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Flood moderation: Declining peak flows along some Rocky Mountain rivers and the underlying mechanism

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SUMMARY

It has been proposed that global warming will amplify the water cycle and intensify river floods. We tested this hypothesis by investigating historic trends in magnitudes, durations and timing of the annual peak flows of rivers that drain the Rocky Mountains around the North American hydrographic apex, the source for rivers flowing to the Pacific, Arctic (including Hudson Bay) and Atlantic Oceans. We sought century-long records and to reduce influences from land-use we assessed drainages from parks and protected areas. Of 30 rivers and reaches that were free-flowing or slightly regulated, seven displayed declining peak flows (7 $p < 0.1$, 4 $p < 0.05$), and one showed increase ($p < 0.05$); three of five moderately regulated rivers displayed decline ($p < 0.05$). Substantial floods, exceeding the 1-in-5 year recurrence (Q_5), were more common in the early versus latter halves of the records for some Arctic drainages and were more common during the Pacific Decadal Oscillation negative phase for all regions. The timing of peak flows was relatively unchanged and Q_5 flood durations declined for a few rivers. These results indicate flood moderation rather than flood intensification, particularly for Arctic Ocean drainages. This could reflect regional hydrological consequences from climate change including: (1) declining overall annual river flows; (2) winter warming that would increase the rain versus snow proportion, thus reducing snow accumulation and melt; and (3) spring warming that advances snow melt, lengthening the melt interval before peak flows. These changes would shift the seasonality of river flows and reduce annual peaks. We might expect continuing moderation of peak flows but there will probably still be occasional major floods from exceptional rain events such as occurred in northern Montana in 1964 and in southern Alberta in 2013.

1. Introduction

While there is growing concern related to global warming, in many regions an even greater challenge from climate change relates to impacts on water resources (Bates et al., 2008). There has been a common view that atmospheric warming will accelerate or intensify the global water cycle (Durack et al., 2012) and that this could result in heavier rain events that would produce more severe river floods (Huntington, 2006). As summarized by Karl and Melillo (2009), 'Floods ... are likely to be amplified in most regions.'

Supporting this view, Milly et al. (2002) reported that there had been more major floods in recent versus prior decades, and that this was consistent with some hydroclimatic projections based on impacts from greenhouse gases and aerosols. However, those data were very limited (only 21 flood events) and confounding the influences from climate change, land-use alterations would increase rates of surface run-off, thereby worsening river floods (Wheater and Evans, 2009). In particular, forest harvesting, woodland clearing for crops or pasture, wetland drainage and infilling, and the construction of roadways, buildings and other impermeable surfaces can increase and accelerate run-off, thus increasing flood peaks. Conversely, dams create reservoirs than can attenuate flows and flood-control is a primary objective of many projects. Due to these and other human impacts, it is difficult to assess flood histories and resolve the impacts of climate change versus other human influences.

In considering the literature, the International Panel on Climate Change (IPCC) technical group concluded that it is likely that since about 1950 the number of heavy precipitation events over land has generally increased and that this conclusion is more confident for North America (Stocker, 2013). However, the transition from heavy rains to intense floods has been less certain. In reviewing the broader literature, including papers assessed by the IPCC report, Kundzewicz et al. (2014) suggested that there is low confidence

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in the conclusion that anthropogenic climate change has resulted in increased magnitude or frequency of global river floods over recent decades. This uncertainty partly reflects the confounding complexities from land-use impacts, the natural variability in river flows and limited intervals of flood flow records for most river systems.

To investigate changes in river regimes associated with climate change, we analyzed a study system that straddles the east–west and north–south Continental Divides of North America (Rood et al., 2005, 2008). This study system reflects influences from weather systems from the Pacific Ocean, Gulf of Mexico and Arctic Ocean, and includes the hydrographic apex of North America, the headwater source for some of the major North American river systems that drain to the Pacific, Arctic and Atlantic Oceans. This zone includes the transboundary Rocky Mountain region around the Canada-United States border, which provides a global focus for parks and protected areas, with Jasper, Banff, Kootenay and Waterton Lakes National Parks, Canada; and Glacier, Yellowstone and Grand Teton National Parks, USA (Fig. 1). With substantial landscape protection that extended back to the nineteenth century, this zone includes relatively pristine Rocky Mountain watersheds, thus reducing the confounding influences from human developments. There has been some river damming and flow regulation within these protected areas and this influence must be recognized in analyses of historic flow patterns (Tables 1a–c).

Consequently, we assessed the records of historic peak flows for rivers that drain this transboundary conservation corridor, and these analyses follow from our prior analyses of the historic annual and seasonal river flow patterns of these rivers (Rood et al., 2005, 2008). We investigated records for individual rivers, and then for the three major drainage regions, and the prospective correspondence with the Pacific (multi) Decadal Oscillation (PDO). Following the principles of water cycle amplification and flood intensification, our primary expectation was that there would have been increasing flood severity, with higher peak magnitudes and longer flood-durations over the past century. As a secondary prediction, following winter warming and earlier snow melt (Barnett et al., 2005; Cunderlik and Ouarda, 2009; Shepherd et al., 2010), we also anticipated that annual flow peaks would occur earlier.

2. Methods

We selected rivers and gauging locations with criteria that extended from our prior studies of annual and seasonal flow

Fig. 1. Map of western North America with the locations of the studied 30 hydrologic gauging stations, sequenced by major watersheds as listed in Tables 1a–c. For the region east of the Continental Divide, the American/Canadian border approximates the north–south Hudson Bay Divide. The triangle orientation indicates the direction of apparent change (Δ upright = increasing, with positive regression slope; inverted = decreasing); the size represents the statistical effect (small = not statistically significant; medium = statistical trend, $p < 0.1$; and large = statistically significant, $p < 0.05$); and the fill indicates the extent of regulation (open = free-flowing or slight regulation, gray = moderate regulation).

Table 1a
Study gauges for rivers flowing to the Hudson Bay and Arctic Ocean, with correlation analyses of flow characteristics and trends ($p < 0.1$) underlined and significant patterns ($p < 0.05$) in bold. The rivers are generally sequenced from north-to-south, west-to-east and upstream to downstream. Status refers to the extent of damming and reservoir storage.

	River and gauge	Period of record	Years	Status	Pearson r; p value	Kendall τ p value		
					Log Q_{max}	Q_{max}	Q_5 Duration	Q_{max} Date
	Arctic Ocean – Mackenzie River Basin							
1	Smoky R. at Watino, AB (07GJ001)	1916–1921; 1955–2013	65	Free-flowing	−.131 .299	−.129 .131	.026 .795	−.014 .865
2	Athabasca R., Hinton & Entrance, AB (07AD001 & 07AD002)	1915–1939; 1955–2011	82	Free-flowing	**−.373** **<.001**	**−.268** **.001**	−.133 .131	.089 .240
	Hudson Bay – Nelson River Basin							
3	North Saskatchewan at Edmonton, AB (05DF001)	1911–2013	103	Moderate Regulation	**−.285** **.004**	**−.189** **.005**	−.070 .370	.038 .572
4	Red Deer River at Red Deer, AB (05CC002)	1913–1932; 1935–2013	100	Slight regulation	−.171 .088	−.109 .108	**−.179** **.023**	.040 .557
5	Bow River at Banff, AB (05BB001)	1909–2012	104	Free-flowing	**−.244** **.013**	**−.170** **.011**	−.130 .093	−.050 .460
6	Bow River at Calgary, AB (05BH004)	1911–1950; 1952–2013	102	Moderate regulation	**−.206** **.037**	**−.331** **< .001**	**−.230** **.004**	.008 .910
7	Elbow River at Bragg Creek, AB (05BJ004)	1935–2012	78	Free-flowing	.071 .539	.047 .540	.029 .747	.016 .832
8	Highwood R., Diebel's Ranch, AB (05BL019)	1951–2012	62	Free-flowing	−.078 .546	−.059 .500	−.092 .363	−.019 .831
9	Oldman R., Waldron's Corner, AB (05AA023)	1950–2008	59	Free-flowing	−.042 .753	−.040 .652	.094 .365;	.073 .417
10	Castle R. near Beaver Mines, AB(05AA022)	1945–2011	67	Free-flowing	−.104 .404	−.120 .153	−.038 .697	**.166** **.049**
11	Waterton R. near Waterton Park, AB (05AD003)	1908–1930; 1948–2012	88	Free-flowing	−.116 .283	−.137 .060	−.072 .401	−.015 .837
12	Belly R. at Mountain View, AB (05AD005)	1912–2012	101	Almost free-flowing	.106 .292	.074 .274	.082 .300	.011 .876
13	St Mary R. Int'l Boundary, AB (05AE027)	1903–2014	112	Slight regulation	−.110; .249	−.084 .188	−.045 .548	.026 .691
14	South Saskatchewan at Medicine Hat, AB (05AJ001)	1911–2013	102	Moderate regulation	−.134 .178	−.068 .310	−.014 .861	.080 .237

Table 1b
Study gauges and rivers flowing to the Pacific Ocean, presentation as in Table 1a.

	River and gauge	Period of record	Years	Status	Pearson r; p value	Kendall τ p value		
					Log Q_{max}	Q_{max}	Q_5 Duration	Q_{max} Date
	Pacific Ocean – Fraser River Basin							
15	Fraser River at Hansard, BC (08KA004)	1953–2010	58	Free-flowing	−.213 .108	−.162 .073	.055 .601	−.100 .271
16	Fraser River at Hope, BC (08MF005)	1912–2012	101	Moderate regulation	−.068 .502	−.085 .211	.066 .402	.006 .930
	Pacific Ocean – Columbia River Basin							
17	Columbia R. at Nicholson, BC (08NA002)	1903–2013	109	Free-flowing	−.014 .882	−.029 .654	−.016 .834	−.103 .117
18	Kootenay R. at Kootenay Crossing, BC (08NF001)	1939–1941; 1945–1946; 1948–2013	71	Free-flowing	.064 .596	.039 .634	.006 .947	.012 .881
19	Bull River near Wardner, BC (08NG002)	1914–1915; 1919–1922; 1928–2013	94	Slight regulation	.131 .208	.084 .233	.140 .089	−.026 .717
20	Elk River at Phillips Bridge, BC (08NK005)	1925–1996; 1997–2013	89	Almost free-flowing	−.022 .838	−.051 .483	−.102 .224	.129 .076
21	North Fork of Flathead R. near Columbia Falls, MT (USGS 12355500)	1912–1917; 1929–2013	92	Free-flowing	.068 .518	.011 .879	−.040 .632	−.029 .685
22	Middle Fork Flathead R. near West Glacier, MT (USGS 12358500)	1940–2013	74	Free-flowing	−.058 .626	−.052 .516	−.024 .799	−.021 .790

regimes (Rood et al., 2005, 2008). We investigated rivers that drained the central Rocky Mountains region and favored rivers that drained relatively pristine watersheds (Fig. 1). We required peak flow records of more than 50 years and sought century-long records to increase statistical confidence and to dampen influences from climate oscillations, especially the PDO (Whitfield et al., 2010; Rood et al., 2015).

While free-flowing rivers were favored, these were limited and we also included regional rivers with some damming and regulation. We assessed the extent of regulation based on the storage

Table 1c
Study gauges and rivers flowing to the Gulf of Mexico, presentation as in Table 1a.

	River and gauge	Period of record	Years	Status	Pearson r; p value Log Q_{max}	Kendall τ p value Q_{max}	Q_5 Duration	Q_{max} Date
	Gulf of Mexico – Missouri Sub-basin of Mississippi River Basin							
23	Milk R. at the Western Crossing of International Boundary, AB (11AA025)	1931–1985; 1987–2014	83	Slight regulation	.146 .187	.116 .120	.111 .204	**.200** **.008**
24	Marias R. near Shelby, MT (USGS 06099500)	1904–1907; 1911–2013	109	Slight regulation	−.090 .352	−.079 .223	.036 .636	.055 .400
25	Teton R. near Dutton, MT (USGS 06108000)	1955–2013	59	Almost free-flowing	**−.361** **.005**	**−.236** **.008**	−.170 .103	−.021 .814
26	Sun R. near Vaughn, MT (USGS 06089000)	1934–2013	80	Extensive diversions	−.174 .123	**−.165** **.031**	−.104 .249	.047 .541
27	Missouri R. at Toston, MT (USGS 06054500)	1890; 1911–1916; 1941–2013	80	Moderate regulation	**−.225** **.045**	−.125 .100	−.094 .287	−.046 .549
28	Gallatin R. near Gallatin Gateway, MT (USGS 06043500)	1890–1894; 1930–1969; 1972–1981; 1985–2013	84	Free-flowing	.093 .401	.104 .163	−.023 .791	−.066 .378
29	Madison R. near West Yellowstone, MT (USGS 06037500)	1915–1917; 1919–1973 1983–1986 1989–2013	85	Free-flowing	**.264** **.015**	**.190** **.010**	.126 .141	**−.148** **.047**
30	Yellowstone R. near Livingstone, MT (USGS 06192500)	1897–1905; 1928–1932; 1937–2013	90	Free-flowing	.042 .697	.038 .601	.029 .724	**−.164** **.024**

index, the total storage capacity of the onstream reservoirs along the river and it tributaries upstream from the gauging location (based on websites of the respective agencies) as a percentage proportion of the average total annual flow. This provided four status categories: free-flowing (unregulated), or slight (up to 15%), moderate (16–30%) or extensive (>30%) regulation. We subsequently rejected the regional rivers with extensive regulation and, along with our requirements for relatively intact watersheds and a minimum half-century time series, this resulted in 30 study rivers and reaches (Table 1a–c).

Discharge (Q) records were obtained from the online 'HYDAT' data set of the Water Survey of Canada for Canadian rivers (http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm) and the United States Geological Survey website for American rivers (http://waterdata.usgs.gov/nwis, both accessed to January 2015). We assessed peak flows as the maximum mean daily discharges (Q_{max}), since the instantaneous peak ($Q_{max\text{-}i}$) records are often incomplete for the early intervals. Either approach would be almost identical, since very tight associations exist between Q_{max} and $Q_{max\text{-}i}$ for these medium to large rivers (e.g. Bow River at Banff (#5); $Q_{max\text{-}i} = 1.037 \times Q_{max}$; $r^2 = 0.993$). These Rocky Mountain river systems consistently display 'nival patterns' with maximum annual flows in the open water interval (Burn and Whitfield, 2015) and we included only peaks from May through October to avoid localized winter floods from ice jam events. For the Elk River, we coordinated peak discharge data from sequential gauges that displayed 95% correspondence (Fig. 2).

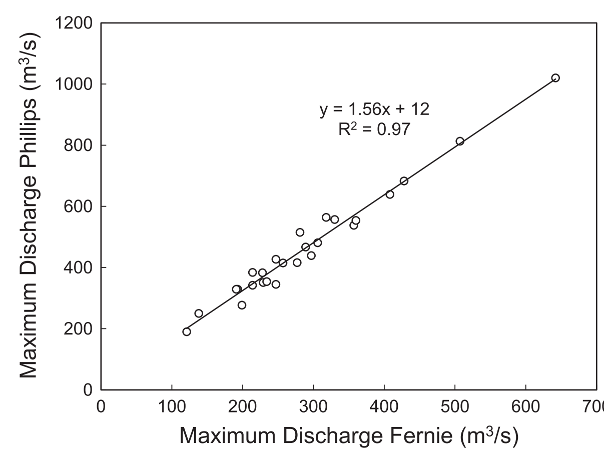

Fig. 2. The maximum discharge of the Elk River at Fernie, BC versus at Phillips Bridge, BC (#20) for the overlapping historic record. This illustrates the coordination of discharge data across sequential gauges enabling extension of the time series.

We developed spreadsheets with five river discharge parameters for the interannual time series for each river (Table 1, Fig. 3). These included (1) the Q_{max} and to normalize the distribution for the parametric Pearson correlation the Q_{max} values were also log-transformed (2). We assessed the occurrences of moderate to major floods, considering peaks exceeding the 1-in-5 year recurrence (Q_5). These substantial floods would considerably exceed the bank-full discharge for these cool-region rivers where ice formation and break-up can widen the channels (Smith, 1979; Polzin and Rood, 2006). The Q_5 thresholds were calculated with the log Pearson Type III distribution that closely fit the data series through the Q_5 range. We investigated the occurrences of these substantial floods over the historic intervals (3) and assessed whether there were more in the recent versus prior halves of the time series, with the χ^2 (chi-square) test and an expected equal split for the two half-series. We also assessed the durations of moderate to major floods as the numbers of days (including 0) that the flow exceeded the Q_5 (4) and investigated trends in these flood durations. The final parameter was the Julian date of the peak flow (5), allowing investigation of changes in peak timing.

Statistical analyses investigated trends for each parameter over the interval of record, with the parametric Pearson r and the non-parametric rank-order tests, Kendall τ b, and Spearman's ρ, using SPSS19 (IBM, Armonk, NY). The Kendall and Spearman's tests provided very similar outcomes and we only present the Kendall results. The Pearson test results were also generally consistent with the non-parametric tests and to streamline the Results tables

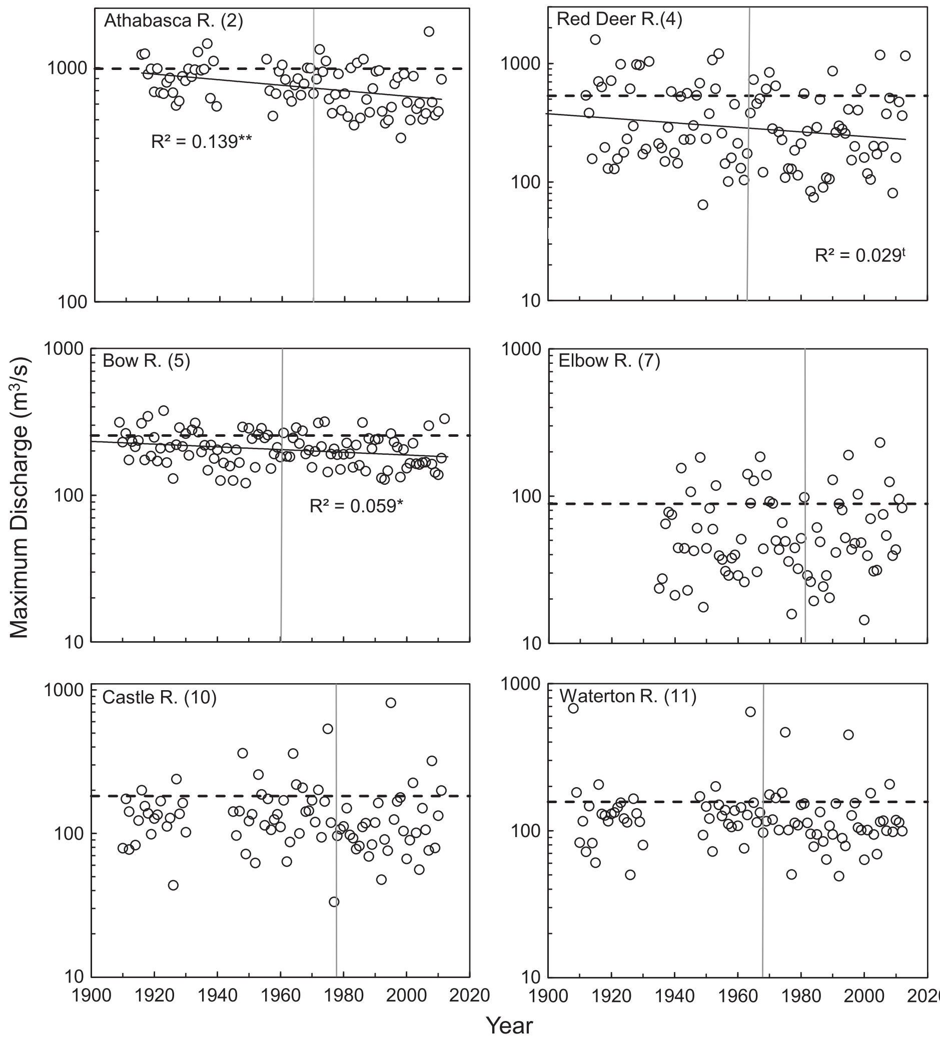

Fig. 3. The mean annual discharge for five free-flowing rivers and the slightly regulated Red Deer River that all flow to the Hudson Bay. Regression lines are plotted for significant ($p < 0.05$) declines and the Kendall τ test indicated a declining trend for the Waterton River ($p = 0.06$). The horizontal dashed line represents the Q_5 value for the data set and the vertical gray line represents the midpoint of the time series for each river.

we present the Kendall test results for all parameters and the Pearson test results only for the annual maxima (Tables 1a–c).

To investigate regional trends in the peak flows, we applied the regional Kendall test (RKT) (Helsel and Frans, 2006) using the library rkt (Marchetto, 2015) in the programming language R. The RKT is a non-parametric rank-order test that performs a standard Mann–Kendall test on all individual rivers within a specified grouping separately, and then evaluates their results for an overall trend. Since each river had more than 15 data points, we corrected for inter-block covariance by calculating p-values for significance with the original Regional Kendall test as well as with the test modified to account for serial dependence (Helsel and Frans, 2006). We grouped the data into the Arctic, Pacific, and Gulf of Mexico drainages but excluded the four moderately regulated rivers.

To investigate possible correspondence with the PDO, yearly PDO conditions were categorized as either positive or negative based on values from the University of Washington (http://jisao.washington.edu/pdo/PDO.latest). Positive intervals, which are often characterized by warmer and drier conditions in western North America (Whitfield et al., 2010), were assigned to the periods 1934–1943, 1957–1960, 1976–1988, 1992–1998 and 2002–2006. Conversely, negative phase intervals, frequently associated with cooler and wetter conditions were assigned to 1916–1922, 1944–1956, 1961–1975, 1989–1991, 1999–2001 and 2007–2013. Years in which Q_5 values were exceeded were assessed as either PDO positive or PDO negative and the distribution across these two groups was assessed using a χ^2 analysis with the expected values reflecting the number of record years with the alternate PDO phases for each river's peak flow time series. This was undertaken for each drainage region and for the collective data set.

3. Results

3.1. Historic trends in annual peak flows

From the 30 rivers and reaches that were free-flowing or slightly to moderately regulated, eleven displayed statistical patterns (11 $p < 0.1$; 8 $p < 0.05$; Tables 1a–c). Ten of these displayed declining peaks, a proportion significantly different from a random distribution (10 of 11 $\chi^2 = 7.36$, $p = 0.007$ for all χ^2 presented, df = 1). For the full set of rivers and reaches, 21 of 30 displayed negative correlation coefficients, further indicating an overall pattern of declining annual peaks ($\chi^2 = 4.80$, $p = 0.029$).

There were apparent differences across the three watersheds. For the rivers flowing north or northeast to the Arctic Ocean or Hudson Bay, 12 of 14 displayed negative correlation coefficients, strongly indicating regional peak flow decline ($\chi^2 = 7.14$,

$p = 0.008$; Table 1a). This conclusion was also supported with the significant regional Kendall test (RKT) result (Table 2).

Conversely, there was no consistent pattern for annual peaks of the Pacific drainages (5 of 8 with negative coefficients, $p = 0.405$; Table 1b), and this conclusion was supported by the non-significant RKT result (Table 2). There was no overall pattern for the Gulf of Mexico drainages (4 of 8 negative, $p = 1.00$; and non-significant RKT result, Table 2), but apparent regional variation (Table 1c). The Madison River near West Yellowstone, MT was the single river that displayed a significant increasing trend, and the adjacent Yellowstone and Gallatin Rivers also displayed positive but not significant trends (Table 1c). Conversely, three of the more northerly rivers in the Missouri River basin displayed declining trends (Table 1c). This suggested variation within this watershed and patterns for the northern drainages were more similar to the nearby Hudson Bay drainages.

3.2. Substantial floods

Our next consideration assessed peak flows that exceeded the Q_5, indicating substantial overbank flood events. Similar to Milly et al. (2002), we investigated whether these substantial floods were more prevalent in the recent versus earlier half of each time series. Specific intervals varied across the rivers since the commencement years varied and there were gaps in some historic records (Tables 1a–c).

Historic patterns are plotted for the rivers that drain the Canadian east-slope national parks since this region provided the strongest pattern in the annual peak flow series (Table 1a). In Fig. 3, the dashed lines indicate the Q_5 thresholds and for each plot, the vertical line splits the time series in half. For the rivers that drain to the Arctic Ocean and Hudson Bay, in 10 of the 14 cases there were more floods in the earlier than later half-series ($\chi^2 = 2.57$, $p = 0.109$), also opposing flood intensification over the past century. The collective record for the moderate floods in this region supported that analysis, with 99 peaks exceeding the Q_5 in the early half-series versus 73 in the recent half-series, differing from a random 1:1 ratio ($\chi^2 = 3.93$, $p = 0.048$).

Of the 30 study rivers and reaches, only the Red Deer River displayed a significant declining trend in the flows greater than the Q_5 over the record (Table 1a). Both the Teton River (Table 1c) and Bow River at Banff (Table 1a) showed a tendency for a decrease in Q_5 duration, while there was a tendency for increase along the slightly regulated Bull River (Table 1b). Eighteen of these 30 provided a negative correlation coefficient for flood duration, and this was not statistically different from a random split.

Our investigation of peak flow timing was uncertain relative to our prediction that annual peaks would be occurring earlier within the year. Overall, 14 of the 30 rivers and reaches displayed apparent negative correlation coefficients (Tables 1a–c), indicating little effect ($\chi^2 = 0.133$, $p = 0.715$). There were significantly earlier peaks along the Yellowstone and nearby Madison Rivers (Table 1c) but there were apparently later peaks along the Castle, Milk and Elk Rivers (Tables 1a–c), suggesting some regional differentiation in the hydrologic patterns. Overall, these results indicate that the timing of flow peaks has not changed as substantially as the advancement of the spring peak along these same rivers (Rood et al., 2008). While there were uncertain trends in peak timing, a spatial pattern was clear, with later peaks occurring at higher latitude (Fig. 4).

The investigations demonstrated significant coordination between the Q_5 flood flows and the phase of the Pacific Decadal Oscillation (PDO, Table 3). For all three drainage regions, Q_5 peaks were apparently more common during the PDO negative phase and less common during the PDO positive phase. For the overall assessment, the Q_5 peaks were about one-third more common (31%) during the PDO negative phase.

Table 2
Results from the regional Kendall test (RKT) that investigates interannual trends in annual peak flows for multiple rivers, with watershed groupings. Rivers with moderate regulation were excluded (Table 1).

Watershed	Standard model		Corrected for covariance		Slope
	Variance	p	Variance	p	
Arctic Ocean and Hudson Bay	818,392	**0.000**	3,528,379	**0.050**	−.238
Pacific Ocean	515,727	0.718	2,097,867	0.858	−.037
Gulf of Mexico, Atlantic Ocean	566,122	0.719	2,448,509	0.863	−.054

4. Discussion

Following from the anticipated amplification of the water cycle, the flood intensification hypothesis predicts that floods would become more severe with climate change and particularly global warming (Huntington, 2006; Karl and Melillo, 2009; Durack et al., 2012). We tested this prediction by analyzing the historic

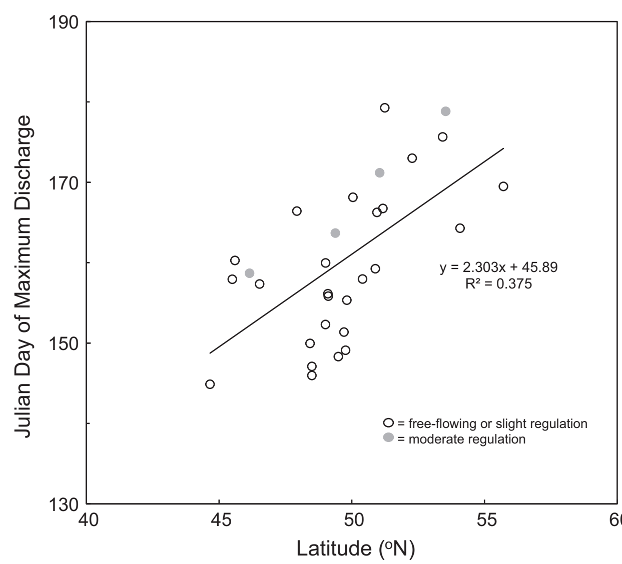

Fig. 4. The mean Julian day of the maximum flow versus the latitude of the gauging station for the study rivers.

Table 3
The interannual coordination between the Pacific Decadal Oscillation (PDO) phase and flood events (>Q_5) for the 30 study rivers (df = 1 for χ^2). The expected value reflects the proportion of years in the particular records with negative (−) versus positive (+) PDO phases.

Drainage Region	PDO Phase	Observed	Expected
Arctic Ocean and Hudson Bay			
$\chi^2 = 27.1$, $\boldsymbol{p < .001}$	−	146	109.5
	+	53	89.6
Pacific Ocean			
$\chi^2 = 19.1$, $\boldsymbol{p < .001}$	−	95	70.4
	+	33	57.6
Gulf of Mexico			
$\chi^2 = 5.9$, $\boldsymbol{p < .02}$	−	78	64.9
	+	40	53.1
All Rivers and Reaches			
$\chi^2 = 50.1$, $\boldsymbol{p < .001}$	−	319	244.75
	+	126	200.25

records for the annual peak flows along 30 rivers and reaches draining relatively pristine headwaters in the North American central Rocky Mountains. Our study outcome clearly opposed the flood intensification prediction. Instead, we found that annual flow peaks had declined along a number of the rivers. Thus, peak flows did not increase but instead there were trends of flood moderation over the past century.

There was regionalization of this response and the strongest patterns were observed for the rivers draining the Canadian Rockies to the northeast (Table 1a). There were negative coefficients for twelve of these fourteen reaches, with statistical differences or trends for six, and four more with tendencies ($p < 0.2$). However, while peak flows have thus historically been declining, major floods still persist, including the 2013 flood of the Bow River Basin and through Calgary, Alberta, which may have provided the most costly natural disaster in Canadian history.

There was uncertainty in the historic patterns of peak flows for the drainages to the Gulf of Mexico, and especially the Pacific Ocean (Table 1b). There were significant declines for some rivers in the Missouri River system and probably more so for the northern rivers closer to the Hudson Bay Divide. The Pacific drainages showed little evidence for changes in peak flows, even though some of these records exceeded a century and should thus have been sufficient to dampen the influence of the Pacific Decadal Oscillation and reveal progressive trends (Whitfield et al., 2010).

Other researchers have also investigated trends in peak flows for North American rivers with relative unaltered sites. Lins and Slack (1999) and McCabe and Wolock (2002) assessed locations within the American Hydro Climatic Data Network (HCDN) and found few statistically significant patterns in peak flows from 1941 to 1999. Villarini et al. (2009) reviewed American studies of the early 2000s, and undertook further analyses to reach the same conclusion, that there had not been substantial changes in annual peak flows of the American rivers in our study region.

Prior studies have generally assessed common time series but this reduces the record durations and the prospects for detecting statistical trends that are superimposed on the naturally variable patterns (Merz et al., 2012). This strategy was applied for Canadian rivers by Cunderlik and Ouarda (2009) who found declining annual peak flows for some rivers over the short interval from 1974 to 2003. Some of the rivers in our study were included in that study but there were no statistically significant trends for these rivers over the shorter interval. Subsequent analyses by Burn and Whitfield (2015) investigated patterns from 1961 to 2010 and found some declines in peak flows in the Canadian Rocky Mountain rivers draining to Hudson Bay and the Arctic Ocean, consistent with our findings. In contrast to our findings for Pacific drainages, Burn and Whitfield (2015) reported some declines but their analysis included rivers with greater variation in land-use development and regulation, thus confounding the prospective influence from climate change.

For American rivers, Hirsch and Ryberg (2012) sought to maximize the historic intervals for each river, investigating records with 85–127 years duration, and found statistically significant trends for some American rivers and particularly declining peak flows in the interior region of the American southwest. For their northwest region that included parts of the Rocky Mountain corridor that we investigated, slight patterns suggested declining peak flows for their study intervals up to 2008.

Like Hirsch and Ryberg (2012) we have sought the longest available records in our studies (Rood et al., 2005, 2008). We have even extended the data series by coordination across sequential hydrometric gauges and by interpolation for short data gaps. With the lengthening data series and the consideration of rivers in both Canada and the United States, our study provides a fairly confident outcome, which is generally consistent with the prior reports. This rejects the hypothesis that peaks are increasing. Instead, our longer term analyses complement the Hirsch and Ryberg (2012) and Burn and Whitfield (2015) studies, indicating the opposing response, with declining peak flows along some Rocky Mountain rivers.

A complexity with these trend analyses is contributed by the PDO. As expected, we found coordination, whereby substantial Q_5 floods were more likely to occur during the negative phase of the PDO. We had previously found even stronger correspondence between the PDO and annual flows of these rivers (Rood et al., 2005). The partial correspondence between Q_5 floods and the PDO was observed for all three drainage regions and is relevant for studies of trend detection associated with climate change, and also provides a prospective management measure. Dam and reservoir management could increase consideration for flood prospects when the PDO phase is negative, and conversely, there is reduced flood risk when the PDO phase is positive.

4.1. Flood moderation: the underlying mechanism

With the conclusion that annual peak flows have been declining for some Rocky Mountain rivers, we may consider the underlying processes. While there was the proposal that global warming would amplify the water cycle and thus intensify floods (Huntington, 2006; Karl and Melillo, 2009; Durack et al., 2012), an alternate outcome would be reduced flooding with warming conditions. This might match the seasonal pattern in which weather conditions in many regions of North America involve spring seasons that are cool and wet and produce river floods, while the warmer summer is characterized by lower precipitation and fewer floods. This correspondence between cooler and wetter conditions, and major floods also apparently matches the 7,000 year geologic record for the Mississippi River system (Knox, 1993).

To analyze the underlying mechanism of the decline in peak flows from some rivers in this Rocky Mountain region, we considered the regional hydrological consequences of climate change. This present study of historic peak flows followed two studies of the same rivers in which we first investigated patterns in overall annual flows over the past century (Rood et al., 2005), and subsequently investigated changes in the seasonal patterns of those river flows (Rood et al., 2008). The results from those prior studies are combined with the current results to develop a likely mechanism for the moderation of peak flows, as displayed in Fig. 5. Our first finding (Fig. 5, '1') was declining annual flows over past century (Rood et al., 2005), with typical decline rates of ~2% per decade. Associated with this reduction in the overall river flows, there would be a corresponding reduction in the general contributions to peak flows. The lower overall flows would probably also reflect correspondingly dryer watersheds and this would increase the availability for infiltration of some of the precipitation from heavy rain events that are associated with peak flows (Whitfield et al., 2010).

In this Rocky Mountain region the river flow seasonality has also been changing over the past century (Regonda et al., 2005; Rood et al., 2008). Regional warming has been greatest during the cool, winter interval (Akinremi et al., 1999; Cayan et al., 2001) and winter warming will increase the rain versus snow proportions and elevational transitions (Knowles et al., 2006). This results in increased winter flows (Fig. 5, '2') and declining mountain snow packs (Lapp et al., 2005; Mote et al., 2005; Rood et al., 2008). This would reduce snow melt that represents winter precipitation that was temporarily stored as snowpack. Regional warming extends from the winter into the spring, and particularly producing warmer nights. The interval of rapid snow melt relies on night temperatures remaining above freezing and with the night-time warming the commencement of the major snow melt

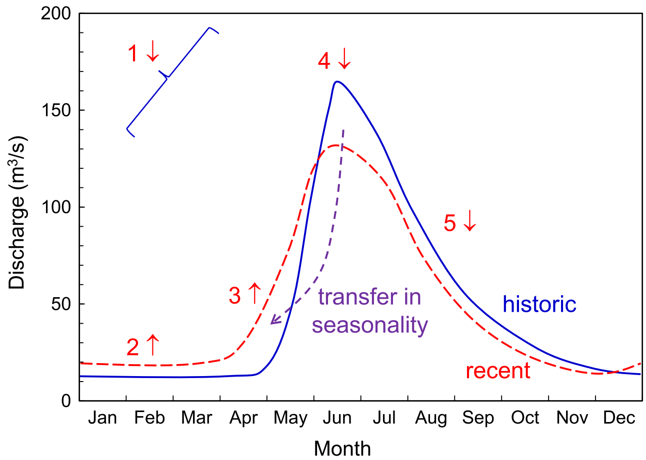

Fig. 5. The prospective hydrological mechanism for flood moderation with climate change, with scaling based on the Bow River at Banff, Alberta (#5). The numbers represent the relevant changes: (1) declining overall annual flows over the past century; (2) with winter warming there is an increase in the proportion of rain versus snow and this increases winter river flows and decreases snow packs; (3) with spring warming there is an advancement in the period of snowmelt, (4) the timing of peak flows is relatively unchanged and there is consequently a longer interval after snowmelt commences. These (3 & 4) reduce the snowmelt contribution to the peak and also reduce the extent of watershed saturation, decreasing runoff from rain. The consequence of (1) through (4) is the reduction in annual peak flows and there is also the subsequent decline in summer flows (5).

interval has become progressively earlier (Fig. 5, '3'), becoming two to four weeks earlier for some regional rivers (Whitfield, 2001; Regonda et al., 2005; Rood et al., 2008; Cunderlik and Ouarda, 2009). Daylength and solar insolation are not altered by climate change, and with the shorter days and less intense sunshine in early spring, the earlier snow melt would be slower, producing a more gradual rise of the spring peak, as we observed (Rood et al., 2008, Fig. 5 '3'). While the period of major snow melt is commencing earlier (Rood et al., 2008), in this study we observed that the timing of the flow peaks was relatively unchanged. There would consequently be a longer snow melt interval prior to the annual peak, leaving less snow melt to contribute to that peak (Fig. 5, '4').

In this region, major river flow peaks and especially flood flows result from the combination of snow melt and heavy rain on a saturated watershed (Shook, 2015). The hydrological alterations accompanying climate change would reduce two of these three factors, with less snow melt contribution due to the transfer in flow seasonality (Fig. 5, following '2' and '3'), and lower watershed saturation (Fig. 5, '1') that would increase infiltration with a heavy rain event. These changes would contribute toward the decline in peak flows (Fig. 5, '4'), which we observed in this study. Following the reduced peak flows, there subsequently be lower summer flows (Fig. 5, '5'), as we previously reported (Rood et al., 2008).

Finally, these analyses emphasize annual flow peaks but there could be somewhat different patterns for extreme flood events (Merz et al., 2012; Shook, 2015). As displayed for the Castle and Waterton rivers (Fig. 3), the historic series apparently includes two separate distributions of peak flows. Modest peaks occur most years providing the common contribution to the peak flow record. Occasional, extreme flows are much higher than would be anticipated from a single, normal distribution, suggesting different hydroclimatic influences. The extreme floods might thus follow from a rare combination of weather events (Shook, 2015) and as these events are more fully investigated, there could be a better understanding of the influences from climate change on extreme floods. Thus, while our study demonstrates that annual flow peaks are declining along some Rocky Mountain rivers, an understanding of the possible pattern for extreme floods will require a longer time series.

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