irrigation, providing a compound challenge. The canal diversion thus tripled from the initial postdam interval to the drought interval (May–Oct mean: 5.8 + 1.0 vs. 18.2 + 1.8 m^3/s). The drought was somewhat relieved in the environmental flow interval but canal diversion remained high, partly reflecting irrigation expansion (18.2 + 0.7).

Flow seasonality is reflected in the monthly flows (Figure 4), with maximal flows in June, progressive decline to August, and low flows extending to October. Initially after damming, there were minor changes in monthly flows; however, major flow reductions began in the drought interval. Part of the reduction was natural, reflecting reduced upstream flows (displayed in Foster, 2016), but with the additional water diversion, river flows were especially low in the intensive irrigation interval of June, July, and August. These monthly flows recovered somewhat during the environmental flow interval.

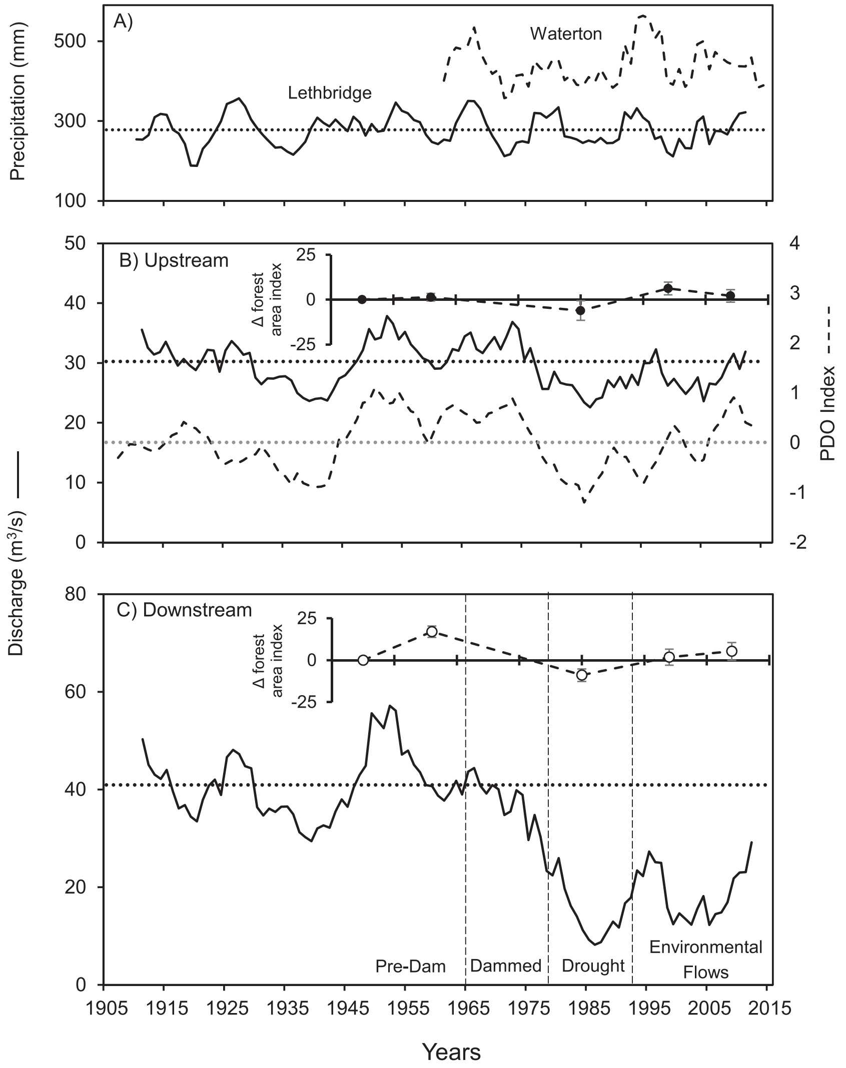

FIGURE 3 Interannual patterns (5-year moving averages) for (a) precipitation at two locations; (b) mean May to October discharges for the Waterton River upstream, with the Pacific Decadal Oscillation index; and (c) downstream reach of the Waterton River. Dotted lines indicate the pre-1964 (predam) averages. The inset figures in (b) and (c) display changes in the forest area index, incorporating area and apparent density, based on sequential aerial photographs. The river regulation intervals are indicated for the downstream reach

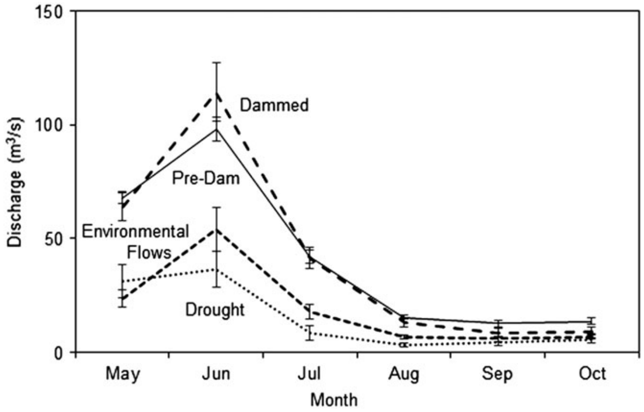

FIGURE 4 Mean (+SE) monthly growth season discharges during four flow management intervals for the lower Waterton River (a plot for the upstream reach is provided in Foster, 2016)

Cottonwood decline would probably reflect drought stress (Cooper et al., 1999; Rood et al., 2000; Scott et al., 1999) and consequently the occurrences of very low flows could be critical. As part of the functional flow strategy, the minimum flow was increased from 0.93 to 2.27 m^3/s and this was reflected in the dramatic reduction in the number of growth season days with lower flows in the drought versus environmental flow intervals (Figure 5a). As another comparison, upstream or downstream flows seldom dropped below the base flow prior to damming but were frequent in the drought interval and persisted with the environmental flows (Figure 5b). Thus, the environmental flow regime avoided severely low flows, but low flows persisted.

Cottonwood replenishment follows flood events and flood flow attenuation has hindered riparian recruitment along some rivers (Scott et al., 1996, 1997; Tiedemann & Rood, 2015). Conversely, the Waterton Reservoir is small relative to the river *Q* and with most high

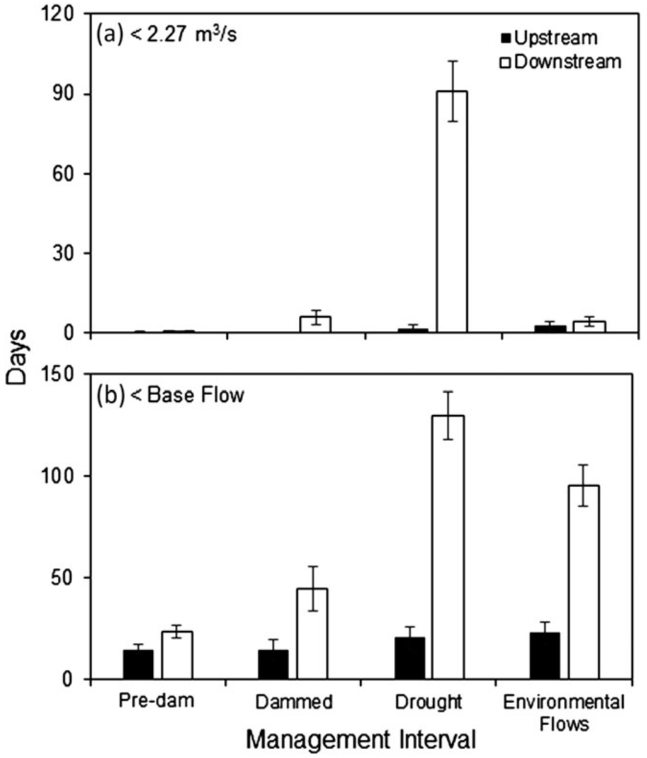

FIGURE 5 The mean (+SE) number of days during the growth season (May to October) below the (a) minimum flow criterion (2.27 m^3/s) and (b) base flow along the Waterton River (4.56 and 6.78 m^3/s: upstream and downstream)

flow events, the reservoir fills and spills, passing flood flows downstream (Figure 6). For individual flood flows, there were generally similar increases along the downstream versus upstream reaches in the predam and postdam intervals. The exception was for the major flood of 1964 that provided the second highest Q_{max} upstream but was substantially reduced downstream. The Waterton Dam was completed just prior to this flood event and the filling of the empty reservoir produced substantial attenuation. Flood recurrence analyses are provided in Foster (2016).

3.2 | Temporal patterns of riparian woodlands

The 1:30,000 scale aerial photographs were suitable for the riparian woodland mapping and revealed the historic changes in channel positions and in the occurrences and abundances of riparian cottonwood groves, with losses through bank and floodplain erosion, gains through colonization, and increasing density with woodland maturation (Figure 7). Although the interpretation was somewhat subjective, a single observer provided the density assignments and some segments were reassessed, with consistent outcomes. The different woodland classes were thus mapped and the key analyses assessed changes in the areal extents across the sequential images (Figure 8).

Within the narrow river valley along the upstream reach, the woodlands were limited and the aerial abundances for most segments differed only slightly over the time series (Figure 8). The overall changes along the upstream reach were consequently slight, with consistency in the pre-dam interval (Figure 3b). There was slight decline in the initial dammed interval and into the drought period, which was substantially due to woodland erosion with the major floods in that interval (Figure 6). There was subsequently some woodland increase along with the river flow recovery after the drought (Figure 3b).

Along the broader alluvial valley, the downstream reach supported more extensive riparian woodlands (479 vs. 114 ha). The downstream patterns were also more dynamic. There was substantial increase in the woodland area index in the predam interval (Figure 3c), due to woodland maturation and changes from open to closed canopy groves (Figure 8). The second interval involved substantial woodland decline that was partly due to loss through erosion from the major floods (Figures 3c and 6). The decline also reflected woodland transitions from closed canopy to open or even sparse groves (Figure 8), probably due to drought stress. Subsequently, there was some recovery with the environmental flow regime (Figure 3c). This involved woodland canopy increases due to both maturation and expansion, although there was considerable variation across the sequential segments (Figure 8).

4 | DISCUSSION

Concern for the health of riparian woodlands along the Waterton River followed from the observed collapse of riparian cottonwoods along the nearby St. Mary River (Rood & Heinze-Milne, 1989). That observation occurred during the Oldman River Dam Project and there was interest in preventing a similar loss of the extensive riparian woodlands downstream from that new dam. This prompted further study of the associations between river regulation and riparian woodlands, which subsequently resulted in the prescription and implementation of the functional flow components as part of the environmental flow regime

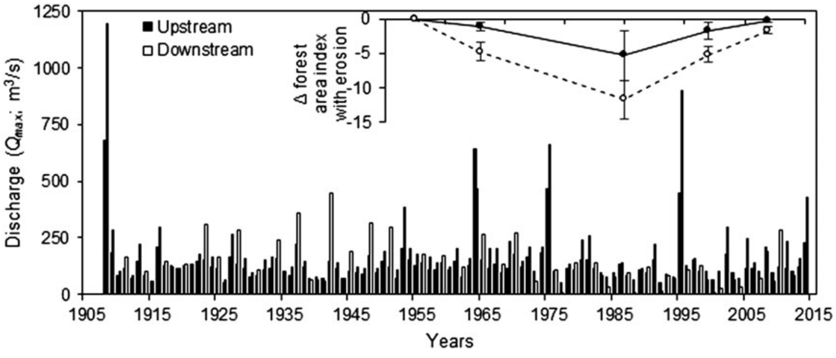

FIGURE 6 The annual maximum mean daily discharges for the Waterton River, upstream and downstream of the Waterton Dam. The inset figure displays the overall loss of forest area index through channel erosion, based on sequential aerial photographs for the upstream (●) and downstream (○) reaches

FIGURE 7 Aerial photographs of the (a) lower Waterton River displaying typical dynamics with an abandoned channel that is colonized, (b) extension of a meander lobe point bar, and (c) subsequent colonization. Foothill Ck. inflows at the top. [Colour figure can be viewed at wileyonlinelibrary.com]

for the new Oldman Dam, and also for the older dams on the St. Mary and Waterton Rivers, which are tributaries of the Oldman River.

The functional flows strategy emphasized two components (a) increases in minimum instream flows and (b) flow ramping, gradual postpeak recession. These functional flows probably improved the health of established trees and increased seedling recruitment along the Oldman River (Rood et al., 1998; Willms, Pearce, & Rood, 2006) and along the final reach of the St. Mary River, downstream of Pothole Creek (Rood et al., 2000). Conversely, the sparse cottonwood groves in the confined, canyon segment from the St. Mary Dam to Pothole Creek were almost completely lost and without the parental trees there was no opportunity for seedling replenishment (Rood et al., 2016).

In contrast to the St. Mary River with diversion commencing in 1898, and the Oldman River, with diversion from 1920, damming and water diversion from the Waterton River were more recent. The Waterton Dam was completed in 1964 and diversion progressively increased over the subsequent three decades. Prior analyses of aerial photographs indicated that there was some woodland decline from 1951 to 1985 (Rood et al., 1995) and this was supported with field observations in the late 1980s. Extending those analyses, the current study confirms correspondences between river flow characteristics and the condition of riparian woodlands along the Waterton River.

This study revealed that the riparian woodlands matured and cottonwood abundances increased during the predam interval, which had higher river flows during a regionally wet phase of the PDO. River damming followed, and confounding the impacts from river damming, a PDO phase transition and drought interval occurred that produced some woodland decline even upstream from the new dam. Woodland decline was greater below the dam and this reflected more severe reductions in instream flow due to the combined influence of the climatic drought and irrigation water withdrawal, which was increased due to that regional drought. In addition, that study interval included two major natural floods and these produced extensive bank erosion producing some further loss of riparian woodlands. Thus, although major floods are essential for the long-term replenishment of riparian cottonwood populations (Richter & Richter, 2000; Scott et al., 1996, 1997), these can be destructive in the short term. The study system was further complicated since the flood-induced erosion prompted diking and bank stabilization at certain sites, and this involved some further woodland clearing. Thus, the overall reduction in riparian woodland abundance was the outcome from the natural drought amplified by water withdrawal, flood-induced bank erosion, and some localized human alterations.

With some resolution of the interacting factors, the time course does indicate increase in the abundance and density of the riparian woodlands along the downstream reach following the implementation of the environmental flow regime. This indicates a favorable response to the combination of increased minimum flow and flow ramping. The apparent benefit for riparian woodlands suggests that it is not only the overall, seasonal, or monthly river flows (Andersen, 2005; Stromberg, 2001; Stromberg, Beauchamp, Dixon, Lite, & Paradzick, 2007), but particularly the occurrence of severely low flows that could be particularly harmful for riparian cottonwoods (Amlin & Rood, 2003 Cooper et al., 1999; Shafroth, Stromberg, & Patten, 2000). The flow ramping would also likely benefit established trees and would

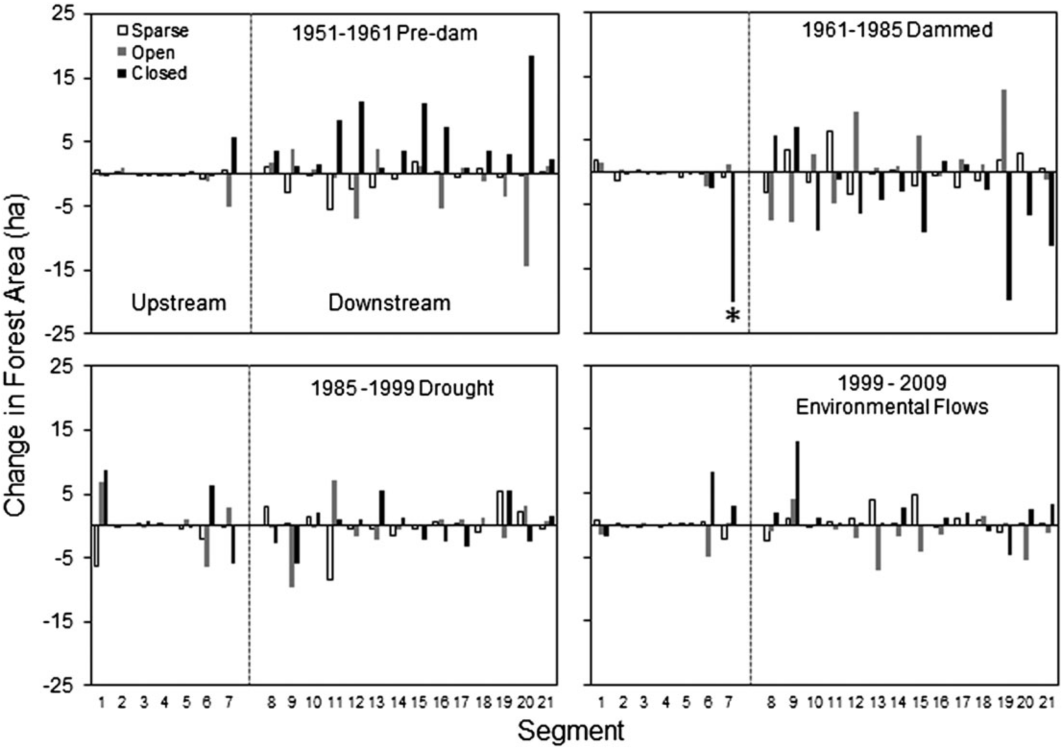

FIGURE 8 Changes in forest density classification along the Waterton River by segment between photographed years. The dashed vertical lines indicate the Waterton Reservoir. *Removal through human clearing

especially promote cottonwood replenishment, but this would only be partly observable in the final aerial photograph series of this study, since the saplings were still maturing. We thus conclude that the environmental flow regime was beneficial to the riparian woodlands downstream of the Waterton Dam and further study of the particular growth patterns of established trees and of cottonwood recruitment would be instructive to better understand the prospective ecophysiological benefits (Foster, 2016).

As a final consideration, this study suggests that the apparent decline in the riparian woodlands along the Waterton River through the drought interval after damming was temporary. The stress and die-back of the 1980s was apparently relieved with the natural recovery from the more severe drought interval, combined with the implementation of the environmental flow regime. The decline was reversible, in contrast to the cottonwood collapse in the canyon reach downstream of the St. Mary Dam (Rood et al., 1995, 2016). There are two important differences that probably contributed to the different outcomes following the implementation of similar environmental flow regimes along these two nearby rivers. First, water withdrawal from the St. Mary River had occurred for a much longer interval, commencing in 1898, versus 1964 for the Waterton River, and for both rivers, the environmental flow regime commenced with the 1991. It is likely that chronic drought stress would have persisted for many decades along the lower St. Mary River, whereas the stress interval was much shorter downstream from the Waterton Dam. Manipulative, ecophysiological studies have confirmed the correspondence between drought-stress, crown and branch die-back, and tree mortality, and also demonstrated that these involve multiple year responses, and that there is substantial recoverability, with improvement in the alluvial water supply (Amlin & Rood, 2003; Scott et al., 1999). Relative to evolutionary adaptation, short-term droughts occur naturally and riparian cottonwoods are apparently able to cope with these.

The second important difference between the lower Waterton River and the St. Mary River below the St. Mary Dam is the geomorphic condition of the river valley and floodplain zones, and the subsequent habitability for riparian woodlands. The St. Mary includes a canyon with an incised, sinuous channel with steep sandstone walls that limit channel migration. There is very limited alluvial floodplain and the riparian cottonwoods were naturally restricted to scattered narrow bands and occasional groves. This distribution was mapped in the early 1880s (Dawson & McConnell, 1884) and indicates that this was naturally a marginal landscape for riparian woodlands. This marginal system was apparently more vulnerable to the stress that followed river damming and water withdrawal. In contrast, the 19th century riparian woodlands were much more extensive on the broader, alluvial floodplains along the lower Waterton River, suggesting a more favorable environment for cottonwoods. This would likely produce a system with lower vulnerability to the impacts of damming and diversion and greater resilience to cope with natural droughts or the challenge from the combined water stress due to a natural drought and water withdrawal for irrigation.

This second proposed influence, with increased riparian vulnerability in canyon reaches, prompted further investigation of the two short canyon segments downstream from the Waterton Dam (Foster, 2016). We anticipated that these might be more vulnerable to impacts from river regulation and have periodically visited these locations after our observations of some decrepit groves in the 1980s (Figure 2). There has not been woodland collapse in these canyon segments, and they currently support apparently healthy riparian cottonwood groves, as displayed in photographs taken in 2015 versus 1881 (Figure 9). This provides a 124-year comparison

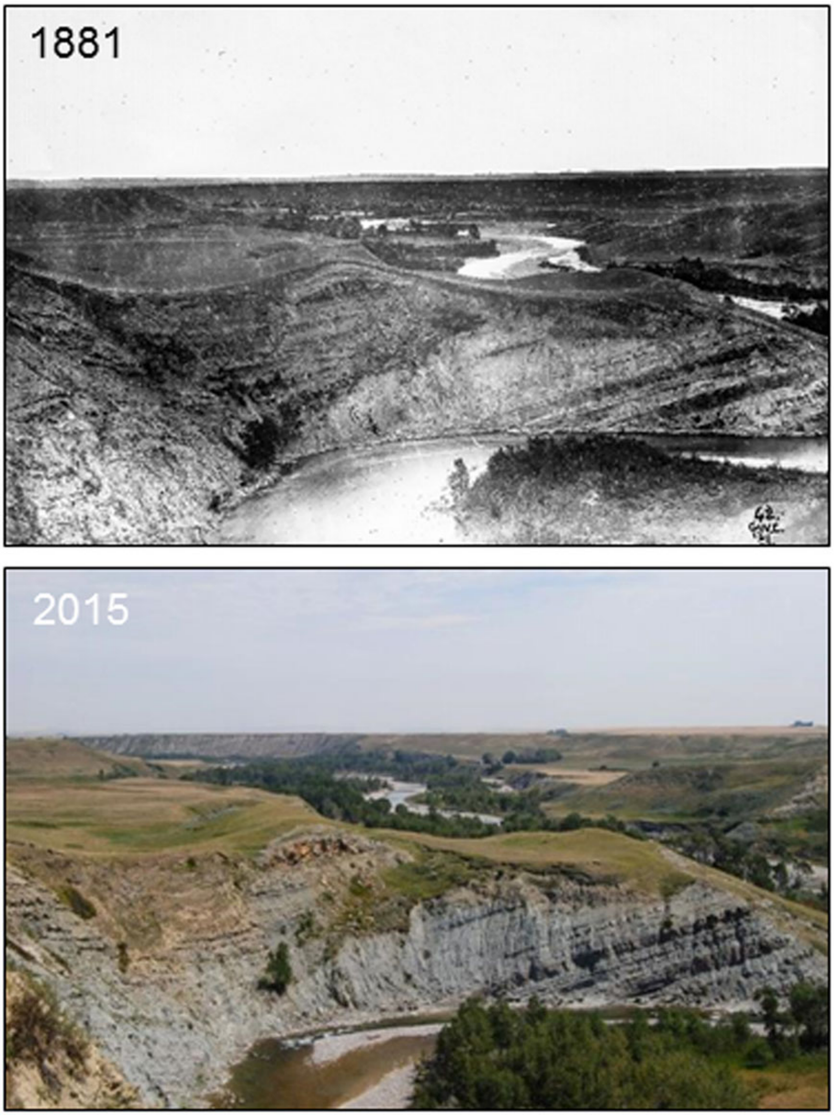

FIGURE 9 River valley views at a canyon along the downstream reach of the Waterton River in 1881 and 2015 (49.4°N; 113.7°W. Photos: G. Dawson; S. Foster). [Colour figure can be viewed at wileyonlinelibrary.com]

that extends the study time series and confirms the key conclusion that riparian woodlands persist downstream from Waterton Dam. This photo comparison and another in Foster (2016) even suggest more extensive riparian woodlands in 2015 in the alluvial zones along the river. This might reflect prior impacts from buffalo and frequent fires that were deliberately set by the indigenous Blackfoot and may have suppressed woodland development in southwestern Alberta a century ago.

5 | CONCLUSION

This study indicates that the riparian woodlands along the lower Waterton River have a promising future with the current environmental flow regime. The forested area has not substantially changed from the predam condition suggesting that the increased minimum flow has reduced drought stress and avoided substantial woodland mortality. However, cottonwoods along the downstream reaches still experience lower river flows due to the withdrawal of water for irrigation, and chronic drought stress may accumulate. Due to this, thinning of the riparian woodlands further from and higher above the river might occur, resulting in narrower riparian woodland bands in the future (Rood et al., 2008).

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