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Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests

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Summary In analyzing hydrologic consequences of climate change, we previously found declining annual discharges of rivers that drain the hydrographic apex of North America, the Rocky Mountain headwaters region for adjacent streams flowing to the Arctic, Atlantic and Pacific oceans. In this study we investigated historic changes in seasonal patterns of streamflows, by comparing mean monthly flows and analyzing cumulative hydrographs over the periods of record of about a century. We tested predictions of change due to winter and spring warming that would increase the proportion of rain versus snow, and alter snow accumulation and melt. We analyzed records from 14 free-flowing, snow-melt dominated rivers that drained relatively pristine parks and protected areas, thus avoiding the effects of river damming, flow regulation, or watershed development. The collective results indicated that: (1) winter flows (especially March) were often slightly increased, (2) spring run-off and (3) peak flows occurred earlier, and most substantially, (4) summer and early autumn flows (July–October) were considerably reduced. The greatest changes were observed for the rivers draining the east-slope of the Rocky Mountains toward the northern prairies and Hudson Bay, with late summer flow decline rates of about 0.2%/year. This would have considerable ecological impact since this is the warm and dry period when evaporative demand is maximal and reduced instream flows would reduce riparian groundwater recharge, imposing drought stress on floodplain forests. In combination with the decline in annual discharge, earlier peaks and reduced summer flows would provide chronic stress on riparian cottonwoods and willows and especially restrict seedling recruitment. We predict a loss of floodplain forests along some river reaches, the narrowing of forest bands along other reaches, and increased vulnerability of these ecosystems to other

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impacts including livestock grazing, encroachment of upland vegetation, and weed invasion.

Introduction

While there is considerable current concern for global warming, in many regions worldwide a more serious environmental threat from climate change is diminishing water supply (Barnett et al., 2005). Climate change consequences relative to water supply are difficult to model and global circulation models (GCMs) produce somewhat variable predictions (Shepherd and McGinn, 2003). Additionally, precipitation patterns have extensive regional variation that complicates modeling of specific watersheds and rivers.

Empirical analysis provides a complementary approach to climate change modeling and also provides foundational data for model development and testing (Leung et al., 2004; Lapp et al., 2005). Streamflows are useful for understanding water supply since they integrate precipitation over catchment areas, revealing larger scale spatial and temporal patterns (Burn, 1994; Burn and Hag Elnur, 2002; Déry and Wood, 2005; Regonda et al., 2005; Rood et al., 2005b). Analyses of streamflows are especially useful for studying mountain regions since the higher elevations generally receive abundant precipitation but have limited meteorological monitoring.

The central Rocky Mountain region of North America provides the intersection of the east–west Continental Divide and the north–south Hudson Bay Divide near the United States-Canada border. This creates the hydrographic apex of North America where adjacent headwater streams flow to the Pacific Ocean, the Arctic Ocean, to Hudson Bay that contributes to the Arctic and Atlantic oceans, and to the Gulf of Mexico and thus the Atlantic Ocean. The various catchments are differentially influenced by many atmospheric patterns making this zone a 'sentinel' that is particularly useful for analyzing North American patterns of streamflow and climate change. Using this study region, we previously detected gradual declines in annual streamflows from many of the free-flowing streams that drained relatively pristine parks and protected areas (Rood et al., 2005b). The annual discharge patterns were also correlated with climatic patterns, especially with the Pacific (multi)-Decadal Oscillation (PDO) that provides a prominent signal for hydrometeorology in western North America (Mantua et al., 1997; Mauget, 2003; Rood et al., 2005b).

It is not only the overall annual discharge that is ecologically and economically important, but the seasonal pattern of streamflow is also critical (Barnett et al., 2005). This Rocky Mountain region receives considerable snow in the winter and this snow-pack supports the spring peak and provides a natural store of water that is released through the summer period, when warm and dry conditions increase demands for irrigation and other human uses. The summer is also when the naturally low streamflows may impose physiological stress on aquatic and riparian organisms (Schindler and Donahue, 2006). Consequently, in this study we investigated the historic patterns of streamflow seasonality from the free-flowing river reaches that drain relatively pristine watersheds around the hydrographic apex.

Based on our prior study and previously reported regional climatic changes we developed several hypotheses for changes in streamflow seasonality, that are reflected in the hydrographs for two relatively typical years, 1911 versus 2003 (Fig. 1). To account for declines in annual streamflow there would be flow declines in at least some months (Fig. 1). Additionally, regional studies have revealed that summer temperatures have been relatively unchanged over the past century, whereas winter and spring temperatures, especially minima, have increased (Akinremi et al., 1999; Cayan et al., 2001). Increasing winter and spring temperatures would increase the proportion of rain versus snow and thereby increase winter streamflows and diminish snow-packs (Cutforth et al., 1999; Leung et al., 2004; Lapp et al., 2005; Mote et al., 2005; Regonda et al., 2005; Knowles et al., 2006). Warming in late winter and spring would also advance melting of the snow-pack and hence advance spring flows and the spring peak (Fig. 1). This prediction is consistent with some prior, shorter-term analyses of streamflows in western North America (Burn, 1994; Burn et al., 2004; Cayan et al., 1998; Cutforth et al., 1999; Whitfield, 2001; Stewart et al., 2005). With diminished snow-packs, the duration and magnitude of the spring peak could also be reduced (Fig. 1).

Perhaps most critically, reduced snow-pack and earlier snow-melt would result in reduced summer streamflows, especially in the late summer (Fig. 1). We anticipated that this is the prospective hydrologic change that could impose severe ecological stress on aquatic as well as riparian, or streamside, ecosystems. Instream flow needs (IFN) represent the essential flow characteristics of magnitude, timing,

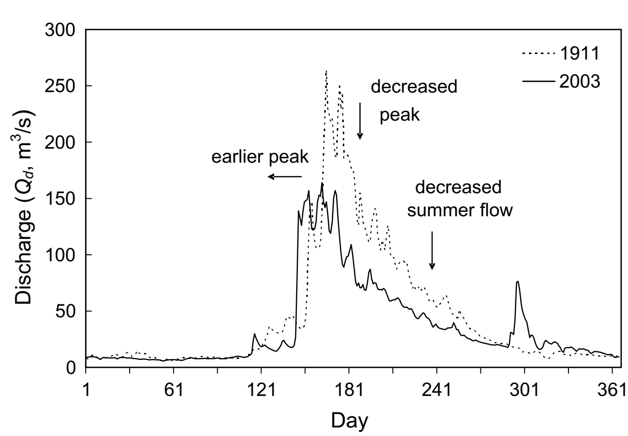

Figure 1 Annual hydrographs for the Bow River at Banff for 1911 and 2003, typical years for the historic intervals, that reveal three of the changes in streamflow seasonality predicted to accompany recent and near-future climate change.

and variation, which are required for particular organisms or communities within the aquatic and riparian ecosystems (Annear et al., 2004) and IFN analyses may enable predictions of the ecological impacts of changing streamflow seasonality. Riparian trees are terrestrial, large, sedentary and long-lived, and consequently especially suitable for IFN analyses that benefit from the coordination of historic streamflow patterns and population characteristics, through approaches including the assessment of sequential aerial photographs and dendrochronology (tree ring interpretation, Rood et al., 2003a). As a result, IFN models for riparian cottonwoods and floodplain forests are particularly well developed (Stromberg and Patten, 1990; Segelquist et al., 1993; Mahoney and Rood, 1998; Shafroth et al., 1998) and these could permit semi-quantitative analyses of impacts from the historic and prospective future changes in streamflow seasonality.

Consequently, following analyses of historic hydrology, in this study we apply an IFN model to analyze probable impacts of the changing seasonal patterns of stream flow on floodplain forests. In many regions around the Northern Hemisphere these forests are dominated by shrubs and trees of the *Salicaceae*, cottonwoods (*Populus* species) and willows (*Salix* species) (Karrenberg et al., 2002; Rood et al., 2003a). We consequently applied the Recruitment Box Model (Mahoney and Rood, 1998; Amlin and Rood, 2002) that integrates hydraulic and ecophysiological characteristics for these riparian plants. It been successfully applied for the conservation and even partial restoration of floodplain forests along a number of North American rivers (Rood et al., 1998, 2003b, 2005a; Shafroth et al., 1998).

Methods

Study rivers

This study extended from our prior study of annual river discharge and included overlapping criteria for the selection of streams and hydrometric gauges (Rood et al., 2005b). We considered prospective streams in the Rocky Mountain region from east-central British Columbia, southeasterly through Alberta and Montana to northwestern Wyoming (Fig. 2). For each prospective stream we assessed the apparent watershed conditions on 1:50,000 scale topographic maps and we have visited every stream.

We selected undammed river reaches that had minimal water diversion and were consequently relatively free-flowing. We included the dammed North Saskatchewan and Red Deer rivers but those analyses were restricted to the pre-dam interval. Watersheds were generally located in national or provincial parks or protected areas, where land-use impacts such as from mining, logging and grazing would be somewhat limited. We considered hydrometric gauges with at least 50 years of record, and only analyzed the records from the current gauges.

We subsequently recognized 14 rivers with 16 hydrometric gauges that satisfied our criteria (the Fraser and Columbia rivers each had 2 gauges that were considered, Table 1). Of the 14 rivers, two contribute to the Mackenzie River that flows into the Arctic Ocean, four flow to Lake Winnipeg and subsequently Hudson Bay. Three rivers contribute to the Missouri River and ultimately the Gulf of Mexico of the Atlantic Ocean. Two of these rivers drain the east-slope of Glacier National Park, Montana, and are slightly regulated. West of the Rocky Mountain Continental Divide, five rivers are in the Fraser and Columbia River basins and flow to the Pacific Ocean.

Hydrometric analyses

Mean daily (Q_d), monthly (Q_m), and annual (Q_a) discharge data for the Canadian hydrometric sites were obtained from the Water Survey of Canada's hydrological database (HYDAT) (http://www.wsc.ec.gc.ca/hydat/H2O/; data accessed up to September, 2006). Discharge data for American hydrometric gauges were obtained from the United States Geological Survey website (http://water.usgs. gov/; data accessed up to September, 2006).

Statistical analyses of daily Q_d, monthly Q_m, and seasonal Q for the spring (March—May), summer (June—August), fall (September—November) and winter (December—February), utilized SPSS 14.0 (SPSS Inc., Chicago) to investigate patterns over the period of record for each river. Consistent with prior studies of historic streamflows, we applied both parametric and non-parametric statistical tests (Zhang et al., 2001; Yue et al., 2002; Rood et al., 2005b). The parametric linear regression analysis produced Pearson Product Moment correlation coefficients (Pearson r), and the non-parametric rank-order analyses included the Kendall's τ (tau), and the Spearman's ρ (rho) tests. Statistically meaningful patterns were recognized with three levels of confidence: a trend (t) for $p < 0.1$, a significant pattern (*) for $p < 0.05$, and a highly significant pattern (**) for $p < 0.01$. Note that we use the term 'trend' as it is commonly used in statistical science to indicate a probable pattern, whereas some prior hydrology studies have used this term to designate a statistically significant change over time.

For individual rivers, rates of change were calculated as the slope of the linear regression (b)/mean Q. To consider possible patterns across the collective rivers, the apparent direction of streamflow change for each river was designated as increasing (+) or decreasing (−), based on the regression slope. Chi-square (χ^2) analyses were applied to investigate significant deviations from the expectation that without any regional, temporal pattern, equal proportions of the rivers would show increasing versus decreasing Q parameters.

We derived 'cumulative hydrographs' as another approach to investigate changes in streamflow seasonality. We summed all values of Q_d for each year to provide an index of the total annual flow and the contribution of each Q_d to that annual flow was then calculated. The cumulative hydrographs represent proportional rather than absolute flows, an approach that simplifies comparisons of seasonality across years or streams but neglects the influence of high- versus low-flow years (components that were considered in the Q_m analyses).

To detect changes over the cumulative hydrographs, we applied pentile-scaling to determine the Julian day to achieve 20%, 40%, 60% or 80% of the total flow for the year. We predicted that winter warming would increase winter flows and advance the snow-melt, which would reduce the duration to reach 20%, which approximated the

Figure 2 Map of western North America, showing the locations of hydrometric gauges along 14 study rivers that drain the central Rocky Mountains. East of the Continental Divide, the north—south Hudson Bay Divide occurs between '6' and '7'.

commencement of the rising limb of the spring peak. We anticipated that the Julian day to the 40% flow and perhaps the 60% flow would also be advanced. Conversely, due to the anticipation of reduced late summer flow, we anticipated less influence on the duration to the 80% flow. We also considered changes in the durations between flow pentiles that would reflect change in the shape of the annual hydrograph, particularly altering the slope of the rising- or falling-limb of the snow-melt peak.

Probable impacts on floodplain forests

To analyze probable impacts on floodplain forests we considered the impacts of the changes in flow seasonality and analyzed prospective seedling reproduction since this is probably the most hydrologically-sensitive component of the life cycle of cottonwoods and obligate riparian willows (Mahoney and Rood, 1991, 1998; Segelquist et al., 1993; Scott et al., 1997; Shafroth et al., 1998; Amlin and Rood, 2002). We applied the Recruitment Box Model, which analyzes river stage dynamics relative to seedling establishment and survival (Segelquist et al., 1993; Mahoney and Rood, 1998; Amlin and Rood, 2002). The analysis was somewhat qualitative (i.e. direction of change), and we also considered the quantitative hydrologic criteria developed by Braatne et al. (2007).

We assessed cottonwood seedling recruitment in a typical recruitment year in about the middle of the twentieth century ('past' = about 1950s), versus the middle of the twenty-first century ('future' = about 2050s) based on extrapolation from the historic patterns. This simplistic analysis would only approximate the typical future streamflow pattern. Recruitment years would involve a 1-in-5 year flood peak, a moderately high flow that is essential for the naturally episodic, cottonwood seedling recruitment (Scott et al., 1996; Mahoney and Rood, 1998). We considered hydraulic characteristics and ecophysiological parameters that would be fairly typical for the northwestern prairie region through which the Rocky Mountain rivers of the Hudson Bay drainage flow, since our analysis of historic hydrology

Table 1 Information about rivers and hydrometric records that were analyzed relative to streamflow seasonality

Stream gauge	Period of record	Years	Watershed origins	Comments
Arctic Ocean — Mackenzie River Basin				
1. Smoky R. at Watino	1916–1920; 1956–2005	55	Jasper National Park (NP)	
2. Athabasca R. near Jasper	1914–1921; 1924–1930; 1971–2005	50	Jasper NP	
Hudson Bay — Nelson River Basin				
3. North Saskatchewan R. at Edmonton	1912–1961	50	Banff NP	Bighorn Dam, 1972
4. Red Deer R. at Red Deer	1913–1930; 1936–1979	62	Banff NP	Dickson Dam, 1983
5. Bow R. at Banff	1911–2005	95	Banff NP	
6. Waterton R. near Waterton Park	1908–1933; 1948–2005	80	Glacier NP, USA and Waterton Lakes NP	
Gulf of Mexico — Missouri Sub-basin of Mississippi River Basin				
7. Cut Bank Creek at Cut Bank	1906–1918; 1923; 1952–1972, 1982–2004	58	Glacier NP, USA	Relatively free-flowing
8. Marias R. near Shelby	1902–1907, 1911–2005	101	Glacier NP, USA	Slight regulation
9. Yellowstone R. near Livingston	1898–1905; 1929–1931; 1938–2005	79	Yellowstone NP, USA	
Pacific Ocean — Fraser River Basin				
10. Fraser R. at Hansard	1954–2005	52	Mount Robson Provincial Park	
Pacific Ocean — Columbia River Basin				
11. Columbia R. at Nicholson	1917–1930; 1933–2003	84	Purcell Wilderness Conservancy	
12. Kootenay R. at Kootenay Crossing	1946; 1948–1950; 1953–1957; 1961–2003	54	Kootenay NP	
13. North Fork Flathead R. near Columbia Falls	1911–1915; 1936–2005	75	SW B.C. and Glacier NP, USA	
14. Middle Fork Flathead R. near West Glacier	1940–2005	66	Bob Marshall Wilderness and Glacier NP, USA	

Rivers are sequenced from north to south relative to headwater origin for the east-slope (numbers 1–9) and then the west-slope (Pacific) drainages.

revealed that across the study regions these rivers displayed the greatest change over the past century. We specifically selected the Oldman River around Fort Macleod since this river reach has been extensively studied with respect to riparian hydrology and supports three native cottonwood species (Rood et al., 1998; Willms et al., 2006). This selection determined the riparian water flux characteristics that are partly dependent on the substrate sediment texture that influences water drainage and the extent of the capillary fringe, the moist zone above the saturated water table that represents the primary zone for water uptake (Mahoney and Rood, 1991).

Results

Historic hydrology

All 14 of these central Rocky Mountain rivers displayed snow-melt dominated seasonal discharge patterns, generally similar to that shown for the Bow River in Banff (Fig. 1). The Bow River provided one of the most complete hydrometric data sets since the record is uninterrupted back to 1911. For many of the other streams, data gaps exist, particularly during a period of drought in the 1930s, and hydrometric gauge relocations resulted in a number of records commencing in about 1950. The shorter records impose a challenge since regional streamflows demonstrate strong coordination with the Pacific (multi-)Decadal Oscillation (PDO, Mantua et al., 1997; Mauget, 2003) and may thus reflect a phase of this oscillation, rather than a longer-term pattern of progressive climate change (Cayan et al., 1998; Leung et al., 2004; Rood et al., 2005b).

For all of these Rocky Mountain rivers, winter flows were low and increased rapidly through May. Peak flows were typically around the first week of June, similar to the peak-flow timing of other Rocky Mountain streams draining a broader latitudinal range (and reflecting a trade-off between latitude and altitude (Mahoney and Rood, 1998). Streamflows declined fairly steeply through June and July and more gradually through the late summer. Thereafter, autumn flows remained low and this continued into the next winter (Fig. 1).

These patterns of streamflow seasonality are retained but attenuated in the mean monthly hydrographs (Fig. 3).

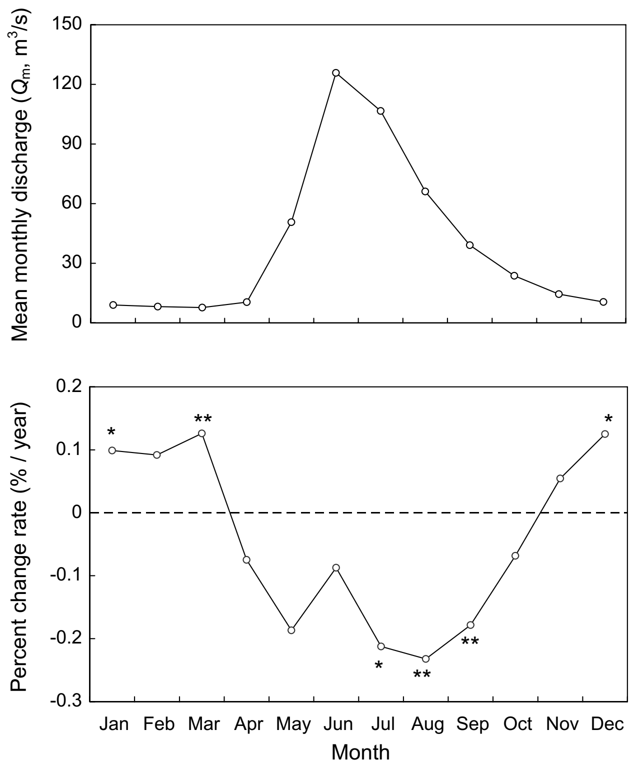

Figure 3 Mean monthly discharge Q_m (top) and percent change rate (bottom) based on the linear regression of Q_m versus year for the Bow River at Banff (1911–2005). Significant patterns from the Kendall's τ test are designated: * = $p < 0.05$, ** = $p \leqslant 0.01$.

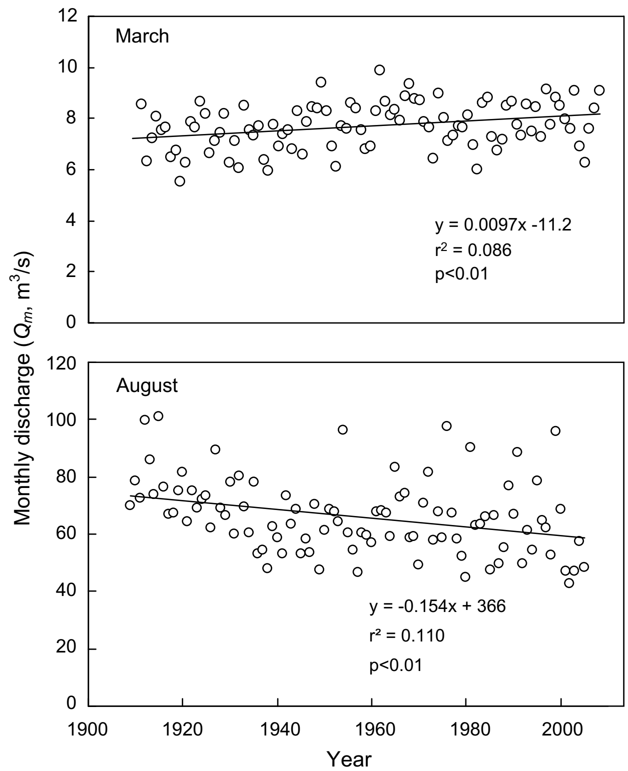

Figure 4 Annual monthly discharges showing increase in March flows (top) and decrease in August flows (bottom) of the Bow River at Banff from 1911 to 2005.

In particular, with monthly averaging the rising limb is much more gradual (Fig. 3 vs. Fig. 1). In addition to monthly analyses, we also analyzed weekly discharge patterns that resulted in similar statistical results and interpretations (not presented).

There was considerable scatter for monthly Q_m data, but as shown for the Bow River at Banff, there were progressive increases and decreases (Fig. 4) over the periods of record for some months. Statistical analyses of these patterns produced very similar results with either the parametric Pearson r or the non-parametric Kendall's τ and Spearman's ρ tests (Table 2). The parametric approach provides a function of best-fit that allows an assessment of the response magnitude and also permits preliminary near-future forecasting by extending the regression.

There were two seasonal intervals in which flows had particularly changed (Table 3, Fig. 4). First, winter season flows, typically from December through March, were often slightly increased over the historic record (Figs. 3 and 4). For the Bow River, there were increases of about 0.1%/year during the winter season (Fig. 3) resulting in an increase of about 10% over a century. However, winter flows are naturally very low (Fig. 3) and thus, this increase produces a very slight change in overall annual discharge.

The second and larger seasonal change was a decrease of summer flows, especially in the late summer. For the Bow River at Banff, flows decreased from April through October, with statistically significant declines in July, August and September (Fig. 3). The magnitude of the decline was about 0.2%/year, thus producing about a 20% reduction over the historic record of almost a century. These declines are important relative to the overall annual discharge since June and July represent the highest flow months (Fig. 3).

The most northerly rivers in the study contribute to the Slave River and then the Mackenzie River, which flows into the Arctic Ocean. These hydrometric records suffered from extensive data gaps and differ in the nature of the catchment areas. The Smoky River drains the most northern zone of the Rocky Mountains, but the hydrometric gauge is located well downstream from the headwaters and thus reflects mountain run-off and also contributions from an extensive region of boreal forest. The apparent pattern with respect to streamflow seasonality from this river gauge differed somewhat from the other Alberta rivers as flows were reduced in May and June but relatively unaltered through the late summer (Fig. 5A). These data suggested an increase in March flow but the data were variable.

In contrast to the Smoky River, the hydrometric gauge for the Athabasca River is located in Jasper National Park within the Rocky Mountain region. This river has headwaters near that of the North Saskatchewan and Bow rivers and its seasonal flow pattern demonstrated a pattern similar to those adjacent rivers, with decreasing flows in July through September and summer seasonal flow reductions of about 0.2%/year (Fig. 5A).

The strongest patterns of change in streamflow seasonality were observed for the rivers of the Saskatchewan River

Table 2 Probabilities from three statistical tests of historic change of monthly and annual discharges of the Bow River at Banff (1911—2005)

	Pearson r	Kendall's τ	Spearman's ρ
January	**0.047**	**0.046**	**0.045**
February	0.088	0.100	0.085
March	**0.004**	**0.006**	**0.005**
April	0.499	0.777	0.741
May	0.226	0.299	0.295
June	0.325	0.295	0.289
July	**0.018**	**0.023**	**0.020**
August	**0.001**	**0.000**	**0.000**
September	**0.009**	**0.002**	**0.002**
October	0.328	0.320	0.325
November	0.417	0.630	0.606
December	**0.023**	**0.038**	**0.041**
Annual	**0.024**	**0.022**	**0.016**

Bold figures indicates $p < 0.05$.

Basin that contributes flows to Lake Winnipeg, the Nelson River and ultimately, Hudson Bay (Fig. 5B). The two northerly tributaries within this basin, the North Saskatchewan and Red Deer rivers, were only analyzed for the intervals prior to damming, from the early 1910s to 1961 and 1979, respectively (Table 1). Similar to the Bow River that has adjacent headwaters to both of these rivers, the North Saskatchewan and Red Deer rivers demonstrated significant flow declines in late summer, with dramatic reductions in late summer flow of about 1%/year (Fig. 5B). The largest decline detected in the study was for the Red Deer River, but this analysis assessed a limited hydrometric record that ended with a PDO phase associated with regionally lower flows (Rood et al., 2005b) and this probably exaggerated the seasonal pattern.

South of the Bow River, the Waterton River of the Oldman River Basin provided an extensive record and is internationally important since it drains the Waterton-Glacier International Park, of Montana, USA and Alberta, Canada (Table 1, Fig. 2). There were significant reductions throughout the spring and summer months with decreasing flows from April through October (Fig. 5B). The response magnitudes ranged from about 0.2% to 0.6%/year, producing a late summer flow reduction of about 0.3%/year, or about a 30% reduction over a century. However, this hydrometric record lacked data for the drought interval of the 1930s and early 1940s and we anticipate that consideration of lower flows during those periods would diminish the magnitude of the historic response.

Continuing southward, the streams that drain the east-slope of Glacier National Park, Montana towards the Gulf of Mexico demonstrated generally similar patterns (Fig. 6A) to those for the Alberta east-slope rivers. Cut Bank Creek is the first Rocky Mountain drainage south of the Hudson Bay Divide, with a headwater region near that of the Waterton River. Cut Bank Creek is a small stream that is relatively free-flowing with flow records that extend back a century, but with major data gaps (Table 1). These limited records indicated declining flows throughout the summer months (Fig. 6A). Cut Bank Creek joins with the dammed Two Medicine River to form the Marias River that has a more complete hydrometric record, and also demonstrated reduced flows throughout the summer (Fig. 6A). However, flow regulation of the Two Medicine River complicates this analysis.

Relatively distant from the Marias River (Fig. 2), the most southerly river of the study, the free-flowing Yellowstone did not demonstrate major change in streamflow seasonality over its hydrometric record that exceeds a century (Fig. 6A). There have been slight increases in April and May flows and apparent, but not significant, decreases in late summer flows. The increases in spring flows of the Yellowstone River contrast with the patterns for the other Montana streams draining the east-slope of the Rocky Mountains (Table 4).

West of the Continental Divide, the Fraser River flows to the Pacific Ocean at Vancouver, British Columbia. The

Table 3 Summaries of patterns of historic changes in mean monthly discharges for 14 rivers draining the central Rocky Mountains

Month	Individually significant results		Collective results		
	+	–	(#/14)	χ^2	p
January	1*	1**	10+	2.6	
February	1**		11+	4.6	*
March	1*, 4**	1*	13+	10.3	**
April	1*	1t, 2*	8+	0.3	
May	1t	4*, 1**	10–	2.6	
June		1t, 4*	11–	4.6	*
July		1t, 3*	13–	10.3	**
August		1t, 5*, 4**	11–	4.6	*
September		1t, 3*, 3**	12–	7.1	**
October		4*	14–	14.0	**
November		1*	9–	1.1	
December	1*	1**	10+	2.6	

($t = p < 0.1$; * = $p < 0.05$; ** = $p < 0.01$).

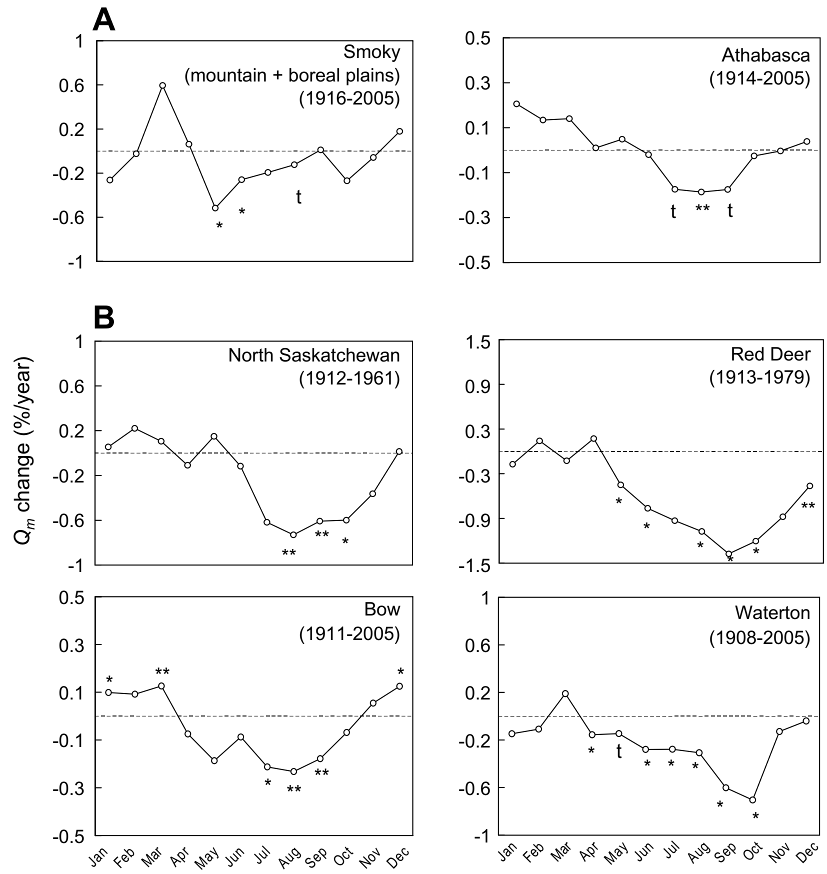

Figure 5 Change rates based on the linear regression of monthly discharge (Q_m) vs. year, for rivers draining the central Rocky Mountains (sequenced from north to south relative to headwaters origin) towards the (A) Arctic Ocean and (B) Hudson Bay. Statistical results ($t = p < 0.1$; $* = p < 0.05$; $** = p < 0.01$) are based on the Kendall's τ test. Note that *y*-axis scales differ.

hydrometric record was limited to the past half-century and the pattern of change was uncertain (Fig. 6B). This was also often the case for the rivers of the adjacent Columbia River Basin that are situated sequentially southward down to the two forks of the Flathead River that define the boundaries of Glacier National Park, Montana (Fig. 2). For these Pacific drainages, there were often increased flows in March and in a few cases, decreased flows in late summer, especially September (Fig. 6B). With flows grouped into the four tri-monthly seasons, the Pacific drainages demonstrated increased winter flows, but unlike the Rocky Mountain rivers east of the Continental Divide, the Pacific rivers did not consistently demonstrate flow declines in the summer and early fall (Table 4).

Results of the cumulative hydrograph method (Fig. 7) demonstrate an advancement of the spring-peak as the annual date at which cumulative discharge reached 20% decreased for all 14 rivers (Table 5). There was significant flow advancement for the North Saskatchewan River and a trend for this advancement for the Yellowstone River (Table 5). Overall, the dates at which cumulative flows reached 40% and 60% were also often advanced, with the North Saskatchewan, Columbia and Yellowstone showing the strongest patterns (Table 5). Declining late summer flows may have partly compensated for any changes towards an earlier date for the 80% cumulative flow, and thus the analysis for this pentile did not show a consistent change (Table 5).

The intervals between flow pentiles also changed over the historic record. The interval between the date of the 20% and 40% flow increased for 13 of the 14 rivers (Table 5). This reflected a slight change in the hydrograph shape with the rising limb of the late spring peak becoming more gradual and consequently, the cumulative hydrograph rising less steeply. Thus, the change in seasonality was not simply an advancement of the spring freshet since there were also some changes in the peak flow pattern. In contrast to the lengthening interval between the 20% and 40% flow, the subsequent intervals between the 40%, 60% and 80% cumulative flows were less consistently altered, although these were apparently expanded for some rivers particularly of the Columbia River Basin (Table 5).

Impacts of changing streamflow seasonality on floodplain forests

From these analyses of historic hydrology, there have been four changes in the seasonality of streamflows over the past century (Fig. 8): (1) winter flows have slightly increased, (2) early spring flows have increased and produce a more gradual rising limb of the spring peak, (3) the spring peak has occurred earlier, and most substantially, (4) summer flows,

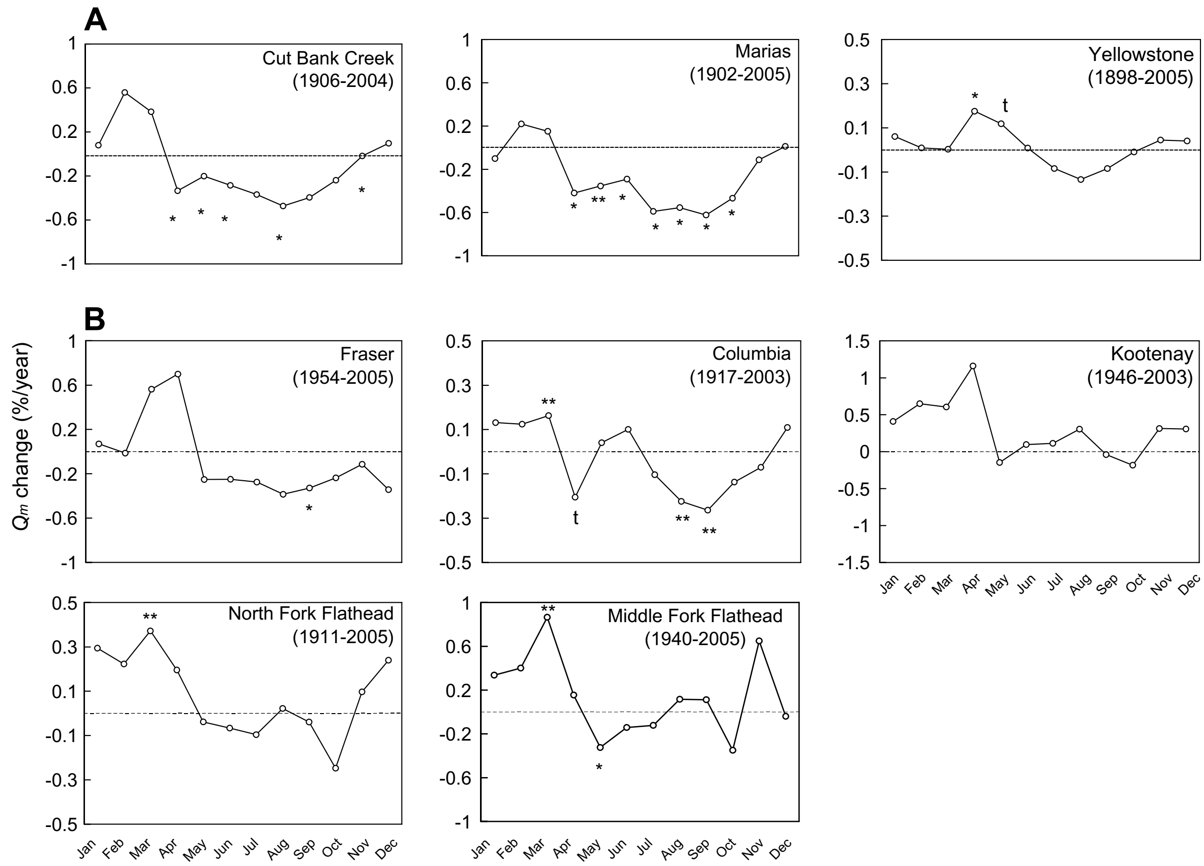

Figure 6 Change rates based on the linear regression of monthly discharge (Q_m) versus year, for rivers draining the central Rocky Mountains (sequenced from north to south relative to headwaters origin) towards the (A) Gulf of Mexico and (B) Pacific Ocean. Statistical results ($t = p < 0.1$; $* = p < 0.05$; $** = p < 0.01$) are based on the Kendall's τ test. Note that y-axis scales differ.

and especially late summer flows have declined. It would be predicted that (1), the slight increase in late winter flow, would have minimal influence since cottonwoods, willows and other deciduous riparian shrubs and trees are leafless and physiologically inactive in winter (Table 6). However, a changing winter flow regime would impact ice formation and break-up that are important for floodplain forests since break-up events provide fluvial geomorphic disturbances that produce colonization sites suitable for seedlings, and scarify cottonwoods and willows, promoting clonal suckering (Rood et al., 2007).

We would expect that change (2), the earlier and more gradual rise in flow prior to the peak, might provide a slight benefit for riparian cottonwoods and willows. This flow increase would occur when reproductive and then vegetative buds are emerging and the supplemental moisture would be favorable. Conversely, this interval is typically cool and wet, and this would decrease the evaporative water demand and consequently, this increase in water supply might occur at a time when water is not limiting (Karrenberg et al., 2002; Rood et al., 2003a).

The advancement of the spring peak (3) would probably have a more substantial influence because riparian plants are adapted to the natural flow regime (Lytle and Poff, 2004). This coordination is prominent for riparian cottonwoods and willows that produce vast numbers of small, short-lived seeds that are generally shed during the flow recession following the spring peak (Mahoney and Rood, 1998). This is ideal timing because the peak flow provides extensive, newly-exposed, saturated and barren mineral surfaces that are ideal nursery sites for seed germination and seedling survival (Mahoney and Rood, 1998; Karrenberg et al., 2002).

The advancement of the spring peak would partially uncouple this coordination between the seasonal flow pattern and seedling establishment. Although winter and spring warming would also advance the timing of flowering and seed development (Stella et al., 2006) reproductive phenology is partly determined by photoperiod, or day-length. This would be unaltered by climate change and consequently the interval of seed release would not be advanced as much as the spring peak (Fig. 8).

Of the four changes in streamflow seasonality, we predict that (4) the decline in late summer flows will have the greatest ecological influence on floodplain forests. This would impose chronic drought stress along river reaches in arid and semi-arid ecoregions (Rood et al., 2003a). In these ecoregions, there is infiltration of water from the stream into the riparian groundwater table during the hot and dry summer period (Mahoney and Rood, 1998). The riparian water table is consequently closely coordinated with river stage — as the river recedes, the riparian water table also

Table 4 Patterns of change in seasonal flow (mean of three months) for 14 rivers draining the central Rocky Mountains, with probabilities from the Kendall's τ test

Stream gauge name	Winter DJF	Spring MAM	Summer JJA	Fall SON
Arctic Ocean — Mackenzie River Basin				
Smoky River	−	− t	−	−
Athabasca River	+	+	−*	+
Hudson Bay — Nelson River Basin				
North Saskatchewan River (to 1961)	+	+	−	−*
Red Deer River (to 1979)	−**	−	−	−
Bow River	+t	−	−*	−t
Waterton River	−	−	−*	−t
Gulf of Mexico — Missouri Sub-basin of Mississippi River Basin				
Cut Bank Creek	+	−t	−*	−t
Marias River	+	−*	−*	−*
Yellowstone River	+	+*	−	−
Pacific Ocean — Fraser River Basin				
Fraser River	−	+	−	−t
Pacific Ocean — Columbia River Basin				
Columbia River	+	+	−	−t
Kootenay River	+	−	+	+
North Fork Flathead River	+	+	−	+
Middle Fork Flathead River	+	−	−	+
Collective results (#/14)	10+	8−	13−	10−
χ^2	2.6	0.3	10.3	2.6
p			**	

($t = p < 0.1$; $^* = p < 0.05$; $^{**} = p < 0.01$).

recedes (Naiman et al., 2005). The diminished water supply would impose drought stress on the riparian willows and cottonwoods that are exceptionally vulnerable to drought-induced xylem cavitation (Tyree et al., 1994). Old and young cottonwoods are probably most vulnerable to environmental stress and thus the reduced summer flows would especially lead to mortality of old trees situated further from the stream and young saplings, and especially seedlings (Mahoney and Rood, 1991; Karrenberg et al., 2002).

To further assess the prospective impact on seedlings, we applied the streamflow changes to the Recruitment Box Model, which defines the instream flow and stage requirements for seedling recruitment of riparian plants, and especially cottonwoods and willows (Fig. 8; Mahoney and Rood, 1998; Amlin and Rood, 2002). For Fig. 8, the hydrographs are smoothed and simplified, and the Recruitment Box parameters reflect those that would be typical for the western prairie reaches of the rivers of the current study that flow towards Hudson's Bay since these showed the greatest hydrologic change through the past century. The Recruitment Box represents the position in space and time that is required for successful seedling establishment and survival. The spatial component, expressed in the *y*-axis, represents the recruitment band, the elevational band along the river bank in which seedlings could survive. The typical recruitment band is from 60 to 180 cm above the base stage, the typical low stage that commonly occurs in late summer (Fig. 8). This elevation is determined by two contrasting processes: erosive scour in the lower zone that removes seedlings and drought stress above the upper limit where the seedlings are unable to maintain sufficient root contact with the receding moisture zone (Mahoney and Rood, 1998).

The time component of the Recruitment Box, expressed on the *x*-axis, relates to the plant's phenology and especially the interval of seed release during June and July. Additionally, following seedling establishment, survival relies on gradual river stage recession, as the roots must grow downward fast enough to maintain contact with the reced-

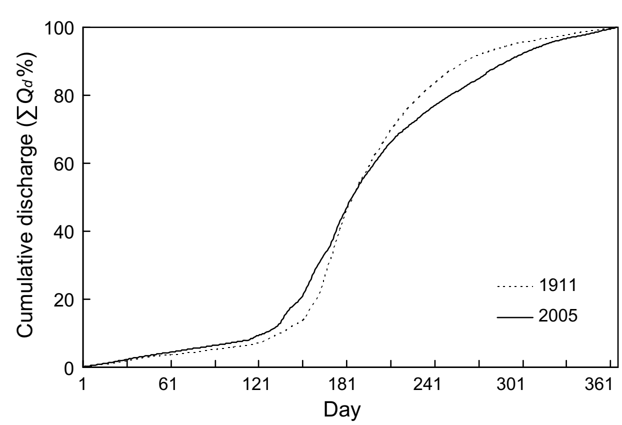

Figure 7 Annual cumulative% discharge (Q_d) for the Bow River at Banff for 1911 and 2005.

Table 5 Results of cumulative hydrograph analyses for 14 rivers draining the central Rocky Mountains, with probabilities from the Kendall's τ test

River	Duration to				Interval from		
	20%	40%	60%	80%	20% to 40%	40% to 60%	60% to 80%
Arctic Ocean — Mackenzie River Basin							
Smoky River	–	+	+	+	+	+	–
Athabasca River	–	–	–	–	+	+	+
Hudson Bay — Nelson River Basin							
North Saskatchewan River	–*	–	–t	–	+	–	+*
Red Deer River	–	–	–	–	+	–	–
Bow River	–	–	–	+	+	+	+
Waterton River	–	–	–	–	–	–	–
Gulf of Mexico — Missouri Sub-basin of Mississippi River Basin							
Cut Bank Creek	–	–	–	–	+	+	–
Marias River	–	–	–	–	+	+	–
Yellowstone River	–t	–*	–*	–*	+	+	+
Pacific Ocean — Fraser River Basin							
Fraser River	–	–	–	–	+	+	–
Pacific Ocean — Columbia River Basin							
Columbia River	–	–	–t	–	+	+	+
Kootenay River	–	+	+	+	+*	+*	+
North Fork Flathead River	–	–	–	–	+	–	+
Middle Fork Flathead River	–	–	+	+	+	+	+
Individually significant	1t, 1*	1*	2t, 1*,	1*	1*	1*	1*
Collective results (#/14)	14–	12–	11–	10–	13+	10+	8+
χ^2	14.0	7.1	4.6	2.6	10.3	2.6	0.3
p	**	**	*		**		

* = $p < 0.05$; ** = $p < 0.01$.

ing moisture zone. The survivable rate of water table decline is about 2.5 cm/day for cottonwoods while willows require more gradual rates of river stage recession (Amlin and Rood, 2002).

Following from the observed hydrologic changes, there would be changes in both the spatial and temporal parameters of the Recruitment Box (Fig. 8A and B). For the recruitment band, the reduced summer flows would produce deeper moisture zones thus producing a downward-shift in the upper limit of the Box (Fig. 8B). The shift would reflect the magnitude of change and as late summer flows along some rivers had declined at rates of about 0.2%/year, we'd expect that over a century there would be about a 20% reduction in the base-flow discharge and a corresponding reduction in the upper limit of the Recruitment Box (Fig. 8). While the upper limit of the Box would be shifted downwards, the lower limit would still reflect scour that might be relatively unaltered. Thus, the recruitment band would be narrowed in vertical extent.

In terms of timing of the Box, spring warming would advance seed release but, because the addition cue of photoperiod is invariant, this advancement would be less than the advancement in the timing of the spring peak in stream flow. As a result, there would be some uncoupling and the Recruitment Box would thus be delayed relative to the peak in river flow (Fig. 8A). The survivable recession rate is determined by the physiological capacity for root elongation that would be unchanged.

These prospective changes are provided in Fig. 8 and may reveal the recruitment potential for the two flow patterns. Seedling survival requires gradual recession of the moisture zone and thus, the recruitment band commences when the slope of the falling-limb matches the recession threshold. Seedling establishment advances after this point, until the end of the seed release period or until the hydrograph falls into the scour zone. As shown in Fig. 8, in the prospective future establishment year a narrower recruitment band would occur and this could result in about a one-third reduction in the extent of cottonwood seedling recruitment.

The prospective future hydrograph in Fig. 8 represents single year and over decades there would be many years with no recruitment and only a few years when all conditions are met for extensive recruitment. We anticipate that the changes in streamflow seasonality would continue and consequently there would be fewer years in which the river flow pattern enabled seedling recruitment, in addition to reduced recruitment in the favorable years, as indicated in Fig. 8. Consequently, river reaches that currently experience marginal flow regimes relative to riparian cottonwoods, could experience flow patterns that are insufficient for cottonwood recruitment in any year.

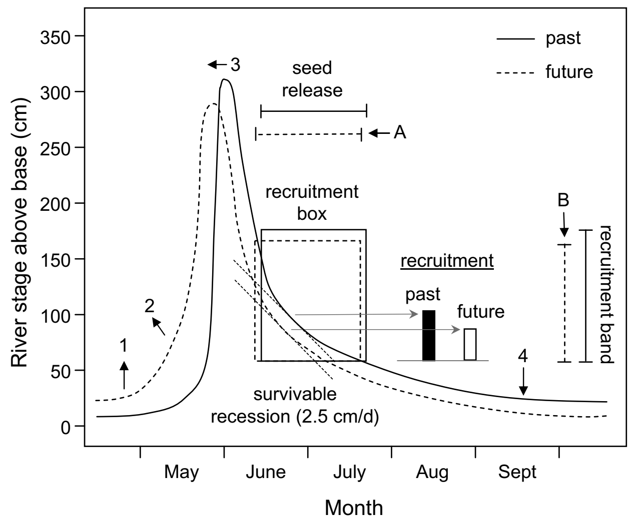

Figure 8 Historic and prospective future pattern of streamflow seasonality (with changes labeled 1 through 4) and prospective impact on the reproduction of riparian cottonwoods, in accordance with the Recruitment Box Model. This Model defines the opportunity for survivable seedling establishment, based on the timing of seed release (change = A) and the elevation of the recruitment band — high enough to avoid subsequent scour and low enough to avoid drought-induced mortality (change = B). Following seedling establishment, the rate of river stage recession must not exceed the root elongation capacity and this survivable recession rate would be unchanged. The parameters plotted in this figure approximate conditions along the Oldman River near Fort Macleod with respect to the magnitude of the river stage change, and the timing of the spring river flow peak and of cottonwood seed release. The two smoothed hydrographs illustrate seasonal patterns in the mid-20th century ('past' = 1950s) versus the middle of the 21st century ('future' = 2050s), with the future hydrograph based on simple extrapolation from the historic record.

Conclusion

This study extended our prior study that revealed declining annual streamflows from many rivers that drain the Rocky Mountain, hydrographic apex region towards three oceans (Rood et al., 2005b). In this follow-up study of streamflow seasonality, the historic stream discharge data reveal:

(1) slightly increased winter flows,
(2) the advancement and more gradual rising limb,
(3) to earlier spring peaks, and most substantially,
(4) considerably decreased summer flows, especially in late summer and early autumn.

Of these results, the advancement of the spring peak has been previously reported (Burn, 1994; Cutforth et al., 1999; Cayan et al., 2001; Stewart et al., 2005), whereas the other changes have been proposed but less consistently verified (Barnett et al., 2005; Schindler and Donahue, 2006). This confirmation of changes in streamflow seasonality suggests that current perspectives regarding winter and spring warming are correct (Stewart et al., 2004; Barnett et al., 2005; Lapp et al., 2005; Mote et al., 2005).

The magnitudes of the apparent changes enable provisional forecasting of future flow conditions from the central Rocky Mountains. It is reasonable to expect that the near-future will extend the recent past in both direction and magnitude of change although the proportional contributions of natural and anthropogenic forcings are changing (Stott et al., 2000; Meehl et al., 2004). The hydrometric analyses indicate generally increasing winter flow and decreasing late summer flow east of the Continental Divide, but changes in the transitional seasons vary across the watersheds.

Our results further suggest that the most prominent changes will occur for the rivers of southern Alberta that drain the east-slope of the Rocky Mountains and contribute flows to the adjacent prairie provinces of Canada and ultimately, Hudson Bay. The more northerly east-slope rivers

Table 6 Probable impacts on floodplain forests from changing seasonality of instream flows of rivers draining the central Rocky Mountains

	Impact on floodplain (riparian) forests
Increased winter flows	Slight influence. Cottonwoods, willows and other deciduous riparian plants are leafless and physiologically relatively inactive and insensitive in winter. Changing winter flow regime will impact ice formation and break-up that provides a fluvial geomorphic force that produces colonization sites for seedlings and scarifies cottonwoods and willows, promoting clonal suckering
Earlier spring run-off and peak flows	Slight to considerable stress. Plant phenology (life cycle timing) is coordinated with patterns of the natural flow regime, including floodplain inundation, bank scour and deposition, and water stage patterns that influence surface moisture and groundwater. The partial uncoupling of the phenology of cottonwoods and willows with the river flow regime would reduce seedling recruitment and may limit colonization to lower bank elevations, resulting in narrower bands of new cottonwoods, and narrower floodplain forests
Major decrease in late summer flows	Major stress. Especially in arid and semi-arid ecoregions, riparian groundwater is recharged with water from the stream during the summer. Decreasing streamflow would reduce this recharge, resulting in drought stress and consequently, xylem cavitation and branch, crown and whole tree die-back. Seedlings and saplings would be particularly vulnerable and this would further diminish reproduction that is essential for long-term forest survival

that contribute to the Mackenzie River will likely experience smaller declines in late summer flow. The results are somewhat ambiguous for the remaining drainages. The Gulf of Mexico drainages may also experience a decline in late summer flows but this effect is minimal for the more southerly Yellowstone River (Fig. 6A). The responses are apparently different for the Pacific drainages, although an increase in late winter (March) flow seems likely (Fig. 6B).

From the overall patterns for the east-slope rivers, we conclude that the historic rates of streamflow decline in the late summer months of July through September were in the range of 0.2%/year. These late summer flows would have decreased by around 20% over the twentieth century and extending this pattern into the twenty-first century, we might cautiously predict a further decline of about 10% by 2050, particularly for the Rocky Mountain rivers that flow through the northern prairies towards Hudson Bay. Following from these hydrologic changes we predict that there would be losses of seedlings, saplings and older trees due to increasing, chronic drought stress as well as decreased clonal and seedling recruitment due to changes in ice scour and the timing of peak flows (Table 6).

Riparian woodlands along many of the rivers draining the east-slope around the hydrographic apex of North America demonstrated declines over the twentieth century, and this had been attributed to impacts of river damming and flow regulation, livestock grazing and invasive plants (Naiman et al., 2005). Declining annual stream-flows (Rood et al., 2005b), changes in stream-flow seasonality, and especially, diminishing late summer flows (Fig. 8) would have provided further stresses, and these are likely to increase through the twenty-first century.

Following from the analyses of historic hydrology and our subsequent assessment of cottonwood seedling recruitment we thus predict that due to the changes in river flow seasonality there would be fewer years with cottonwood seedling recruitment, and narrower bands of recruits during those favorable years. We also anticipate that some river reaches that are currently marginal would become unsuitable and there would thus be extensions of river zones that are barren of floodplain forests along some rivers. Further, due to the chronic stress especially from reduced summer flows, we further predict that some floodplain forests could become more susceptible to other challenges such as from livestock grazing, the encroachment of upland vegetation and from invasive weeds (Rood and Mahoney, 1990; Karrenberg et al., 2002).

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