Temporal trends in annual water yields from the Mackenzie, Saskatchewan-Nelson, Churchill, and Missouri-Mississippi River watersheds in western and northern Canada.

Sierra Rayne [a] *, Kaya Forest [b]

Abstract

Keywords: annual water yields, western and northern Canada, temporal trends, hydrometric data

Historical temporal trends in annual water yields were examined at 109 hydrometric monitoring stations in the Mackenzie, Saskatchewan-Nelson, Churchill, and Missouri-Mississippi River watersheds from the western Canadian provinces of Alberta, Saskatchewan, and northeastern British Columbia, as well as the Northwest Territories and the eastern portion of the Yukon territory. Effective drainage areas range in size from 325 to 1,680,000 (mean=65,600; median=9,300) km^2, with associated hydrometric record lengths ranging between 18 and 97 (mean=41; median=38) years. Approximately three-quarters of the stations have no significant trend in average annual flow, with about equal numbers of stations exhibiting significant temporal increases or decreases in annual water yields. Southwestern Alberta and the southwestern Northwest Territories contain small clusters of stations with increasing water yield trends; clusters of decreasing water yield trends are primarily located in central and southern Alberta. The co-location of regions with clusters of both increasing and decreasing trends, or increasing/decreasing and no trends, complicates generalizing broader scale trends in annual water yields across these regions of Canada. No bias in the trend directions appears evident with either watershed size or the length of the hydrometric record.

Water yields in the prairie and northern regions of western Canada have been the subject of much prior study and are of current interest because of increasing populations and industrial/agricultural/forestry/mining activities in these regions, as well as possible effects from longer term climatic changes [1]. Previous work in these aquatic systems has shown that, over the past century, the timing of the spring freshet is typically trending earlier in the season, summer flows have generally been declining, some winter flows may be increasing, and some annual water yields may be decreasing [2–15]. In the current work, we investigated the historical temporal trends in annual water yields at 109 hydrometric monitoring stations (Table 1) in the Mackenzie, Saskatchewan-Nelson, Churchill, and Missouri-Mississippi River watersheds from the western Canadian provinces of Alberta, Saskatchewan, and northeastern British Columbia, as well as the Northwest Territories and the eastern portion of the Yukon territory (Figure 1). The majority of the hydrometric stations cover watersheds with effective drainage areas <10,000 km^2 (n=57; 52%), with smaller numbers of watersheds having effective drainage areas between 10,000 and 100,000 km^2 (n=38; 35%) and >100,000 km^2 (n=14; 13%) (Table 2).

Historical streamflow data was obtained from the online hydrometric database of Environment Canada [16]. Only years with complete monthly records and continuous recorder data were used. Previous studies have used manually recorded datasets on some of these watersheds dating back to the early 1900s, which often have seasonal and annual discontinuities in the record (particularly during the 1930s and 1940s). We view these records with

*Corresponding author: Tel/Fax: 1.250.487.0166 Email: rayne.sierra@gmail.com. [a] Ecologica Research, 301-1965 Pandosy Street, Kelowna, British Columbia, Canada, V1Y 1R9. [b] Department of Chemistry, Okanagan College, 583 Duncan Ave West, Penticton, British Columbia, Canada, V2A 8E1.

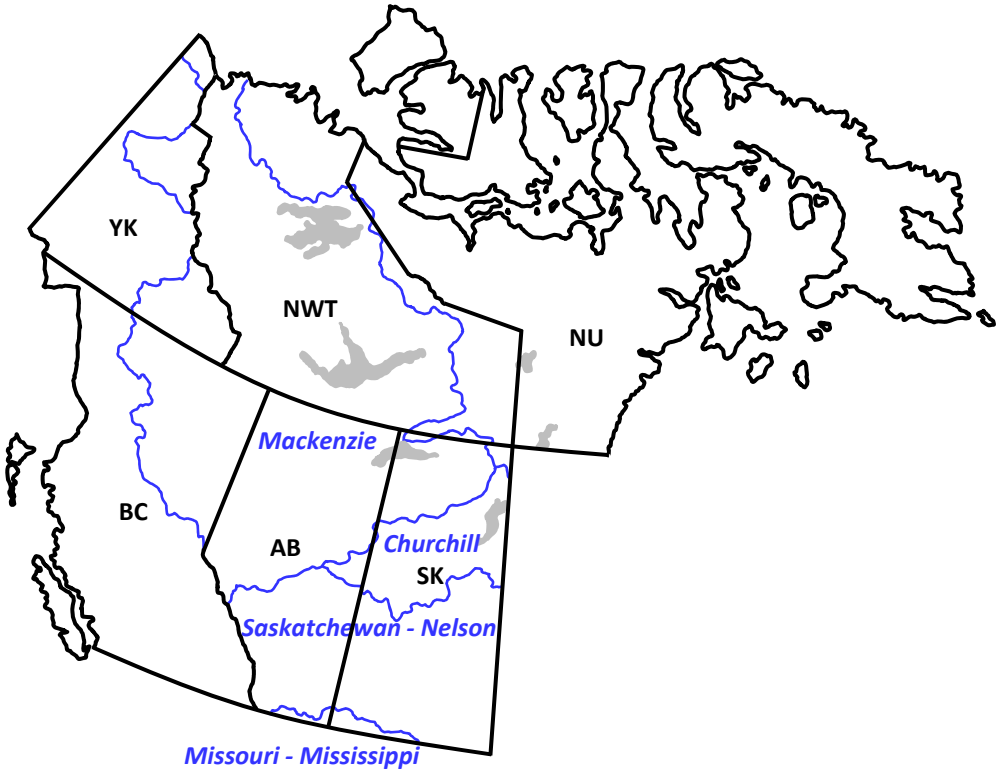

Figure 1: Map of the study area showing province and territory names (BC=British Columbia; AB=Alberta; SK=Saskatchewan; NU=Nunavut; NWT=Northwest Territories; YK=Yukon; borders as solid black lines), major lakes (light grey fill), and outlines of the major watershed boundaries (Mackenzie; Saskatchewan-Nelson, Churchill, and Missouri-Mississippi; blue solid lines).

skepticism as to their data quality, and have chosen not to include them in our analysis. Reconstruction efforts and inclusion of such historical datasets may magnify errors in trending analyses rather than reduce them. Temporal datasets of average annual flow at each station were analyzed by conventional parametric linear regression as well as by the non-parametric Mann-Kendall test for the trend and the non-parametric Sens method for the magnitude of the trend [17–21]. Summary statistics for both tests at each station are given in Table 3, and overall summary statistics for the effective drainage areas under consideration and the associated correlation coefficients (parametric linear regression) and standardized test statistics (non-parametric Mann-Kendall test) for temporal series of annual water yields are provided in Table 4. Maps showing qualitative trends at each station are shown in Figures 2 (parametric linear regression) and 3 (non-parametric Mann-Kendall test).

Table 1. Hydrometric station information for the sites under consideration.

Name	Station ID	Latitude (°N)	Longitude (°W)	Gross Drainage Area (km^2)	Effective Drainage Area (km^2)	Period of Record
Arctic Red River near the mouth [NWT]	10LA002	66°47'18"	133°4'46"	18800	n/a	1981-1993
						1995-2009
Assiniboine River at Kamsack [SK]	05MD004	51°33'53"	101°54'58"	13000	4320	1958-2009
Athabasca River at Athabasca [AB]	07BE001	54°43'19"	113°17'16"	74600	73300	1959-2009
Athabasca River at Hinton [AB]	07AD002	53°25'27"	117°34'9"	9760	9720	1962-2009
Athabasca River below McMurray [AB]	07DA001	56°46'49"	111°24'7"	133000	130000	1958
						1960-1962
						1965-1968
						1970-2009
Battle River near Ponoka [AB]	05FA001	52°39'47"	113°34'53"	1820	1550	1972-2009
Battle River near Saskatchewan Boundary [AB]	05FE004	52°51'23"	110°1'9"	25100	9860	1980-2009
Beatton River near Fort St. John [BC]	07FC001	56°16'48"	120°42'0"	15600	n/a	1970-2008
Beaver River at Cold Lake Reserve [AB]	06AD006	54°21'18"	110°13'2"	14500	11800	1970-2009
Birch River at Highway No. 7 [NWT]	10ED003	61°20'12"	122°5'12"	542	n/a	1975-1994
						1996-2009
Blindman River near Blackfalds [AB]	05CC001	52°21'14"	113°47'40"	1800	1460	1974-2009
Bow River at Calgary [AB]	05BH004	51°3'0"	114°3'5"	7870	7740	1914-1949
						1954-2009
Bow River near the mouth [AB]	05BN012	50°2'50"	111°35'27"	25300	19200	1965-2009
Cameron River below Reid Lake [NWT]	07SB010	62°29'27"	113°31'23"	3630	n/a	1976-1996
						1998-2009
Camsell River at outlet of Clut Lake [NWT]	10JA002	65°35'54"	117°45'29"	32100	n/a	1964-1996
						1998-2008
Canoe River near Beauval [SK]	06BB005	55°24'29"	108°2'25"	4730	4710	1974
						1976-2009
Chinchaga River near High Level [AB]	07OC001	58°35'49"	118°20'2"	10400	10400	1970-1978
						1981-2009
Churchill River above Otter Rapids [SK]	06CD002	55°38'47"	104°44'5"	119000	112000	1964-2009
Churchill River at Sandy Bay [SK]	06EA002	55°31'24"	102°19'6"	212000	206000	1975-2009
Clearwater River at Draper [AB]	07CD001	56°41'7"	111°15'19"	30800	30800	1958
						1960-2009
Clearwater River near Dovercourt [AB]	05DB006	52°15'7"	114°51'20"	2250	2250	1976-2009
Dillon River below Dillon Lake [SK]	06BA002	55°42'35"	109°23'8"	2330	2330	1973-1978
						1980-2009

cont'd on next page

Dore River near the mouth [SK]	06AG002	54°55'49"	107°44'37"	2960	2910	1972-1976
						1979-1988
						1990-2009
Douglas River near Cluff Lake [SK]	07MA003	58°19'20"	109°47'10"	1690	1690	1976-2009
Driftwood River near the mouth [AB]	07BK007	55°15'19"	114°13'50"	2100	2100	1971-2009
Elbow River at Bragg Creek [AB]	05BJ004	50°56'56"	114°34'15"	791	791	1978-2009
Elbow River below Glenmore Dam [AB]	05BJ001	51°0'46"	114°5'35"	1240	1240	1975-1981
						1983-2009
Flat River near the mouth [NWT]	10EA003	61°31'51"	125°24'25"	8560	n/a	1973-1996
						1999-2009
Fond du Lac River at outlet of Black Lake [SK]	07LE002	59°8'50"	105°32'20"	50700	50700	1963-1994
						1996-1997
						2001-2009
Geikie River below Wheeler River [SK]	06DA004	57°35'20"	104°12'10"	7730	7730	1967-2009
Haultain River above Norbert River [SK]	06BD001	56°14'40"	106°33'40"	3680	3680	1969
						1972-2009
Hay River near Hay River [NWT]	07OB001	60°44'41"	115°51'35"	51700	51300	1964-2009
Heart River near Nampa [AB]	07HA003	56°3'20"	117°7'47"	1970	1870	1977-2009
Highwood River near the mouth [AB]	05BL024	50°46'59"	113°49'15"	3950	3940	1971-2009
Jean-Marie River at Highway No. 1 [NWT]	10FB005	61°26'44"	121°14'27"	1310	n/a	1980-2009
Kiskatinaw River near Farmington [BC]	07FD001	55°57'25"	120°33'45"	3640	n/a	1966-2008
La Martre River below outlet of Lac La Martre [NWT]	07TA001	63°6'27"	116°58'28"	13900	n/a	1977-2009
Liard River at Fort Liard [NWT]	10ED001	60°14'35"	123°28'45"	222000	n/a	1966-1980
						1983-2009
Liard River at lower crossing [BC]	10BE001	59°24'45"	126°5'50"	104000	n/a	1972-2009
Liard River at upper crossing [YK]	10AA001	60°3'0"	128°54'0"	33400	n/a	1977-2009
Liard River near the mouth [NWT]	10ED002	61°44'49"	121°13'25"	275000	n/a	1973-2009
Little Red Deer River near the mouth [AB]	05CB001	52°1'41"	114°8'25"	2580	2440	1974-2008
Little Smoky River near Guy [AB]	07GH002	55°27'22"	117°9'42"	11100	11100	1963
						1965-2009
Lockhart River at outlet of Artillery Lake [NWT]	07RD001	62°53'39"	108°27'58"	26600	n/a	1964
						1968-1981
						1983-2009
Long Creek at western crossing of International Boundary [SK]	05NA003	49°0'1"	103°21'8"	3210	1210	1959-2007
Long Creek near Estevan [SK]	05NB001	49°6'15"	103°0'48"	4840	1490	1960-1964
						1971-2009
Macfarlane River at outlet of Davy Lake [SK]	07MB001	58°58'0"	108°10'30"	9120	9120	1968-2009
Mackenzie River at Arctic Red River [NWT]	10LC014	67°27'29"	133°44'40"	1680000	n/a	1985-2009
Mackenzie River at Fort Simpson [NWT]	10GC001	61°52'7"	121°21'25"	127000	n/a	1965-2009

cont'd on next page

Mackenzie River at Norman Wells [NWT]	10KA001	65°16'26"	126°50'39"	1590000	n/a	1966-1979
						1982-1995
						2002-2009
Martin River at Highway No. 1 [NWT]	10GC003	61°53'50"	121°36'27"	2050	n/a	1973-2009
McLeod River above Embarras River [AB]	07AF002	53°28'12"	116°37'53"	2560	2550	1973-2009
McLeod River near Rosevear [AB]	07AG007	53°41'49"	116°9'43"	7140	7080	1985-1999
						2001-2009
Medicine River near Eckville [AB]	05CC007	52°19'10"	114°20'39"	1920	1860	1975-2009
Milk River at Milk River [AB]	11AA005	49°8'36"	112°4'54"	2720	2460	1917-2009
Moberly River near Fort St. John [BC]	07FB008	56°5'35"	121°20'49"	1520	n/a	1980-2008
Moose Jaw River near Burdick [SK]	05JE006	50°24'1"	105°23'52"	9230	3470	1973-2009
Moose Mountain Creek above Alameda Reservoir [SK]	05ND010	49°31'22"	102°10'11"	4710	1940	1992-2009
Muskwa River near Fort Nelson [BC]	10CD001	58°47'18"	122°39'33"	20300	n/a	1977-2008
Nordegg River at Sunchild Road [AB]	05DD009	52°49'11"	115°31'12"	876	876	1972-2009
North Saskatchewan River at Edmonton [AB]	05DF001	53°32'13"	113°29'7"	28100	27100	1950-2009
North Saskatchewan River at Prince Albert [SK]	05GG001	53°12'12"	105°46'19"	131000	72300	1965-2009
North Saskatchewan River near Deer Creek [SK]	05EF001	53°31'23"	109°37'4"	57200	41600	1970-2009
Notikewin River at Manning [AB]	07HC001	56°55'12"	117°37'6"	4680	4660	1977-2009
Old Crow River near the mouth [YK]	09FC001	67°38'4"	139°41'47"	13900	n/a	1977-1980
						1983-1987
						1989, 1991
						1993-2009
Oldman River near Brocket [AB]	05AA024	49°33'28"	113°49'21"	4400	4380	1967-1994
						1997-2009
Oldman River near Lethbridge [AB]	05AD007	49°42'33"	112°51'46"	17000	15500	1964-2009
Peace River above Pine River [BC]	07FA004	56°11'58"	120°48'42"	87200	n/a	1980-1985
						1987-2008
Peace River at Peace Point [AB]	07KC001	59°7'5"	112°26'13"	293000	n/a	1961-2006
						2008
Peace River at Peace River [AB]	07HA001	56°14'41"	117°18'51"	194000	192000	1963-2009
Peace River near Taylor [BC]	07FD002	56°8'9"	120°40'13"	101000	n/a	1960-2008
Pembina River at Jarvie [AB]	07BC002	54°27'1"	113°59'35"	13100	12600	1962-2009
Pembina River near Entwistle [AB]	07BB002	53°36'15"	115°0'17"	4400	4330	1965-2009
Pine River at East Pine [BC]	07FB001	55°43'12"	121°12'28"	12100	n/a	1977-2008
Porcupine River near International Boundary [YK]	09FD002	67°25'27"	140°53'28"	59800	n/a	1987-2009
Qu'Appelle River below Craven Dam [SK]	05JK002	50°42'23"	104°47'52"	32900	10400	1965-2009
Qu'Appelle River below Loon Creek [SK]	05JK007	50°47'11"	104°17'21"	36500	11100	1971-2009
Qu'Appelle River near Welby [SK]	05JM001	50°29'28"	101°33'28"	50900	17100	1975-2009
Raven River near Raven [AB]	05CB004	52°5'21"	114°28'38"	645	634	1972-2009

cont'd on next page

Red Deer River at Drumheller [AB]	05CE001	51°28'2"	112°42'41"	24900	19200	1964-2009
Red Deer River at Red Deer [AB]	05CC002	52°16'34"	113°49'2"	11600	11100	1967-2009
Red Deer River below Burnt Timber Creek [AB]	05CA009	51°38'46"	115°1'9"	2250	2250	1973
						1975-2009
Red Deer River near Erwood [SK]	05LC001	52°51'36"	102°11'39"	11000	8550	1974-2009
Reindeer River above Devil Rapids [SK]	06DD002	56°11'35"	103°9'34"	63300	63300	1986-2009
Saskatchewan River below Tobin Lake [SK]	05KD003	53°42'10"	103°17'50"	289000	168000	1963-2009
Sheep River at Black Diamond [AB]	05BL014	50°41'16"	114°14'37"	592	592	1969-2009
Short Creek near Roche Percee [SK]	05NB021	49°1'52"	102°50'57"	1210	325	1960-2009
Sikanni Chief River near Fort Nelson [BC]	10CB001	57°14'3"	122°41'39"	2160	n/a	1978-2008
Slave River at Fitzgerald [AB]	07NB001	59°52'20"	111°35'0"	606000	n/a	1960-2009
Smoky River at Watino [AB]	07GJ001	55°42'52"	117°37'23"	50300	49600	1956-2009
Snare River below Ghost River [NWT]	07SA002	63°58'26"	115°25'59"	13300	n/a	1985-1998
						2000-2009
South Nahanni River above Virginia Falls [NWT]	10EB001	61°38'32"	125°48'12"	14500	n/a	1964, 1970
						1973-2009
South Saskatchewan River at Medicine Hat [AB]	05AJ001	50°2'31"	110°40'39"	56400	41400	1964-2009
South Saskatchewan River at Saskatoon [SK]	05HG001	52°8'26"	106°38'39"	141000	88100	1962-1986
						1992-2009
St. Mary River at International Boundary [AB]	05AE027	49°0'43"	113°17'58"	1210	1160	1913-2009
St. Mary River near Lethbridge [AB]	05AE006	49°34'24"	112°50'48"	3530	3310	1913-1916
						1919-1931
						1933-2009
Sturgeon River near Villeneuve [AB]	05EA005	53°39'19"	113°45'44"	1890	1550	1972-2008
Swan River near Kinuso [AB]	07BJ001	55°18'55"	115°25'1"	1900	1900	1971-2009
Swift Current Creek below Rock Creek [SK]	05HD036	49°50'40"	108°28'46"	1430	1090	1979-2009
Swift Current Creek near Leinan [SK]	05HD039	50°29'38"	107°39'31"	3730	2600	1974-2002
						2004-2009
Trout River at Highway No. 1 [NWT]	10FA002	61°8'23"	119°50'8"	9270	n/a	1970-2009
Wabasca River at Highway No. 88 [AB]	07JD002	57°52'28"	115°23'20"	35800	35800	1971-1978
						1981-2009
Wapiti River near Grande Prairie [AB]	07GE001	55°4'16"	118°48'10"	11300	11100	1972-2009
Wascana Creek near Lumsden [SK]	05JF005	50°38'10"	104°54'35"	3850	1740	1973-2009
Waskahigan River near the mouth [AB]	07GG001	54°45'7"	117°12'20"	1040	1040	1971-2009
Waterfound River below Theriau Lake [SK]	07LB002	58°23'10"	104°36'30"	3160	3160	1975-1976
						1978-2009
Wathaman River below Wathaman Lake [SK]	06DC001	57°5'20"	103°42'40"	10200	10200	1977-2009
West Prairie River near High Prairie [AB]	07BF002	55°26'53"	116°29'33"	1150	1150	1980-2009
Wheeler River below Russell Lake [SK]	06DA005	57°28'40"	104°59'50"	3030	3030	1977-2009

n/a=not available; [AB]=Alberta; [BC]=British Columbia; [NWT]=Northwest Territories; [SK]=Saskatchewan; [YK]=Yukon.

Table 2. Distribution of hydrometric stations by effective drainage area.

Effective drainage area (km^2)	Number of stations
0-4,999	48 [44.0%]
5,000-9,999	9 [8.3%]
10,000-14,999	14 [12.8%]
15,000-19,999	6 [5.5%]
20,000-24,999	1 [0.9%]
25,000-49,999	9 [8.3%]
50,000-99,999	8 [7.3%]
100,000-199,999	7 [6.4%]
200,000-499,999	4 [3.7%]
500,000-999,999	1 [0.9%]
>1,000,000	2 [1.8%]

No efforts were made to correct historical flow data for any short- through long-term natural or anthropogenic forcings. Previous studies have corrected downstream flows in the Peace River during the period between 1968-1972 to compensate for filling of the W. A. C. Bennett dam [8]. However, the hydrology of many other rivers throughout the study area has also been significantly affected with unknown magnitudes, directions, and temporal patterns of forcing during the periods of available flow records by small and medium size dam construction, changes in permafrost, forest fires, mining, and logging activities, alterations in agricultural cropping methods and consumptive water use patterns, inter-basin water transfers and diversions, as well as population increases and migrations. The inability to fully account for all potential effects via reliable corrections led us to use the uncorrected hydrometric datasets for all analyses herein. Various, and sometimes poorly defined, anthropogenic activities also greatly complicate attempts to analyze seasonal flow trends at major hydrometric stations. Similarly, there are documented deficiences in the hydrometric network within the study area that cannot be readily corrected for [22].

For example, Schindler and Donahue [7] reported an apparent 84% reduction in summer flows at the South Saskatchewan River at Saskatoon station, and also fit a continuous single-exponential/quadratic decay to the summer flow data between 1912-2003. However, upstream construction of the Gardiner Dam between 1959-1967 resulted in an intentional hydrologic regime shift for the downstream regions of the South Saskatchewan River. As discussed by Pomeroy et al. [23], prior to the construction of the Gardiner Dam, the lowest mean monthly discharge on the South Saskatchewan River at Saskatoon occurred in January. The post-Gardiner dam construction monthly mean discharge of the South Saskatchewan River at Saskatoon currently peaks in January, with a second smaller peak in June. Consequently, an anthropogenic hydrologic discontinuity occurred in this system during the 1960s, preventing the logical application of continuous linear/non-linear regression fits to seasonal flow patterns. There do not appear to have been any significant changes in the summer flows in the South Saskatchewan River at Saskatoon since Gardiner Dam construction was completed, nor is their overly compelling evidence for trends in pre-dam construction summer flows. The largest influence on the decline in summer flows on the South Saskatchewan River at Saskatoon over the past century appears to be from operations at the upstream Gardiner Dam which intentionally shifted the hydrographic peak from the natural (and historical) spring/early summer freshet period to a post-dam construction (and current) mid-winter flow maximum.

Table 3. Summary best-fit parametric linear regression and non-parametric Mann-Kendall test statistics for temporal trends in regional annual water yields at each of the hydrometric stations under consideration. Annual water yields are expressed as average annual flows in $m^3\ s^{-1}$.

		parametric linear regression			non-parametric Mann-Kendall		
Name	n	p	r	m (±SE)	p	test Z	m (±% CL)
Arctic Red River near the mouth [NWT]	28	0.7	-0.08	ns	>0.05	-0.53	ns
Assiniboine River at Kamsack [SK]	52	0.06	0.27	ns	<0.05	2.08	+0.08±0.07
Athabasca River at Athabasca [AB]	51	0.09	-0.24	ns	>0.05	-1.71	ns
Athabasca River at Hinton [AB]	48	0.13	-0.22	ns	>0.05	-1.61	ns
Athabasca River below McMurray [AB]	48	0.003	-0.42	-4.0±1.3	<0.001	-3.62	-5.2±2.6
Battle River near Ponoka [AB]	38	0.2	-0.21	ns	>0.05	-1.48	ns
Battle River near Saskatchewan Boundary [AB]	30	0.18	-0.25	ns	>0.05	-1.89	ns
Beatton River near Fort St. John [BC]	39	0.99	0	ns	>0.05	-0.1	ns
Beaver River at Cold Lake Reserve [AB]	40	0.005	-0.43	-0.49±0.16	<0.01	-2.74	-0.36±0.31
Birch River at Highway No. 7 [NWT]	34	0.005	0.47	+0.06±0.02	<0.05	2.55	+0.06±0.05
Blindman River near Blackfalds [AB]	36	0.66	-0.08	ns	>0.05	-0.48	ns
Bow River at Calgary [AB]	92	0.046	-0.21	-0.12±0.06	>0.05	-1.63	ns
Bow River near the mouth [AB]	45	0.15	-0.22	ns	>0.05	-1.3	ns
Cameron River below Reid Lake [NWT]	33	0.04	0.36	+0.13±0.06	<0.05	2	+0.14±0.13
Camsell River at outlet of Clut Lake [NWT]	44	0.005	0.42	+0.75±0.25	<0.01	2.94	+0.79±0.50
Canoe River near Beauval [SK]	35	0.89	-0.02	ns	>0.05	-0.26	ns
Chinchaga River near High Level [AB]	38	0.81	-0.04	ns	>0.05	-0.35	ns
Churchill River above Otter Rapids [SK]	46	0.61	-0.08	ns	>0.05	-0.66	ns
Churchill River at Sandy Bay [SK]	35	0.93	-0.02	ns	>0.05	-1.08	ns
Clearwater River at Draper [AB]	51	0.08	-0.25	ns	>0.05	-1.75	ns
Clearwater River near Dovercourt [AB]	34	0.33	0.17	ns	>0.05	0.8	ns
Dillon River below Dillon Lake [SK]	36	0.72	-0.06	ns	>0.05	-0.4	ns
Dore River near the mouth [SK]	35	0.01	-0.43	-0.086±0.032	<0.05	-2.53	-0.089±0.058
Douglas River near Cluff Lake [SK]	34	0.54	0.11	ns	>0.05	0.27	ns
Driftwood River near the mouth [AB]	39	0.04	-0.33	-0.12±0.06	<0.01	-2.9	-0.15±0.11
Elbow River at Bragg Creek [AB]	32	0.15	0.26	ns	>0.05	1.48	ns
Elbow River below Glenmore Dam [AB]	34	0.005	0.47	+0.14±0.04	<0.01	2.79	+0.12±0.09
Flat River near the mouth [NWT]	35	0.03	0.36	+0.48±0.22	>0.05	1.9	ns
Fond du Lac River at outlet of Black Lake [SK]	43	0.24	0.18	ns	>0.05	1.23	ns
Geikie River below Wheeler River [SK]	43	0.43	-0.12	ns	>0.05	-0.4	ns
Haultain River above Norbert River [SK]	39	0.37	0.15	ns	>0.05	0.8	ns
Hay River near Hay River [NWT]	46	0.19	0.2	ns	>0.05	1.67	ns
Heart River near Nampa [AB]	33	0.88	-0.03	ns	>0.05	-0.17	ns
Highwood River near the mouth [AB]	39	0.8	0.04	ns	>0.05	-0.34	ns

cont'd on next page

Jean-Marie River at Highway No. 1 [NWT]	30	0.001	0.57	+0.19±0.05	<0.01	2.75	+0.19±0.12
Kiskatinaw River near Farmington [BC]	43	0.39	-0.13	ns	>0.05	-1.38	ns
La Martre River below outlet of Lac La Martre [NWT]	33	<10-5	0.71	+0.79±0.14	<0.001	4.08	+0.81±0.35
Liard River at Fort Liard [NWT]	42	0.24	0.19	ns	>0.05	1.65	ns
Liard River at lower crossing [BC]	38	0.22	0.2	ns	>0.05	1.11	ns
Liard River at upper crossing [YK]	33	0.1	0.3	ns	>0.05	1.66	ns
Liard River near the mouth [NWT]	37	0.2	0.22	ns	>0.05	1.32	ns
Little Red Deer River near the mouth [AB]	35	0.01	0.41	+0.099±0.038	<0.05	2.24	+0.096±0.086
Little Smoky River near Guy [AB]	46	0.04	-0.31	-0.47±0.22	<0.05	-2.46	-0.45±0.50
Lockhart River at outlet of Artillery Lake [NWT]	42	0.49	0.11	ns	>0.05	0.8	ns
Long Creek at western crossing of International Boundary [SK]	49	0.4	-0.12	ns	>0.05	-0.44	ns
Long Creek near Estevan [SK]	44	0.06	-0.29	ns	<0.01	-3.17	-0.0025±0.0068
Macfarlane River at outlet of Davy Lake [SK]	42	0.42	0.13	ns	>0.05	0.5	ns
Mackenzie River at Arctic Red River [NWT]	23	0.22	0.27	ns	>0.05	1.64	ns
Mackenzie River at Fort Simpson [NWT]	45	0.03	0.32	+19.8±9.0	<0.05	2.38	+17.7±13.6
Mackenzie River at Norman Wells [NWT]	36	0.43	0.14	ns	>0.05	1.13	ns
Martin River at Highway No. 1 [NWT]	37	0.02	0.38	+0.15±0.06	<0.01	2.66	+0.15±0.12
McLeod River above Embarras River [AB]	37	0.36	-0.15	ns	>0.05	-0.93	ns
McLeod River near Rosevear [AB]	24	0.16	0.3	ns	>0.05	0.45	ns
Medicine River near Eckville [AB]	35	0.25	0.2	ns	>0.05	1.05	ns
Milk River at Milk River [AB]	93	0.01	0.26	+0.022±0.008	<0.05	2.37	+0.022±0.019
Moberly River near Fort St. John [BC]	29	0.43	-0.15	ns	>0.05	-0.43	ns
Moose Jaw River near Burdick [SK]	37	0.11	-0.27	ns	>0.05	-0.56	ns
Moose Mountain Creek above Alameda Reservoir [SK]	18	0.28	-0.27	ns	>0.05	-0.68	ns
Muskwa River near Fort Nelson [BC]	32	0.38	-0.16	ns	>0.05	-0.54	ns
Nordegg River at Sunchild Road [AB]	38	0.87	0.03	ns	>0.05	0	ns
North Saskatchewan River at Edmonton [AB]	60	0.02	-0.29	-0.76±0.33	<0.05	-2.32	-0.61±0.51
North Saskatchewan River at Prince Albert [SK]	45	0.09	-0.25	ns	>0.05	-1.54	ns
North Saskatchewan River near Deer Creek [SK]	40	0.54	-0.1	ns	>0.05	-0.71	ns
Notikewin River at Manning [AB]	33	0.7	-0.07	ns	>0.05	-0.57	ns
Old Crow River near the mouth [YK]	27	0.2	0.25	ns	>0.05	1.08	ns
Oldman River near Brocket [AB]	41	0.11	-0.25	ns	>0.05	-1.54	ns
Oldman River near Lethbridge [AB]	46	0.01	-0.38	-0.99±0.37	<0.05	-2.5	-1.1±0.8
Peace River above Pine River [BC]	28	0.77	0.06	ns	>0.05	0.41	ns
Peace River at Peace Point [AB]	47	0.71	-0.05	ns	>0.05	-1.56	ns
Peace River at Peace River [AB]	47	0.9	0.019	ns	>0.05	-0.45	ns
Peace River near Taylor [BC]	49	0.68	0.06	ns	>0.05	-0.11	ns
Pembina River at Jarvie [AB]	48	0.02	-0.34	-0.41±0.17	<0.05	-2.37	-0.33±0.40
Pembina River near Entwistle [AB]	45	0.12	-0.24	ns	>0.05	-1.54	ns

cont'd on next page

Pine River at East Pine [BC]	32	0.53	0.12	ns	>0.05	1.09	ns
Porcupine River near International Boundary [YK]	23	0.83	-0.05	ns	>0.05	-0.69	ns
Qu'Appelle River below Craven Dam [SK]	45	0.58	0.08	ns	>0.05	1.93	ns
Qu'Appelle River below Loon Creek [SK]	39	0.91	-0.02	ns	>0.05	0.9	ns
Qu'Appelle River near Welby [SK]	35	0.81	0.04	ns	>0.05	1.14	ns
Raven River near Raven [AB]	38	0.1	0.27	ns	>0.05	1.03	ns
Red Deer River at Drumheller [AB]	46	0.6	-0.08	ns	>0.05	-0.32	ns
Red Deer River at Red Deer [AB]	43	0.26	0.18	ns	>0.05	0.75	ns
Red Deer River below Burnt Timber Creek [AB]	36	0.39	0.15	ns	>0.05	0.56	ns
Red Deer River near Erwood [SK]	36	0.32	0.17	ns	>0.05	-0.12	ns
Reindeer River above Devil Rapids [SK]	24	0.69	0.08	ns	>0.05	-0.17	ns
Saskatchewan River below Tobin Lake [SK]	47	0.24	-0.18	ns	>0.05	-1.14	ns
Sheep River at Black Diamond [AB]	41	0.52	0.1	ns	>0.05	0.42	ns
Short Creek near Roche Percee [SK]	50	0.55	-0.09	ns	>0.05	0	ns
Sikanni Chief River near Fort Nelson [BC]	31	0.36	0.17	ns	>0.05	1.5	ns
Slave River at Fitzgerald [AB]	50	0.3	-0.15	ns	>0.05	-1.47	ns
Smoky River at Watino [AB]	54	0.02	-0.33	-1.8±0.7	<0.05	-2.19	-1.7±1.4
Snare River below Ghost River [NWT]	24	0.77	-0.06	ns	>0.05	-0.42	ns
South Nahanni River above Virginia Falls [NWT]	39	0.56	0.1	ns	>0.05	0.46	ns
South Saskatchewan River at Medicine Hat [AB]	46	0.06	-0.28	ns	<0.05	-2.01	-1.4±1.3
South Saskatchewan River at Saskatoon [SK]	43	0.25	-0.18	ns	>0.05	-1.55	ns
St. Mary River at International Boundary [AB]	97	0.005	-0.28	-0.063±0.022	<0.01	-2.7	-0.065±0.046
St. Mary River near Lethbridge [AB]	94	0.0002	-0.37	-0.13±0.03	<0.001	-3.59	-0.11±0.06
Sturgeon River near Villeneuve [AB]	37	0.01	-0.41	-0.077±0.029	<0.01	-3.2	-0.057±0.032
Swan River near Kinuso [AB]	39	0.02	-0.36	-0.16±0.07	<0.05	-2.35	-0.18±0.13
Swift Current Creek below Rock Creek [SK]	31	0.67	0.08	ns	>0.05	0.58	ns
Swift Current Creek near Leinan [SK]	35	0.95	-0.01	ns	>0.05	-0.77	ns
Trout River at Highway No. 1 [NWT]	40	0.004	0.44	+0.69±0.23	<0.05	2.37	+0.63±0.56
Wabasca River at Highway No. 88 [AB]	37	0.04	-0.35	-1.6±0.7	<0.05	-2.37	-1.8±1.2
Wapiti River near Grande Prairie [AB]	38	0.1	-0.27	ns	>0.05	-1.48	ns
Wascana Creek near Lumsden [SK]	37	0.3	-0.18	ns	>0.05	0.35	ns
Waskahigan River near the mouth [AB]	39	0.06	-0.3	ns	<0.05	-2.2	-0.062±0.054
Waterfound River below Theriau Lake [SK]	34	0.76	-0.05	ns	>0.05	-0.42	ns
Wathaman River below Wathaman Lake [SK]	33	0.67	-0.07	ns	>0.05	-0.33	ns
West Prairie River near High Prairie [AB]	30	0.85	-0.04	ns	>0.05	-0.68	ns
Wheeler River below Russell Lake [SK]	33	0.02	-0.42	-0.14±0.06	>0.05	-1.41	ns

n=number of annual records; p=p-value; r=correlation coefficient; m=slope; SE=standard error; Z=standardized test statistic;
ns=not significant at α=0.05; [AB]=Alberta; [BC]=British Columbia; [NWT]=Northwest Territories; [SK]=Saskatchewan; [YK]=Yukon.

In light of these types of issues, seasonal temporal trend analyses of the river systems considered herein must be undertaken with caution, and continuous fitting analyses for such effects cannot be reliably applied with confidence across hydrologic discontinuities. Owing to the uncertainty of existence/absence and magnitude/direction of such effects across much of the study area, our current analyses focus only on annual water yields. Choosing the length of streamflow records (and attempting any quantitative reconstruction efforts) in an attempt to compensate for natural hydrometeorological cycles (such as the El Nino/Southern Oscillation (ENSO), the Pacific Decadal Oscillation [PDO] [9, 24, 25], the Arctic Oscillation [26], and the Pacific North American (PNA) pattern [27]) is also complicated by the difficulty in quantitatively assigning the relative magnitudes of these effects between cycle minima/maxima, as well as whether to include other shorter/longer cycles, and the possible presence of as yet - and potentially confounding - unknown hydrometeorological cycles.

Of the 109 stations, 12 (11%) exhibit a statistically significant (α=0.05) increasing average annual flow trend with both regression approaches (Table 5). Using the Mann-Kendall test, 17 (16%) of the stations display a significant decreasing trend, compared to 16 (15%) stations with parametric linear regression. Approximately three-quarters of the stations (parametric: n=81 [74%]; Mann-Kendall: n=80 [73%]) have no significant trend in average annual flow. Where both statistical tests identified a trend for a station (n=25), excellent agreement in the magnitude of the trends was obtained. The average difference in trend magnitude between the parametric linear regression approach and the non-parametric Mann-Kendall test was 10.9%, ranging from 0.0% to 30.6%.

Summing the effective drainage areas of all stations predicted to have significantly increasing and decreasing average annual flows, and normalizing against the sum of effective drainage areas for all stations, results in 2.9%/2.8% (parametric/Mann-Kendall) of the summative effective drainage areas estimated to have increasing flow trends, and 4.4%/4.9% (parametric/Mann-Kendall) estimated to have decreasing flow trends. Southwestern Alberta and the southwestern Northwest Territories contain small clusters of stations with increasing water yield trends using both regression approaches. Similarly, both methods identify clusters of decreasing water yield trends primarily located in central and southern Alberta. The co-location of regions with clusters of both increasing and decreasing trends, or increasing/decreasing and no trends, complicates generalizing broader scale trends in annual water yields across these regions of Canada. This is particularly evident in the major rivers, where upstream and downstream locations may show conflicting or ambiguous trends.

No significant relationships ($p>0.05$) between the correlation coefficient (parametric linear regression) or standardized test statistic (non-parametric Mann-Kendall test) were observed against the effective drainage area (Figure 4). Together with the information in Table 5, this suggests no bias in the trend direction with watershed size. Of the nine largest drainage areas examined (Mackenzie River at Arctic Red River [NWT]; Mackenzie River at Norman Wells [NWT]; Slave River at Fitzgerald [AB]; Peace River at Peace Point [AB]; Liard River near the mouth [NWT]; Liard River at Fort Liard [NWT]; Churchill River at Sandy Bay [SK]; Peace River at Peace River [AB]; and Saskatchewan River below Tobin Lake [SK]), none have significant annual water yield trends. At the furthest downstream hydrometric stations considered in the Mackenzie (Mackenzie River at Arctic Red River [NWT]), Saskatchewan-Nelson (Saskatchewan River below Tobin Lake [SK]), and Churchill (Churchill River at Sandy Bay [SK]) river basins - which integrate all upstream natural process and anthropogenic activities - no significant trends in annual water yields are evident. In addition, we found no significant relationships ($p>0.05$) between the correlation coefficient (parametric linear regression) or standardized test statistic (non-parametric Mann-Kendall test) against the length of the hydrometric record (Figure 5), suggesting the absence of general record length biases for or against increasing/declining annual water yield trends.

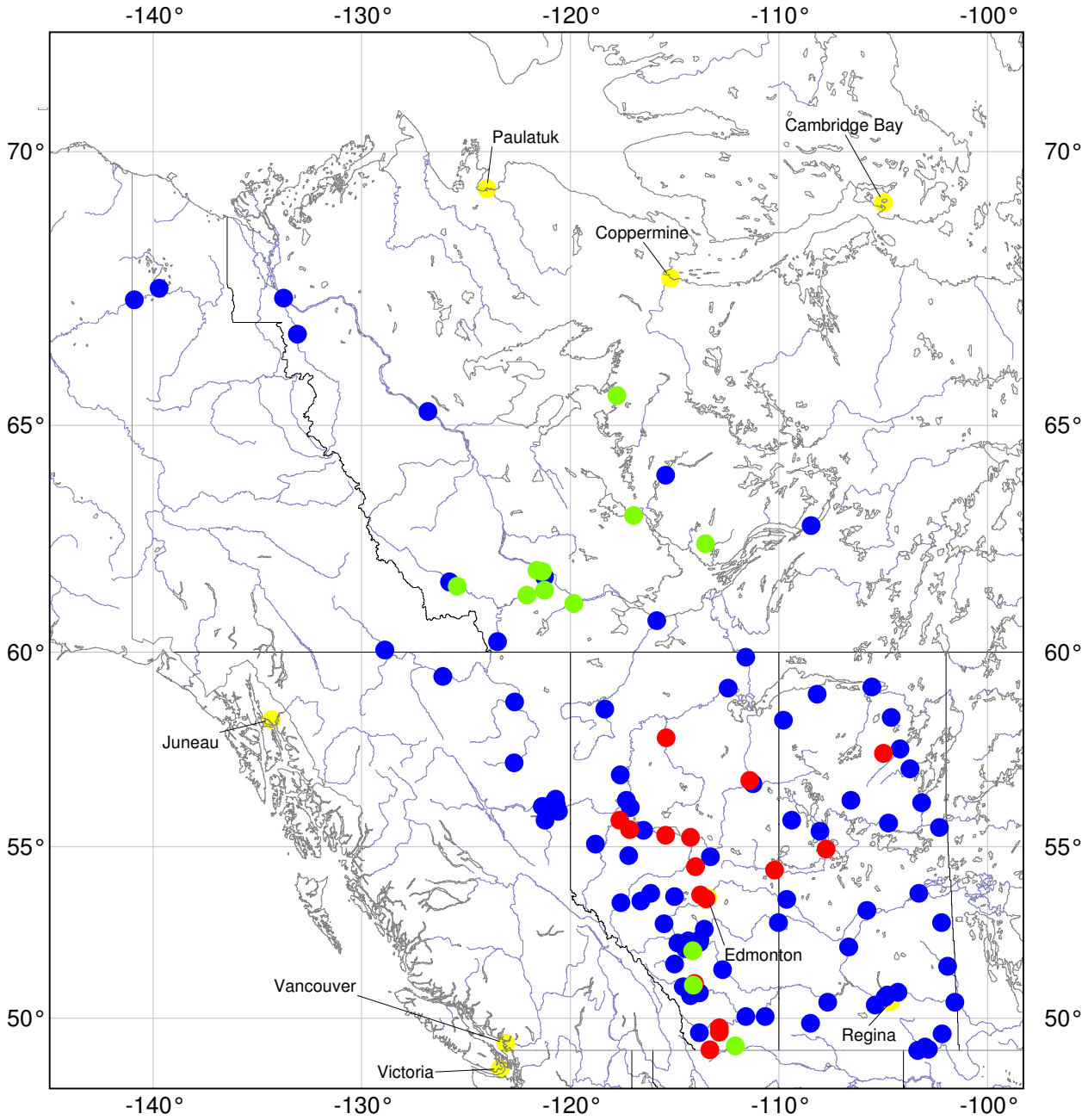

Figure 2: Map of the study area showing selected urban centers (yellow circles) and flow trends at each station using parametric linear regression: no change (blue circles); increasing (green circles); and decreasing (red circles).

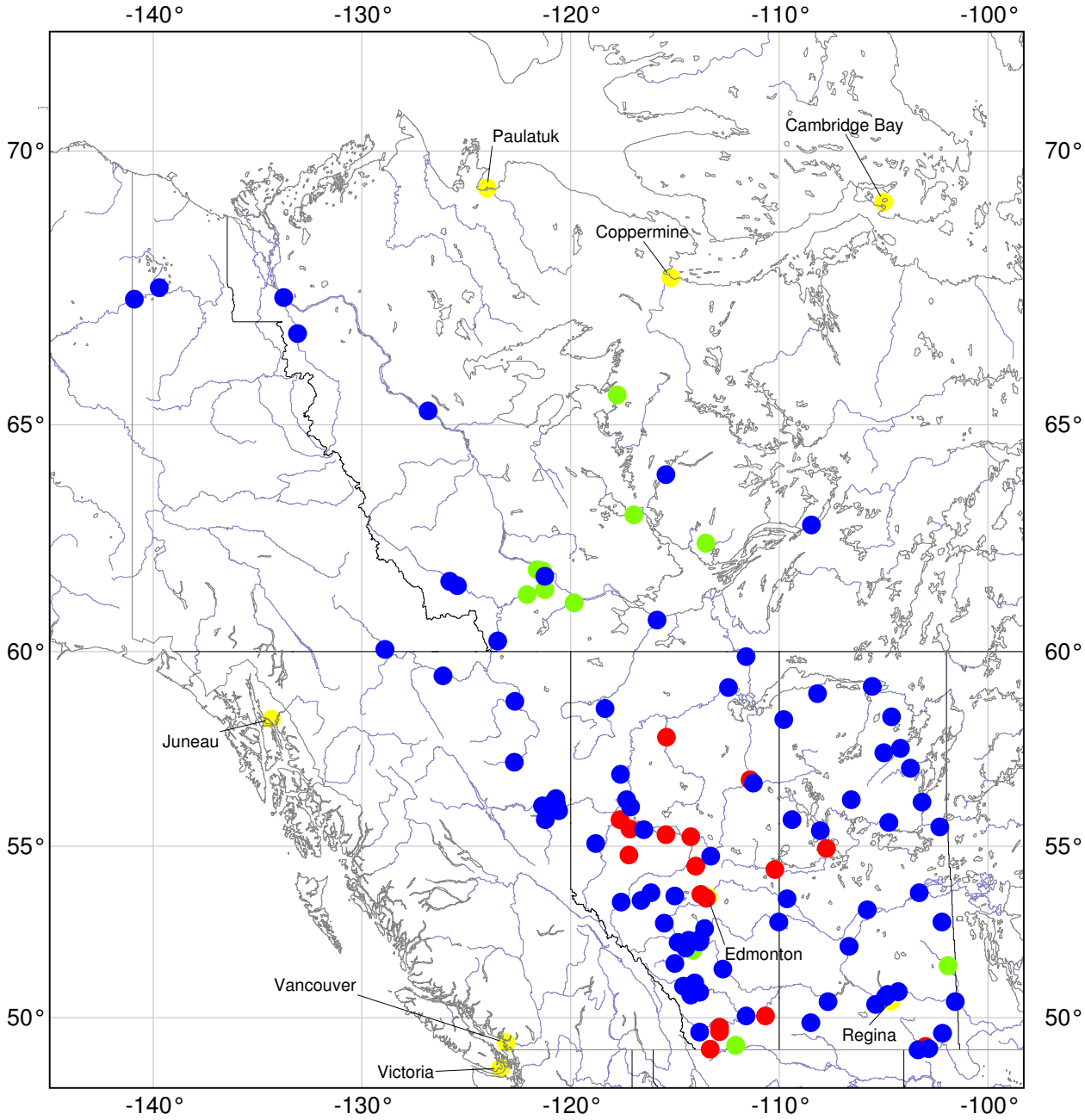

Figure 3: Map of the study area showing selected urban centers (yellow circles) and flow trends at each station using the non-parametric Mann-Kendall test: no change (blue circles); increasing (green circles); and decreasing (red circles).

Table 4. Summary statistics for the effective drainage area, the correlation coefficient (parametric linear regression), and standardized test statistic (non-parametric Mann-Kendall test) for temporal series of annual water yields at the hydrometric stations under study.

parameter	Effective drainage area (km^2)	r	Z
mean	65600	-0.01	-0.21
standard deviation	230000	0.25	1.64
minimum	325	-0.43	-3.62
maximum	1680000	0.71	4.08
median	9300	-0.04	-0.35

Table 5. Summary of annual water yield trends by effective drainage area size.

Effective drainage	parametric linear regression			non-parametric Mann-Kendall		
area (km^2)	no change	increasing	decreasing	no change	increasing	decreasing
0-4,999	34 (72%)	7 (14%)	7 (14%)	32 (66%)	8 (17%)	8 (17%)
5,000-9,999	6 (67%)	2 (22%)	1 (11%)	8 (89%)	1 (11%)	-
10,000-14,999	10 (71%)	1 (7%)	3 (21%)	10 (71%)	1 (7%)	3 (21%)
15,000-19,999	5 (83%)	-	1 (17%)	5 (83%)	-	1 (17%)
20,000-24,999	1 (100%)	-	-	1 (100%)	-	-
25,000-49,999	5 (56%)	1 (11%)	3 (33%)	4 (44%)	1 (11%)	4 (44%)
50,000-99,999	8 (100%)	-	-	8 (100%)	-	-
100,000-199,999	5 (72%)	1 (14%)	1 (14%)	5 (72%)	1 (14%)	1 (14%)
200,000-499,999	4 (100%)	-	-	4 (100%)	-	-
500,000-999,999	1 (100%)	-	-	1 (100%)	-	-
>1,000,000	2 (100%)	-	-	2 (100%)	-	-
total	81 (74%)	12 (11%)	16 (15%)	80 (73%)	12 (11%)	17 (16%)

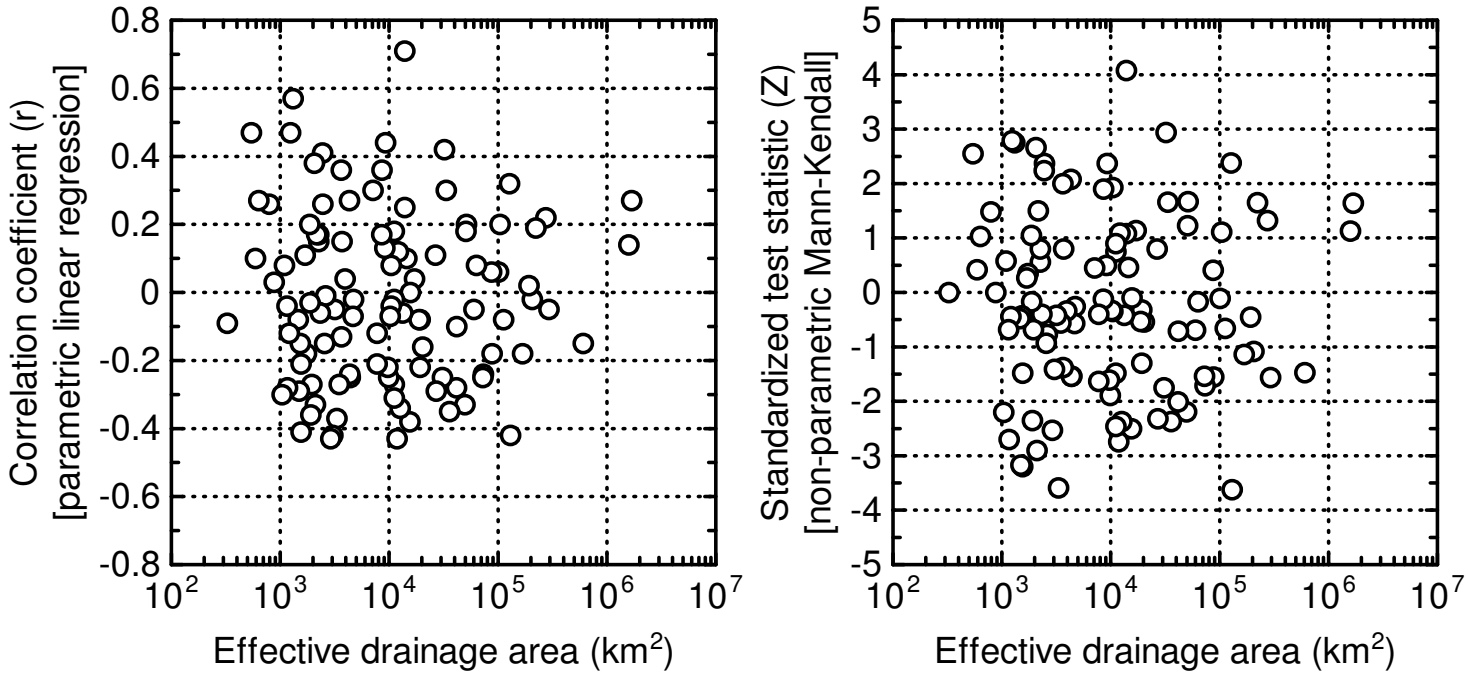

Figure 4: Relationships between the correlation coefficient (parametric linear regression) or standardized test statistic (non-parametric Mann-Kendall test) and the effective drainage area for temporal series of annual water yields at the hydrometric stations under study.

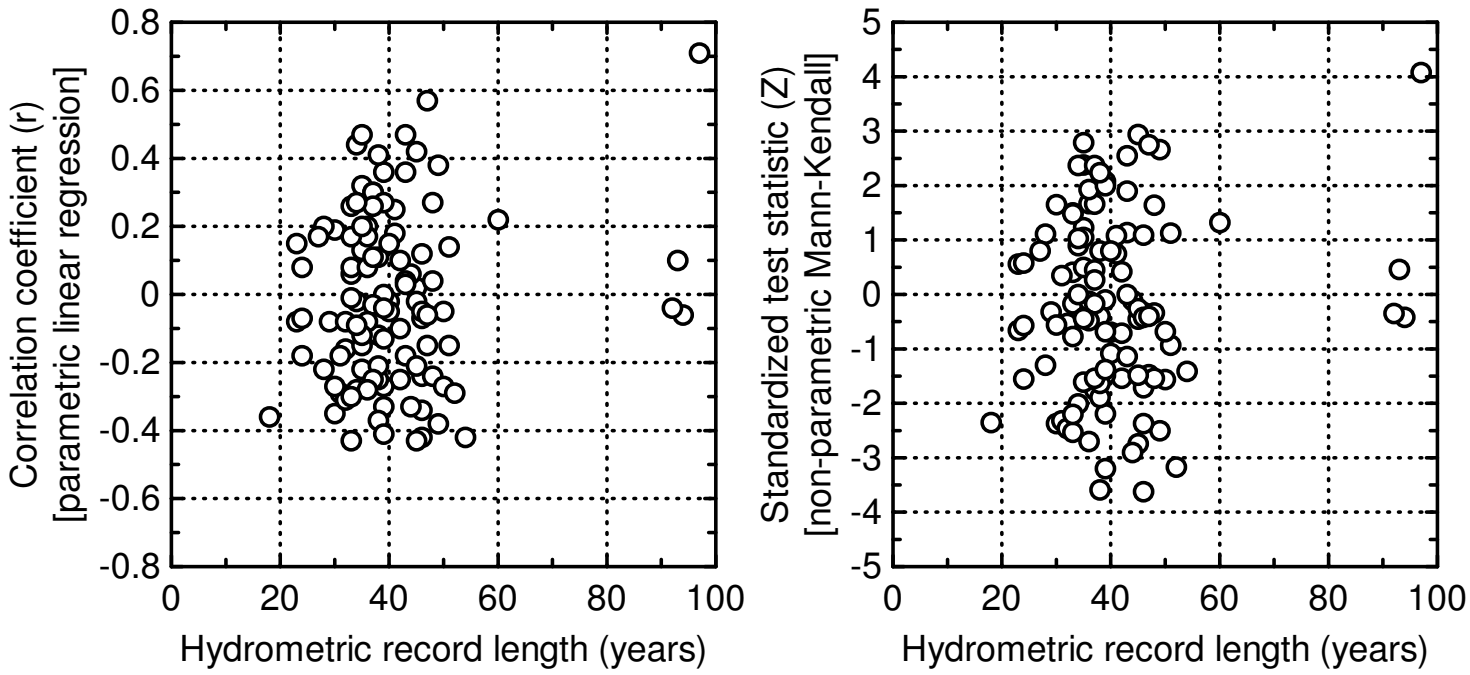

Figure 5: Relationships between the correlation coefficient (parametric linear regression) or standardized test statistic (non-parametric Mann-Kendall test) and the hydrometric record length for temporal series of annual water yields at the hydrometric stations under study.

References

[1] Dewar, H., Soulard, F., *Human Activity and the Environment: Freshwater Supply and Demand in Canada - 2010*, Statistics Canada: Ottawa, ON, Canada, 2010.

[2] Cohen, S.J., "Possible impacts of climatic warming scenarios on water resources in the Saskatchewan River sub-basin, Canada", *Climatic Change*, 19, 1991, 291-317.

[3] Burn, D.H., "Hydrologic effects of climatic change in west-central Canada," *Journal of Hydrology*, 160, 1994, 53-70.

[4] Gan, T.Y., "Hydroclimatic trends and possible climatic warming in the Canadian Prairies," *Water Resources Research*, 101, 1998, 3009-3015.

[5] Gan, T.Y., "Reducing vulnerability of water resources of Canadian prairies to potential droughts and possible climatic warming," *Water Resources Management*, 14, 2000, 111-135.

[6] Zhang, X., Harvey, K.D., Hogg, W.D., Yuzyk, T.R., "Trends in Canadian streamflow," *Water Resources Research*, 37, 2001, 987-998.

[7] Schindler, D.W., Donahue, W.F., "An impending water crisis in Canada's western prairie provinces," *Proceedings of the National Academy of Sciences*, 103, 2006, 7210-7216.

[8] Dery, S.J., Wood, E.F., "Decreasing river discharge in northern Canada," *Geophysical Research Letters*, 32, 2005, L10401 (doi:10.1029/2005GL022845).

[9] Rood, S.B., Samuelson, G.M., Weber, J.K., Wyrot, K.A., "Twentieth-century decline in streamflows from the hydrographic apex of North America," *Journal of Hydrology*, 306, 2005, 215-233.

[10] Barnett, T.P., Adam, J.C., Lettenmaier, D.P., "Potential impacts of a warming climate on water availability in snow-dominated regions," *Nature*, 438, 2005, 303-309.

[11] Prowse, T.D., Beltaos, S., Gardner, J.T., Gibson, J.J., Granger, R.J., Leconte, R., Peters, D.L., Pietroniro, A., Romolo, L.A., Toth, B., "Climate change, flow regulation and land-use effects on the hydrology of the Peace-Athabasca-Slave system: Findings from the Northern Rivers Ecosystem Initiative," *Environmental Monitoring and Assessment*, 113, 2006, 167-197.

[12] Davidson, D.J., Hurley, A.M., *Running out of Steam? Oil Sands Development and Water Use in the Athabasca River-Watershed: Science and Market Based Solutions*, Munk Centre for International Studies, University of Toronto and the Environmental Research and Studies Centre, University of Alberta: Toronto, ON and Edmonton, AB, Canada, 2007.

[13] Rood, S.B., Pan, J., Gill, K.M., Franks, C.G., Samuelson, G.M., Shepherd, A., "Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests," *Journal of Hydrology*, 349, 2008, 397-410.

[14] Yadete, H., Kalinga, O., Beersing, A., Biftu, G., *Assessment of Climate Effects on Water Yield from the North Saskatchewan River Basin*, Golder Associates: Calgary, AB, Canada, 2008.

[15] St. Jacques, J.M., Sauchyn, D.J., Zhao, Y., "Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability?," *Geophysical Research Letters*, 37, 2010, L06407 (doi:10.1029/2009GL042045).

[16] Environment Canada. *Real-Time Hydrometric Data*. Available online at *http* : *//www.wateroffice.ec.gc.ca/* (accessed 30 September 2010).

[17] Mann, H.B., "Non-parametric tests against trend," *Econometrica*, 13, 1945, 245-259.

[18] Kendall, M.G., *Rank Correlation Methods*, Charles Griffin: London, UK, 1975.

[19] Salmi, T., Maatta, A., Anttila, P., Ruoho-Airola, T., Amnell, T., *Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates*, Finnish Meteorological Institute: Helsinki, Finland, 2002.

[20] Khaliq, M.N., Ouarda, T.B.M.J., Gachon, P., Sushama, L., St.-Hilaire, A., "Identification of hydrological trends in the presence of serial and cross correlations: A review of selected methods and their application to annual flow regimes of Canadian rivers," *Journal of Hydrology*, 268, 2009, 117-130.

[21] Khaliq, M.N., Ouarda, T.B.M.J., Gachon, P., "Identification of temporal trends in annual and seasonal low flows occurring in Canadian rivers: The effect of short- and long-term persistence," *Journal of Hydrology*, 369, 2009, 183-197.

[22] Mishra, A.K., Coulibaly, P. "Hydrometric network evaluation for Canadian watersheds," *Journal of Hydrology*, 380, 2010, 420-437.

[23] Pomeroy, J.W., de Boer, D., Martz, L.W., *Hydrology and Water Resources of Saskatchewan*, Centre for Hydrology, University of Saskatchewan: Saskatoon, SK, Canada, 2005.

[24] Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., "A Pacific decadal climate oscillation with impacts on salmon," *Bulletin of the American Meteorological Society*, 78, 1997, 1069-1079.

[25] Mauget, S.A., "Intra- to multidecadal climate variability over the continental United States: 1932-99," *Journal of Climate*, 16, 2003, 2215-2231.

[26] Thompson, D.W.J., Wallace, J.M., "The Arctic Oscillation signature in the wintertime geopotential height and temperature fields," *Geophysical Research Letters*, 25, 1998, 1297-1300.

[27] Wallace, J.M., Gutzler, D.S., "Teleconnections in the geopotential height field during the Northern Hemisphere winter," *Monthly Weather Review*, 109, 1981, 784-812.