ARCTIC
VOL. 67, NO. 2 (JUNE 2014) P. 238–256
http://dx.doi.org/10.14430/arctic4384

Winter Flows in the Mackenzie Drainage System

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(*Received 10 May 2013; accepted in revised form 15 November 2013*)

ABSTRACT. Winter low flow of northern rivers refers to the diminished discharge between the time of rapid flow reduction in the freeze-up period and the arrival of spring freshet, when the flow makes a quick rise. For the Mackenzie River in Canada, the duration of the winter low-flow season so defined varies considerably within the river's large basin (1.8 million km^2); therefore, to give a common time frame that enables between-basin comparison we consider 1 November to 31 March as the winter flow season. Several hydroclimatic conditions influence winter flows to varying degrees. Lengthy periods of sub-freezing temperatures inhibit rain events and prevent snowmelt, while the formation of river ice increases channel storage at the expense of discharge. Groundwater sustains baseflow, and the flow amount at most stations is related to autumnal discharge, which reflects groundwater storage status in the pre-winter season. Large reservoirs and lakes provide substantially higher winter flows than their neighboring non-lake areas. Winter flow increases downstream as more water is gathered from the expanded drainage network, but flow contribution varies: larger baseflow is delivered from uplands than from lowlands, and discharge from the Williston Lake reservoir, regulated for hydropower production, provides about half of the total winter flow of the Mackenzie. Monotonic linear trends in winter flow are detected statistically for some tributaries, but the effect of short-term flow variability and the confounding influence of managed flow should be evaluated when considering long-term tendencies and their causative factors.

Key words: low flow, groundwater, lake storage, river ice, regulated flow, reservoir, trend, Mackenzie River

RÉSUMÉ. L'étiage des rivières du Nord en hiver est lié à la réduction du débit d'eau entre le moment de l'amenuisement de l'écoulement rapide pendant la période de la prise des glaces et l'arrivée de la crue nivale printanière, lorsque le débit augmente rapidement. Dans le cas du fleuve Mackenzie, au Canada, la durée de la saison de l'étiage hivernal ainsi défini varie considérablement à la grandeur du grand bassin du fleuve (1,8 million km^2). Par conséquent, pour aboutir à une période de référence permettant de comparer divers bassins, nous considérons que la saison du débit hivernal se déroule du 1er novembre au 31 mars. Plusieurs conditions hydroclimatiques influencent le débit hivernal selon divers degrés. De longues périodes de températures sous le point de congélation empêchent la pluie et la fonte des neiges de se produire, tandis que la formation de glace fluviale augmente l'emmagasinement en cours d'eau au détriment du débit d'eau. L'eau souterraine nourrit le débit de base, et à la plupart des stations, la quantité d'écoulement est liée au débit d'eau automnal, qui résulte de l'état d'emmagasinement d'eau souterraine pendant la saison préhivernale. En présence de grands réservoirs et de grands lacs, l'écoulement hivernal est beaucoup plus important que dans les milieux environnants où il n'y a pas de lacs. L'écoulement hivernal s'intensifie en aval, au fur et à mesure que de plus grandes quantités d'eau sont recueillies à partir du réseau hydrographique, mais l'écoulement varie : les hautes terres produisent un plus grand débit de base que les basses terres, et le débit d'eau du réservoir du lac Williston, régularisé en vue de la production d'électricité, fournit environ la moitié de l'écoulement hivernal total du fleuve Mackenzie. Des tendances linéaires monotones caractérisant l'écoulement hivernal sont détectées, à l'aide de statistiques, à partir de certains affluents, mais l'effet de la variabilité de l'écoulement à court terme et l'influence confusionnelle de l'écoulement prescrit devraient être pris en compte dans la considération des tendances à long terme et de leurs facteurs causals.

Mots clés : étiage, eau souterraine, emmagasinement dans les lacs, glace fluviale, écoulement régularisé, réservoir, tendance, fleuve Mackenzie

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Low flows of major rivers have impacts on transportation, water supply for riverside communities and hydroelectric generation, water management, planning, and regulation to satisfy legislative mandates. While high water events are noted for their morphological, ecological, and socio-economic effects on the river environment (de Rham et al., 2008), low flows also exert influences on water quality and the ecology of aquatic life. Knowledge of these flow conditions provides a firm hydrological basis for debates and decisions on water resources and environmental management.

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The term "low flow" refers to river discharge that falls below some specified level, which may be a flow magnitude that is of socio-economic, environmental, or operational significance. Most rivers in high latitudes exhibit low flows during the summer and the winter seasons. This paper concerns only winter low flows, which are usually of longer duration than the summer lows, often spanning the time from rapid flow reduction in the freeze-up period to the arrival of the spring freshet, when the flow makes a quick rise.

The Mackenzie is the largest northward-flowing river in North America. It yields about 300 km^3 per year of freshwater to the Arctic Ocean, which has implications for both oceanic and atmospheric circulation (McClelland et al., 2012). Many communities have settled in the valleys of the Mackenzie and its major tributaries, and the river system facilitates movement of people and commodities.

This study aims to examine the systematic downstream change in winter low flow of the Mackenzie River Basin and the natural conditions and artificial forcing that affect the winter flow. For operational and management purposes, it is useful to quantify various aspects of low flow, and we provide details for the Mackenzie main stem and its major tributaries. Information that improves our understanding of low flow occurrences in our study area is not only valuable for assessing the impacts of economic development on the river system (e.g., oil sand development in the lower Athabasca River), but also relevant to addressing development and environmental issues of large basins in other northern regions of the world.

STUDY AREA AND DATA SUPPORT

The Mackenzie River Basin extends from 52˚ to 69˚ N and drains an area of 1.8 million km^2, about one-fifth of the total land area of Canada. It encompasses a diversity of natural environments and possesses abundant potential resources. The basin straddles several physiographic provinces: the Cordillera, the Interior Plains, the Precambrian Canadian Shield, and the Mackenzie Delta, which is outside the domain of this study (Fig. 1). Descriptions of these physical regions are provided in Woo and Thorne (2003) and in Woo et al. (2008).

Extensive wetlands and myriad lakes of different dimensions are linked to the river network and thus are integral parts of the drainage system. Notable for their size are three enormous lakes: Lake Athabasca (surface area of 7.9×10^3 km^2), Great Slave Lake (28.6×110^3 km^2), and Great Bear Lake (31.3×10^3 km^2). While natural river flow prevails in most tributaries of the Mackenzie Basin (Fig. 2), several streams have been dammed to form artificial lakes so that their discharge can be managed for hydropower generation. One large reservoir (Williston Lake, surface area $\approx 1.8 \times 10^3$ km^2) has been created in the upper Peace River, and outflow at Bennett Dam is regulated for power production (Fig. 2f).

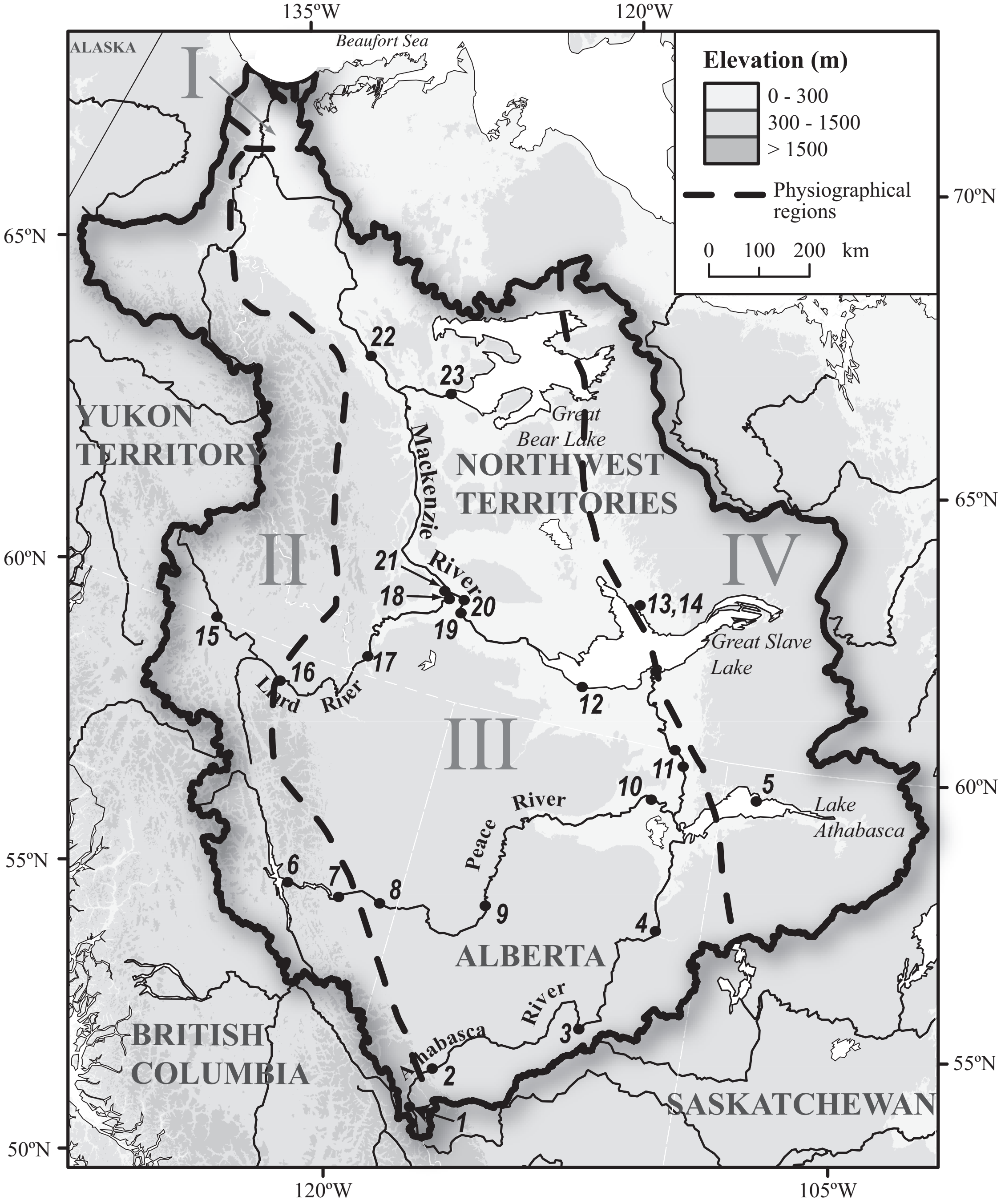
A reasonable number of climatic and hydrometric stations offer sufficiently long records for this study. Streamflow and water level data are obtained from the HYDAT database, the National Water Data Archive compiled by the Water Survey of Canada. Only river basins with areas between 10^3 and 10^6 km^2 are considered. Major rivers chosen for the study (Table 1) offer flow records from 1972 to 2011 that permit us to extract information about winter flow (1 November to 31 March) for analysis. Within this common period of study, however, there are years with missing data. Stations with more than five years of incomplete record are noted when their data are used to obtain statistical results. In addition to hydrometric data, air temperature and precipitation for a number of climatic stations are published by Environment Canada through the Meteorological Service of Canada.

To investigate possible linkage of winter flow with the effects of large-scale atmospheric variability, we make use of such climatic indices as the Southern Oscillation Index (SOI, indicative of ENSO events), the Pacific Decadal Oscillation (PDO), and Arctic Oscillation (AO). ENSO (El Niño Southern Oscillation) is a coupled ocean-atmosphere interaction that occurs across the equatorial Pacific Ocean (Fleming and Whitfield, 2010). The PDO is a low-frequency oscillation that characterizes the interannual variability in average sea surface temperature of the North Pacific (Mantua et al., 1997). The AO is an annular seesaw of atmospheric mass between polar cap regions north of 60˚ and the surrounding regions near 45˚ (Thompson et al., 2000). These various indices are obtained from the Bureau of Meteorology, the Joint Institute for the Study of the Atmosphere and Ocean, and the National Oceanic and Atmospheric Administration Climate Prediction Center. We used only the winter values (November to March) for our analysis.

For statistical analyses of flow data, conventional methods are used, including standard regression and correlation techniques and the non-parametric Spearman rank correlation and Mann-Kendall tests for trend. Computational equations for the non-parametric methods have been summarized in Woo and Thorne (2003) and Woo et al. (2006).

LOW FLOW OCCURRENCE AND DEFINITION

The seasonal discharge pattern of rivers in the Mackenzie drainage follows several major streamflow regimes, which are described in Woo and Thorne (2003). Examples of the nival (snowmelt-dominated), proglacial (glacier-fed), wetland, prolacustrine (lake-fed), and regulated regimes are shown in Figure 2. All these flow regimes contain one or more periods in each year when the discharge is much below, say, the annual median or some specified level, and is considered to be the low flow. Such flow conditions prevail during the winter for all rivers except those with prolacustrine and regulated regimes. The ASCE Task Committee (1980) pointed out that low flows "may be characterized



Hydrometric Stations

1	Athabasca River near Jasper
2	Athabasca River at Hinton
3	Athabasca River at Athabasca
4	Athabasca River below McMurray
5	Lake Athabasca near Crackingstone Point
6	Williston Lake at Lost Cabin Creek
7	Peace River at Hudson Hope
8	Peace River near Taylor
9	Peace River at Peace River
10	Peace River at Peace Point
11	Slave River at Fitzgerald
12	Hay River near Hay River
13	Great Slave Lake at Yellowknife Bay
14	Baker Creek at Outlet of Lower Martin Lake
15	Liard River at Upper Crossing
16	Liard River at Lower Crossing
17	Liard River at Fort Liard
18	Liard River near the Mouth
19	Jean-Marie River at Highway No.1
20	Mackenzie River at Strong Point
21	Mackenzie River at Fort Simpson
22	Mackenzie River at Norman Wells
23	Great Bear River at outlet of Great Bear Lake

FIG. 1. Topography and physiographic regions of Mackenzie River Basin: I – Mackenzie Delta, II – Western Cordillera, III – Interior Plains, IV – Canadian Shield. Arabic numbers indicate locations of hydrometric stations that provided streamflow records for this study.

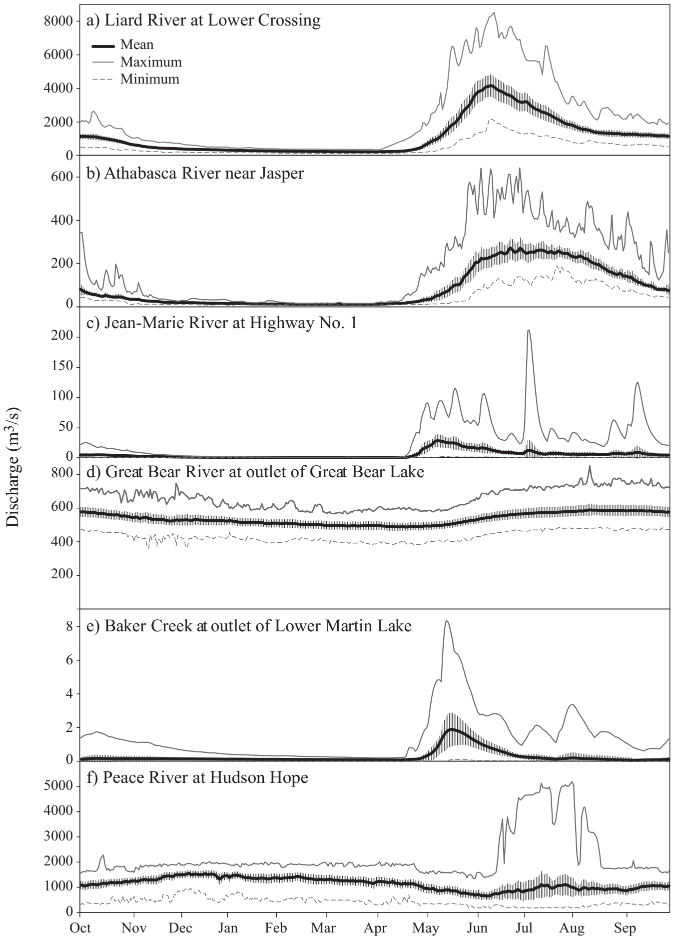


FIG. 2. Streamflow regimes manifested by rivers in the Mackenzie River Basin. Mean (± SD), maximum, and minimum daily discharges are shown for example rivers with (a) nival regime, (b) proglacial regime, (c) wetland regime, (d) prolacustrine regime with continuous flow, (e) prolacustrine regime with interrupted flows, and (f) regulated regime.

in many ways, but no one characterization is suitable for all purposes." For the present investigation, we used the timing of events as the criterion to delimit the duration of winter low flows (Fig. 3).

In order not to split up the winter period, we used water years (from 1 October to 30 September of the following year), so that Day 1 of a water year is 1 October. During the winter, northern rivers usually acquire an ice cover, and one possible way to define the winter low flow period is to associate it with the presence of an ice effect on river flow. For many rivers, this ice effect is denoted by a letter "B" next to the daily data in the HYDAT flow record. However, not all records provide a "B" remark, and for those that do not, the presence of an ice effect must be deduced from the hydrographs. The onset of the ice-covered season (the first day of freeze-up) often corresponds with a steeper drop in the recession flow. Breakup typically begins several days before ice disappears on the channel. In the majority of flow records, the breakup event is heralded by a steep rise in the hydrograph, which signals the end of the low-flow season (e.g., the Liard River shown in Fig. 4). Yet for some rivers, such as the Athabasca near Jasper (Fig. 4), the time of freeze-up and breakup cannot be deduced from the hydrograph shape. When the date of freeze-up (Day f) and the day of sharp hydrograph rise in the spring (Day r) can be delineated from the record, total flow for this period (TFi) is obtained as:

$$\mathrm{TFi} = \sum_{t\text{-}f}^{r} Q(t)\Delta t \qquad (1)$$

where Q(t) is mean discharge (in m^3 per second) on day t, and Δt is time interval (86 400 seconds) between one day and the next. TFi for the period is the sum of the mean discharge values for all days from f to r.

Whereas the low flow period for rivers with a continuous winter ice cover can be considered to begin with ice formation and to end with a steep hydrograph rise, that definition does not apply to some southern hydrometric stations that experience mid-winter thaw, which can interrupt the ice condition and raise the winter flow (Beltaos, 2002). Another complication concerns rivers that have hydrograph rise responding to snowmelt freshet alone, without the presence of ice effect, as is the case for southern rivers like the Athabasca near Jasper, where the ice can be gone before the arrival of the spring freshet. For example, in Fig. 4, the "B" remark in the flow record for the Athabasca disappeared on 2 March, but hydrograph rise did not occur until 8 May. Furthermore, different stations in the vast Mackenzie Basin have freeze-up and breakup times that vary considerably within the same water year. To permit inter-basin comparison of flow conditions, we used a fixed time interval (1 November to 31 March) as an alternative criterion to define the time when winter low flow occurs, irrespective of river ice conditions. Within this five-month period, the seasonal minimum (QMINw), mean (QMEANw), and maximum (QMAXw) discharges are extracted from the records. To place the lowest discharge of each winter in the context of the minimum flow in an entire water year, the annual minimum (QMIN) is obtained for each water year. The flow on 15 October (Qoct15) from each gauging station is used as an indicator of late summer discharge from which the flow recedes into the winter season. Total winter flow between 1 November and 31 March (TFw, in km^3) is obtained as:

$$\mathrm{TFw} = \sum_{t\,=\,1\,\mathrm{Nov}}^{31\,\mathrm{Mar}} Q(t)\Delta t \qquad (2)$$

with the mean discharge converted to daily flow by $Q(t)\Delta t$, and then summed over the November – March period.

Although we define the low-flow period as 1 November to 31 March to permit comparisons, we also examined ice-related conditions if information was available.

LOW FLOW CHARACTERISTICS

Low Flow Period

As defined above, winter flow has a fixed duration of 151 days (152 in leap years) from 1 November to 31 March. In

TABLE 1. Drainage area and total winter flow from 1 November to 31 March (TFw) at hydrometric stations in major tributary basins and along the main Mackenzie River (1972–2011 averages).

Station	Latitude (N)	Longitude (W)	Drainage area (km²)	TFw (km³)
Athabasca River				
Jasper	52°54′36″	118°3′31″	3873	0.20
Hinton	53°25′27″	117°34′09″	9765	0.53
Athabasca	54°43′19″	113°17′16″	14 602	1.52
Fort McMurray	56°46′49″	111°24′07″	132 585	2.62
Peace River				
Hudson Hope	56°01′39″	121°53′56″	73 100	18.28
Taylor	56°08′09″	120°40′13″	101 000	19.42
Peace River	56°14′41″	117°18′51″	194 374	20.94
Peace Point[1]	59°07′05″	112°26′13″	293 000	20.42
Liard River				
Upper Crossing	60°03′00″	128°54′00″	32 600	1.47
Lower Crossing	59°24′45″	126°05′50″	104 000	4.48
Fort Liard	60°14′29″	123°28′31″	222 000	5.87
Fort Simpson, near mouth	61°44′33″	123°28′31″	275 000	7.59
Great Bear River	65°07′42″	123°33′03″	146 400	
Hay River	60°44′34″	115°51′34″	51 700	0.21
Mackenzie River				
Fitzgerald (Slave River)	59°52′20″	111°35′00″	606 000	31.54
Strong Point[2]	61°48′59″	120°47′30″		36.42
Fort Simpson	61°52′06″	121°21′32″	1 270 000	42.13
Norman Wells[3]	65°16′26″	126°50′39″	1 594 500	50.04

[1] Peace Point with two years of data missing.
[2] Strong Point from 1993.
[3] Norman Wells with seven years of data missing.

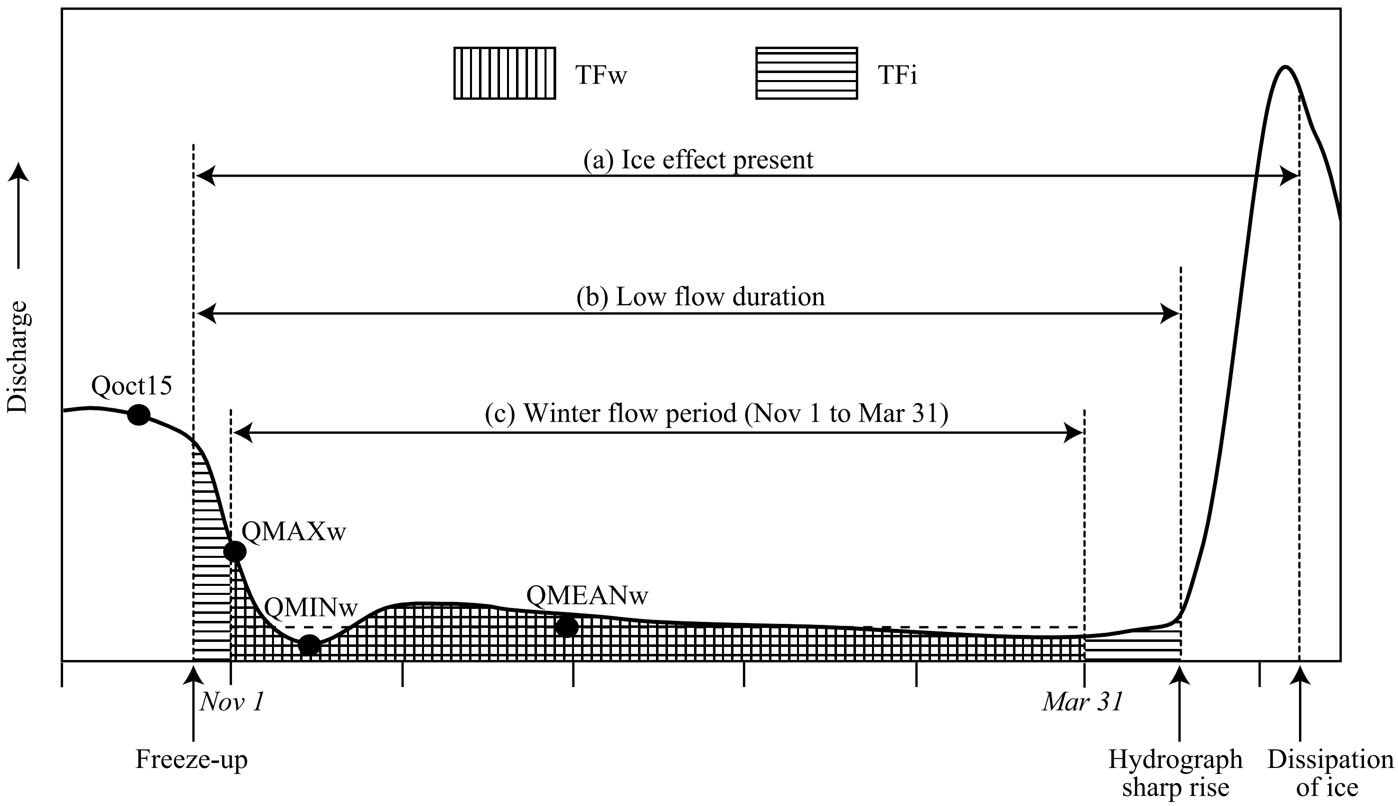


FIG. 3. Illustration of periods and variables used in this study. (a) Ice effect period: the interval between freeze-up and ice dissipation when river ice affects streamflow. (b) Low flow period (TFi): from freeze-up to the abrupt hydrographic rise in early spring. (c) Winter flow period: defined as 1 November to 31 March. Note that (a) is longer than (c), since the spring rise can occur before ice is dissipated. The fixed winter flow period is used to calculate total winter flow (TFw), as well as seasonal maximum (QMAXw), minimum (QMINw), and mean (QMEANw) discharges. Qoct15 is the flow on October 15.

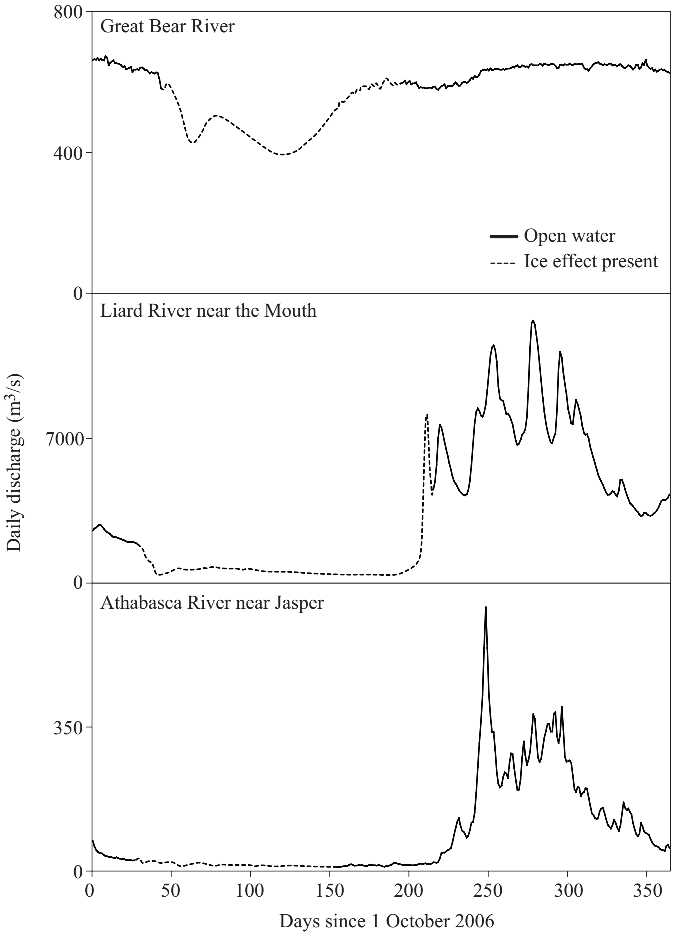


FIG. 4. Hydrographs of the Great Bear River, the Liard River near the mouth at Fort Simpson, and the Athabasca River near Jasper for 2006–07, showing differences in the length of the ice-effect period.

contrast, the interval from freeze-up to steep hydrograph rise in spring varies from station to station and from year to year. For rivers that do not receive outflow from reservoirs or large lakes, the onset of freeze-up is in early to mid-November in the southern Mackenzie Basin, but it can be delayed by two to four weeks in some years. Freeze-up is earlier by a week or more in the central basin than in the southern basin and even earlier in the northern basin. In the spring, hydrograph rise often occurs in April, starting with rivers of lowland areas, and is delayed till late April or early May at high elevations. In general, the length of time between freeze-up and spring hydrograph rise is longer than five months and is not confined to the period from 1 November to 31 March.

Total Flow

Since total flows TFw (1 November to 31 March) and TFi (freeze-up to hydrographic rise) are summed over unequal time periods, their difference varies from year to year. Table 1 lists the mean TFw for the major tributaries and along the main stem of the Mackenzie, and Figure 5 shows the probability distributions of TFw and TFi for several rivers. Note that the non-exceedance probabilities of 0.5 give us the median values of the distribution, while the lower and upper quartile values are given at 0.25 and 0.75, respectively. Greater between-year variability in flow or duration is indicated by a gentler slope of the probability distribution. In all cases, the distribution of non-exceedance for TFi differs from that for TFw, with the same flow amount having a lower probability of being exceeded in TFi than in TFw. As an example, for the low flow of the Slave River (Fig. 5), the probability that total flow would not be higher than 30 km^3 is 0.5 for TFw, but only 0.2 for TFi.

Within the Mackenzie Basin, the relationship between TFw and TFi ranges from moderate in the southwestern corner (upper Athabasca River is significant at the 95% confidence level and shows a wider scatter than all other rivers) to strong (significant at the 99% confidence level) for most other rivers. Table 2 gives the r^2 values and the regression coefficients b_0 and b_1 in the equation $TFi = b_0 + b_1\ TFw$. Note that we did not analyze this relationship for the Peace and Great Bear Rivers because their records lack the steep drops and sharp hydrograph rises that mark winter freeze-up and spring rise events (Fig. 2).

Minimum and Maximum Discharge

The lowest discharge in each water year (the annual minimum or QMIN) and within the period 1 November to 31 March (QMINw) were obtained for various stations, and examples of their probability distributions are shown in Figure 6. A comparison of the probability distributions for QMIN and QMINw shows that they are identical for most stations (e.g., Athabasca at Fort McMurray and Liard at Lower Crossing, with minor differences attributable to several annual minima occurring after 31 March but before the onset of spring). An examination of the dates of QMIN (not shown) verifies that the annual minima of all these stations fall within the period from 1 November to 31 March: that is, the lowest discharge of each year always occurs in winter. Within the winter season, QMINw usually occurs in one of two time periods: either at the time of freeze-up, when some of the flow is transformed into ice and withheld as hydraulic storage, or toward the end of winter, when the flow declines to the lowest value on the recession limb (Fig. 7 provides examples for the Liard River at Fort Simpson).

Exceptions to the above situation are the minimum flows along the Peace River, where the annual minima can be lower than the winter minima (Fig. 6c–f), suggesting that the lowest discharge may occur outside of the winter period. The difference between the distributions of QMIN and QMINw is greatest at the Peace at Hudson Hope station just below the Williston Lake reservoir. It diminishes gradually toward downstream (from Taylor to Peace Point). The dates of minimum discharge at these stations confirm that while QMINw is restricted to 1 November to 31 March (water-year days 31 to 182), the annual minimum can occur any time during the year (Fig. 6g, h). However, the likelihood that the winter minima represent the annual minima increases going downstream. We therefore surmise that the effect of artificial

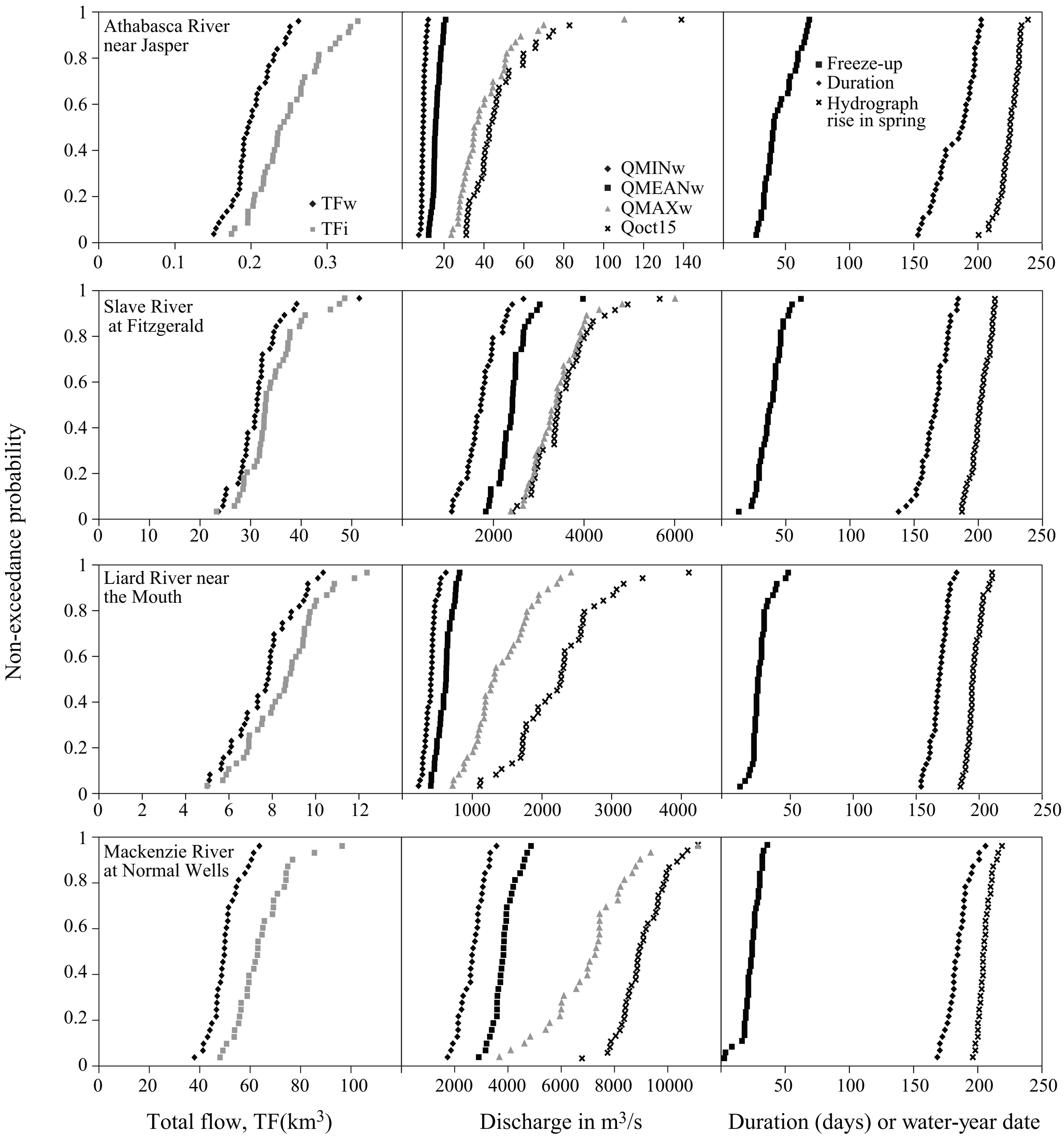


FIG. 5. Probability distributions of flow variables for the Athabasca River near Jasper, the Slave River at Fitzgerald, the mouth of the Liard River at Fort Simpson, and the Mackenzie River at Norman Wells. Column 1: Total winter flow (TFw) and total flow between freeze-up and spring hydrograph rise (TFi). Column 2: Discharge on 15 October (Qoct15) and maximum (QMAXw), minimum (QMINw), and mean (QMEANw) winter discharge from 1 November to 31 March. Column 3: Water-year dates of freeze-up and spring hydrograph rise and duration of low flow period. A water year starts on 1 October.

release of water (which raises the winter flow) is gradually diluted moving downstream by the natural rhythm of winter low flow that characterizes a nival regime river.

The probability distributions of mean (QMEANw) and minimum winter discharge (QMINw) for the 1 November–31 March period have much less variability than that of maximum discharge (QMAXw), as indicated by their interquartile ranges (difference between the highest and lowest quartile values) for the same station (Fig. 5). Whereas QMINw and QMEANw are associated with the period when the flow is relatively steady, QMAXw is usually found at the beginning of winter. It experiences greater

TABLE 2. Relationship between total winter flow from 1 November to 31 March (TFw) and total low flow from freeze-up to the time of spring hydrograph rise (TFi). Also given are values of the regression coefficients b_0 and b_1 for the equation: TFi = b_0 + b_1 TFw. Asterisks indicate statistical significance at the 0.95 (*) or 0.99 (**) confidence level.

Basins	Intercept (b_0)	Slope (b_1)	r^2	Degrees of freedom
Athabasca River				
Jasper	0.121	0.633	0.166*	37
Hinton	0.071	1.089	0.461**	37
Athabasca	0.367	0.694	0.697**	37
Fort McMurray	0.855	0.662	0.697**	37
Hay River	0.005	1.295	0.953**	36
Liard River				
Upper Crossing	0.038	1.136	0.808**	36
Lower Crossing	−0.180	1.108	0.653**	36
Fort Liard	−0.036	1.153	0.734**	34
Fort Simpson, near mouth	0.776	1.023	0.754**	37
Mackenzie River				
Fitzgerald (Slave River)	5.362	0.917	0.689**	37
Fort Simpson	−12.764	1.428	0.834**	36
Norman Wells	−8.603	1.458	0.689**	29

fluctuations from year to year, depending on conditions of the autumnal flow, for which the discharge of October 15 provides an indication. With regard to low flow considerations, QMAXw has less practical relevance than QMINw.

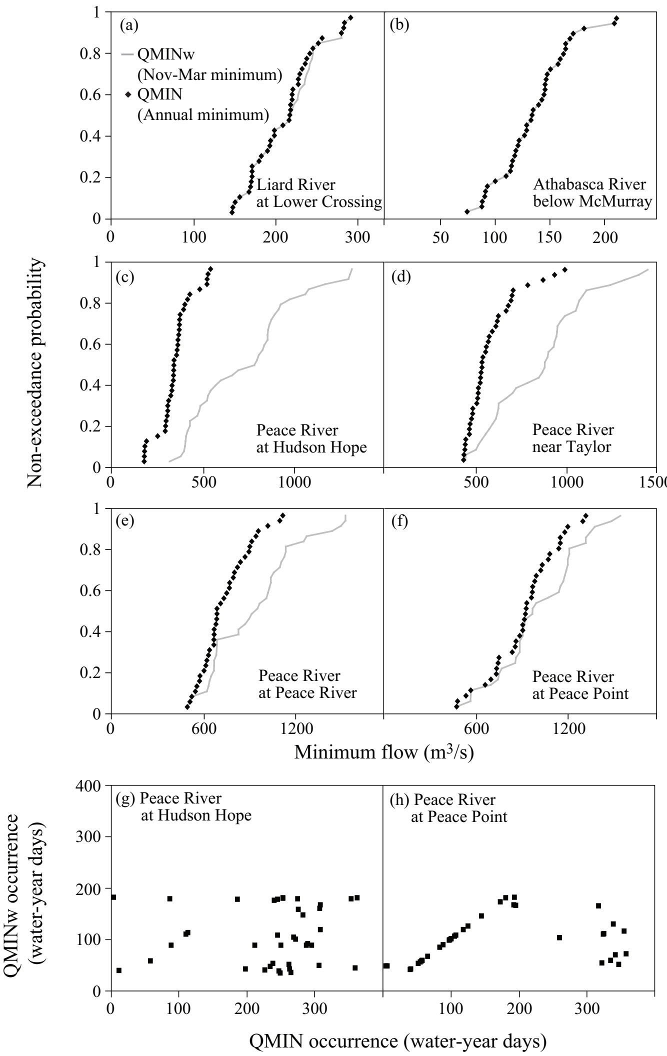


FIG. 6. Comparison of probability distributions of winter minimum (QMINw) and annual minimum (QMIN) discharges for (a) the Liard River at Lower Crossing, (b) the Athabasca River at Fort McMurray, and the Peace River at (c) Hudson Hope, (d) Taylor, (e) Peace River, and (f) Peace Point. Dates of winter minimum and annual minimum discharges for Peace River at (g) Hudson Hope and (h) Peace Point are also shown.

CONDITIONS AFFECTING LOW FLOWS

For a drainage network, a water balance framework appropriately relates streamflow to the water gains and losses along the channels:

$$Q = (M + P) - E + L + G \pm \Delta S \qquad (3)$$

Here, the flow at a hydrometric station (Q) is the result of atmospheric inputs (precipitation P and snowmelt M) and losses (evaporation E) in the river channels, influx from land sources comprising surface flow (L), and groundwater flow (G) to the channels, together with changes in water storage internal to the drainage system, which includes storage in the channels and the lakes of the drainage network. Winter release from lakes and reservoirs adds water to streamflow, producing a ΔS value greater than 0. Ice formation and its attendant effects, on the other hand, lead to a reduction in flow, causing ΔS to be negative. The impacts of lakes, reservoirs, and ice on storage change are elaborated in the sections that follow. The relative importance of each water balance component varies during the year, and so does the seasonal magnitude of river flow.

Lengthy Sub-Freezing Winters

Although the Mackenzie River Basin experiences large interannual variability in its cold season temperatures (Szeto, 2008), its winters are always long and cold. Quoting several climate stations in the basin, Table 3 gives the number of days in each year (long-term mean and standard deviation) when mean air temperature falls below 0˚C, and the mean and standard deviation of freezing degree-days (being the sum of daily air temperature below 0˚C in a year). All the stations have more than 100 days per year with sub-freezing temperatures, and stations in the northern basin, as much as six months per year. The freezing degree-days range from about 1000 in the south (e.g., Jasper) to more than 3750 in the North (e.g., Norman Wells). Such prolonged coldness significantly affects the hydrological linkages of the rivers with the atmosphere and with the land.

(1) Snow and Frozen Ground: In some areas in Canada, such as the West Coast, the Atlantic Provinces, and parts of Quebec or southern Ontario, rainfall and winter snowmelt events can interrupt the low flows (Waylen and Woo, 1987). But in the Mackenzie Basin, winter precipitation

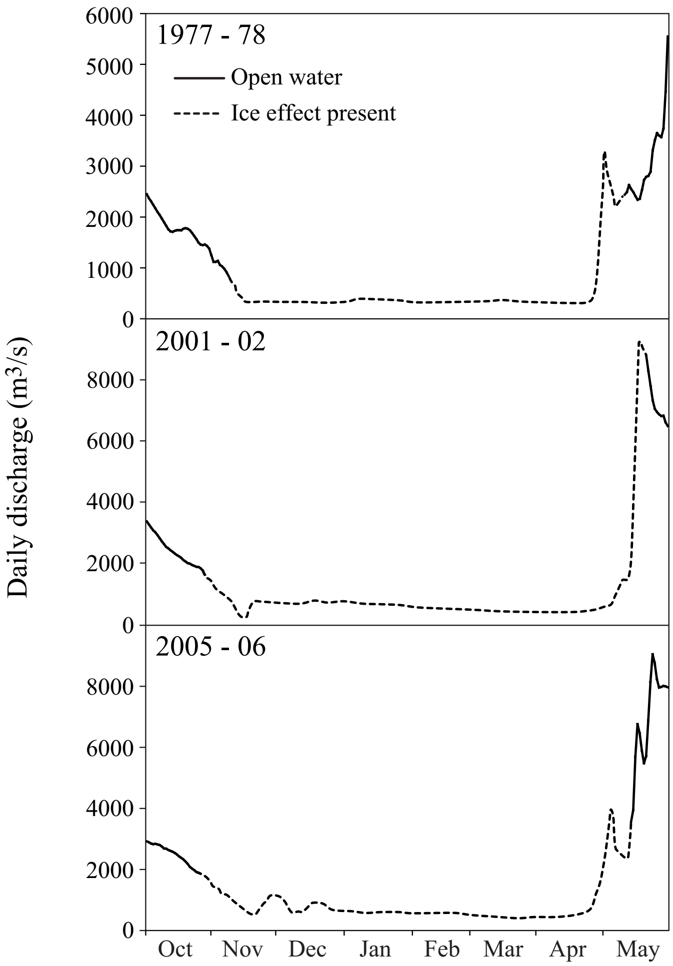


FIG. 7. Selected hydrographs of the Liard River near its mouth at Fort Simpson, illustrating features of freeze-up and hydrograph rise in spring. For this river, the initiation of breakup is always followed by a steep hydrograph rise, but freeze-up may or may not be accompanied by a sharp drop in the hydrograph. During the ice-covered season, ice-related storage can cause multiple rises and falls in the hydrograph.

usually falls as snow. Snowmelt is uncommon in the long winter, and precipitation is seldom directly responsible for winter flow. Snow in the basin and ice on river channels and lakes restrict evaporation, which is therefore of minor consequence in terms of water loss.

With intense cold, wetlands, ponds, and other shallow water bodies freeze during winter. The ground is also subject to seasonal freezing whether it is exposed or under a blanket of snow. Winter frost, together with an absence of heavy rain and snowmelt, results in cessation of surface runoff. Water from deep groundwater sources remains as the primary if not the sole external input to river channels.

(2) River Ice: River ice has two effects on winter flow: it prevents evaporation loss and the entry of rain or snow meltwater to river channels, and it modulates river flows through its storage function. In terms of water storage, the formation of ice removes water from the river to reduce its flow. River flow is further diminished through hydraulic storage. This phenomenon is induced by an increase of water storage in the river channel because the flow is constricted by ice (Gerard, 1990) and by increased flow resistance imposed by the ice that constitutes an additional segment of the wetted perimeter (Prowse and Carter, 2002). These processes can lead to a steepened decline in discharge (Fig. 7). However, if freeze-up proceeds gradually, there is no sudden accumulation of ice in the channel and such a drop is absent.

The duration of ice on rivers is dictated by the dates of freeze-up and breakup, except when occasional warm spells cause mid-winter ice-melt, but this is uncommon for the Mackenzie and its principal tributaries except in some rivers in the southern basin and those that receive outflow from large lakes and reservoirs.

The mean, standard deviation, the earliest and latest dates of freeze-up and ice dissipation (as indicated by the end of the "B" remark) at major stations in the Mackenzie Basin are provided in Figure 8. The date of freeze-up is influenced by several atmospheric and basin conditions. Winter arrives earlier in the north than in the south. For example, along the Mackenzie River, the mean freeze-up dates are 22 October at Norman Wells, 1 November at Fort Simpson, 6 November at Fitzgerald, and 3 November at Fort McMurray. Factors other than atmospheric coldness also influence the arrival of freeze-up. Despite their higher elevations, headwater river sections need not freeze earlier than the downstream reaches, where gentler gradients reduce the velocity of flow to favour more rapid cooling (e.g., the Liard at Fort Simpson near its mouth freezes about five days earlier than at Lower Crossing). Smaller rivers with low gradients also freeze up early (e.g., Hay River has a mean freeze-up date of 22 October). The release of warm water from large lakes and reservoirs carries heat that delays the freeze-up of rivers downstream. Rivers fed by outflow from a large lake, such as the Great Bear River, have a shorter ice-covered period than their non-prolacustrine counterparts (Fig. 4).

Ice breakup can be caused by rotting of the river ice due to continued warming, termed thermal breakup, or it can be related to a sudden flow influx from upstream that fractures the ice cover, termed mechanical breakup (Beltaos, 2002). Although breakup events can be due to a combination of thermal and mechanical processes, river ice breakup does not necessarily link to thawing degree-days alone. This consideration complicates the studies of trends in river breakup, since climate warming or cooling may influence thermal breakup, but its impact on mechanical breakup is far more complex. For lowland rivers, breakup takes place earlier in the south, which as a region warms up earlier than regions farther north. For mechanical breakup events, the influx of large quantities of water from the upper reaches of major rivers paves the way for breakup downstream. Along the Liard, for example, the mean dates when ice effect is dissipated are 5 May at the Lower Crossing, 7 May at Fort Liard, and 11 May at Fort Simpson. For the Athabasca drainage, the mean dates are 19 March at Jasper, 4 April at Hinton, 21 April at Athabasca, and 26 April at Fort McMurray. For the Slave River at Fitzgerald, breakup is delayed to

TABLE 3. Selected climate stations in the Mackenzie Basin, showing the number of days with sub-freezing air temperature and the number of freezing degree-days in each year (means and standard deviations for 1972–2011). Also shown are correlations (non-parametric Spearman's correlation) of winter SOI and PDO climatic indices with winter (1 November to 31 March) air temperature and precipitation. Asterisks indicate statistical significance at the 0.95 (*) or 0.99 (**) confidence level.

				Air temperature[1]		Correlation: (Spearman's r^2)			
	Latitude	Longitude	Elevation	No. of days	Freezing	Temperature and:		Precipitation and:	
Station	(N)	(W)	(m)	below 0°C	degree-days	PDO	SOI	PDO	SOI
Athabasca	54°43′00″	113°32′23″	626.3	137 ± 13	1526 ± 331	0.13*	0.10	0.00	0.10
Dawson Creek	55°44′32″	120°10′59″	654.7	133 ± 15	1599 ± 375	0.11	0.06	0.04	0.03
Fort Liard	60°14′06″	123°28′01″	215.8	166 ± 11	2547 ± 491	0.30**	0.08	0.01	0.00
Fort McMurray	56°39′00″	111°13′00″	369.1	154 ± 10	1995 ± 356	0.11*	0.04	0.00	0.00
Fort Nelson	58°50′11″	122°35′50″	381.9	163 ± 8	2334 ± 392	0.21**	0.07	0.09	0.06
Fort Simpson	61°45′37″	121°14′12″	169.2	184 ± 8	3137 ± 352	0.16*	0.06	0.09	0.10
Fort Smith	60°01′13″	111°57′43″	204.5	178 ± 10	2773 ± 408	0.07	0.04	0.00	0.00
Hay River	60°50′23″	115°46′58″	164.9	183 ± 9	2846 ± 402	0.08	0.04	0.11*	0.02
Jasper	53°14′00″	117°49′00″	1002.8	101 ± 14	908 ± 281	0.01	0.04	0.02	0.01
Muncho Lake	58°55′48″	125°46′00″	836.5	149 ± 13	1762 ± 358	0.12	0.07	0.00	0.00
Norman Wells	65°16′53″	126°47′55″	72.5	203 ± 10	3765 ± 313	0.13*	0.07	0.01	0.01
Peace River	56°13′37″	117°26′50″	570.9	150 ± 12	1767 ± 371	0.14*	0.06	0.01	0.01
Watson Lake	60°06′59″	128°49′20″	687.4	175 ± 7	2748 ± 351	0.15*	0.06	0.07	0.05
Yellowknife	62°27′47″	114°26′25″	205.7	197 ± 9	3394 ± 438	0.07	0.01	0.01	0.01

[1] Values provided are 1972–2011 mean ± standard deviation for each station.

9 May, even though the Slave receives a moderate amount of inflow from the Peace River throughout the winter.

Breakup is frequently but not always preceded by a steep hydrograph rise. Figure 7 gives several examples of a sharp rise in the hydrographs of the Liard River at the time of ice breakup. On the other hand, river ice in the upper Athabasca basin is dissipated in mid to late March, but steep hydrograph rises do not come until mid-May (Fig. 4), and these rises are probably associated with spring snowmelt rather than ice breakup. Such flow behaviour reverses the common tendency for the duration of ice cover to be longer than the interval between freeze-up and hydrograph rise.

Ice condition can be significantly modified by regulated discharge from a reservoir, as evidenced by the artificial release of water from Williston Lake that conveys heat to alter the ice regime of the Peace River. By tallying the number of days when a "B" remark (the presence of ice effect) accompanies the discharge data, we can approximate the ice season duration for each winter. With some reservation about the accuracy of the "B" information, we present the ice-effect duration for three stations along the Peace River in Figure 9a. Construction of the Williston Lake Reservoir began in 1961 and was completed in 1968. The reservoir was filled during the years 1968 to 1971. Before the reservoir came into operation, ice cover duration was similar for all three stations, but since 1970, winter release has greatly reduced the number of ice-affected days at Taylor and also shortened the ice-effect duration at the village of Peace River. The influence of reservoir release becomes much less obvious at Peace Point, as there is little evidence of having a diminished number of "B" days. The small number of "B" days at Peace Point in 2005–06 (only 78 from 1 November to 31 March) was probably the result of a warm winter (the mean December–February temperature at Fort St. John, located near the hydrometric station, was −7.6°C, while its 30-year normal is −12.3°C).

Along the Peace River, the lower course freezes earlier than sections closer to the Bennett Dam, and this pattern can change the normal tendency for discharge to increase downstream. Using the 1997–98 winter as an example (Fig. 9b), a mid-November dip in the hydrograph for Peace Point suggests that river ice formation was withdrawing water into hydraulic storage. The station at Peace River village upstream did not develop a significant ice cover (suggested by the absence of "B" remark next to the data) until mid-January. Since some water was removed into hydraulic storage in early winter, constricting the flow under the ice, less flow passed through at Peace Point than at Peace River (which had a shorter ice season), producing higher flow upstream than downstream (TFw of 25.32 at Peace River village compared to 24.56 km^3 at Peace Point).

Outflow from Large Lakes

The many lakes that constitute parts of the Mackenzie drainage network serve an important storage function. High inflows are temporarily absorbed, to be released later as outflows that enhance discharge of the rivers below the lakes. Large lakes have greater capacity for storage and can influence the seasonal flow pattern of their downstream rivers, which acquire a prolacustrine regime.

(1) Natural Flow: On small to medium size lakes (surface area < 100 km^2), ice forms in early November, but large lakes like the Great Slave and the Great Bear are not completely ice-covered until late November or December (Rouse et al., 2008). During winter, large lakes release more outflow to the rivers downstream than they receive as the inflow from their upstream tributaries. In this way,

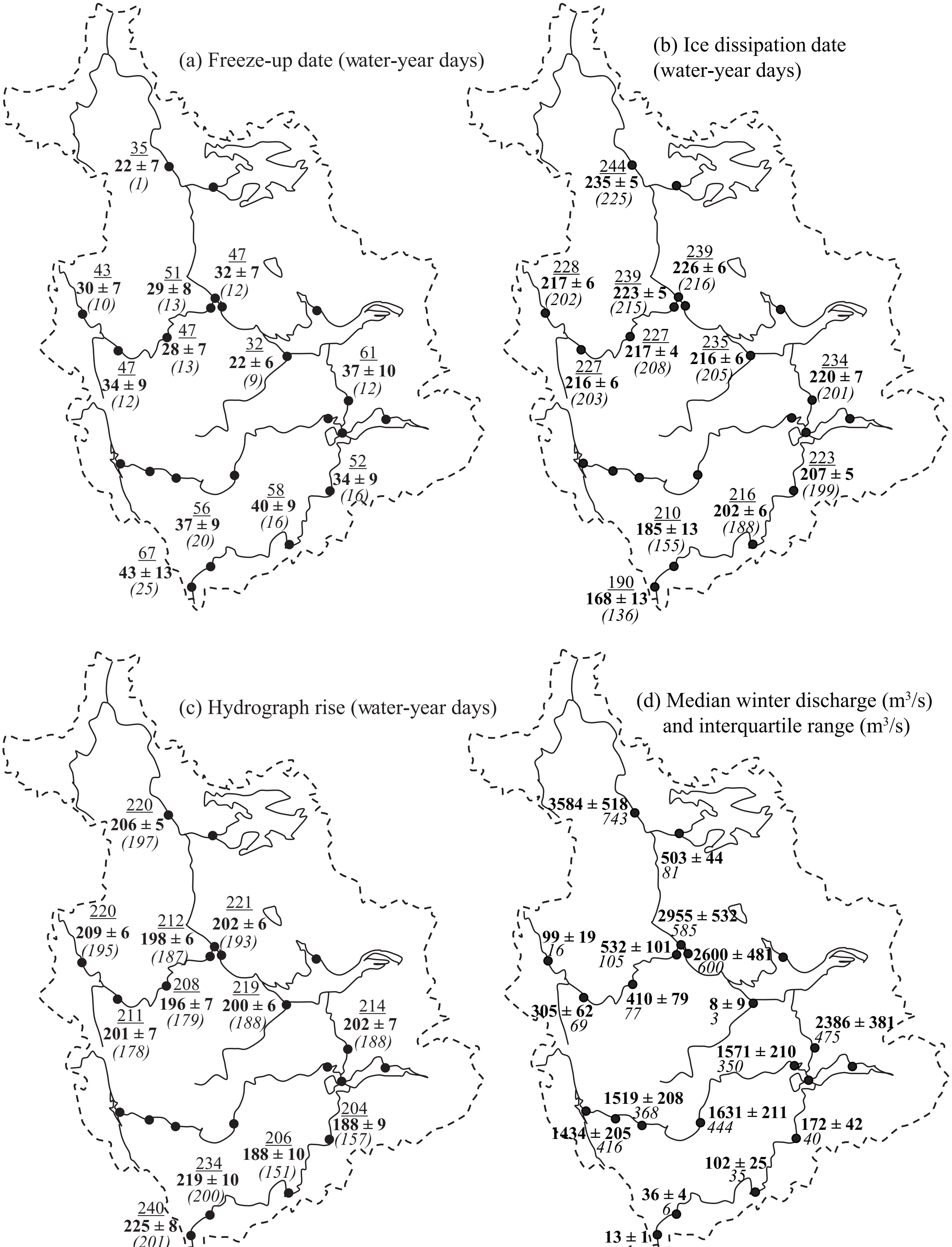


FIG. 8. Means (± SD) for (a) freeze-up date, (b) ice dissipation date, and (c) date of spring hydrograph rise (water-year days, shown in bold numbers) at selected stations in the Mackenzie drainage. Also given are the earliest (italics in parentheses) and latest (underlined) dates on record between 1972 and 2011. Part (d) shows the median (bold) and interquartile range (italics) of minimum winter discharge (QMINw), in m^3s^{-1}.

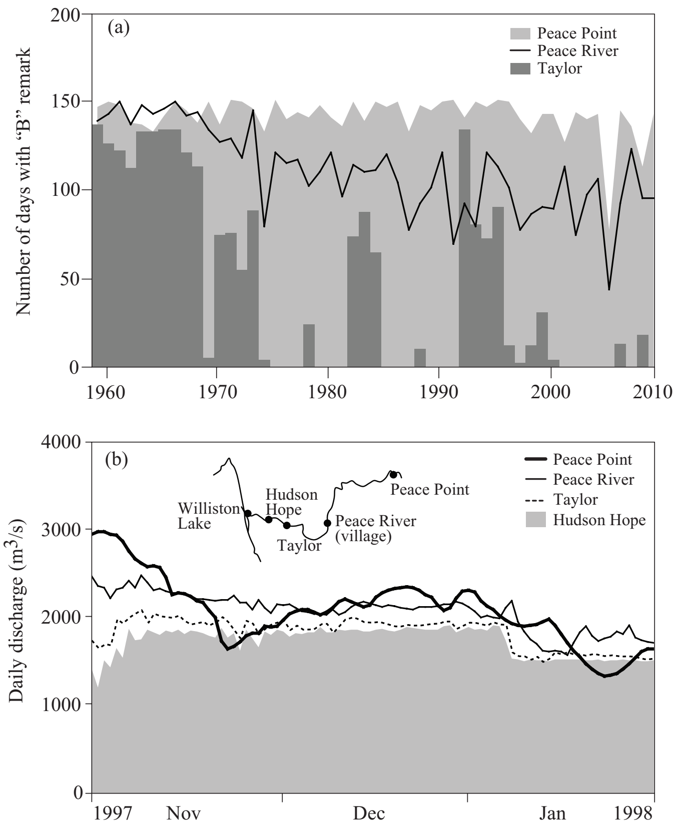


FIG. 9. (a) Three stations along the Peace River, showing the number of days in each winter when flows were affected by ice (indicated by "B" remark on the discharge record). (b) Hydrographs of the Peace River at four stations (see inset) showing mid-November freeze-up (indicated by a steep drop in discharge) at Peace Point, but not at the other stations. Sharp drops in January were likely due to reduced outflow from Williston Lake, with the reduced discharge propagating down the river from Hudson Hope to Peace Point.

lakes are a net internal exporter of water to the rivers downstream. The reverse situation occurs in the spring, when more water enters the lakes than is discharged, thus replenishing the winter drain on lake storage.

Lake outflow in winter can greatly enhance downstream discharge, as illustrated by the comparison of a basin area that contains a large lake with an adjacent area that relies principally on groundwater as the input for river flow. The Great Bear River, which drains 146 400 km^2, yields a mean winter flow of 6.6 km^3 to the Mackenzie River (based on 15 years of complete record), while 178 100 km^2 of relatively flat terrain between Fort Simpson and Norman Wells provides an average of only 1.3 km^3 (based on 31 years of data).

(2) Reservoir Discharge: Operation of reservoirs on the tributaries of large northern rivers (e.g., the Ob, Yenisei, and Lena in Siberia; Ye et al., 2003; Yang et al., 2004a, b) has notable effects on the flow of the main stem, and the Mackenzie is no exception (Peters and Prowse, 2001). The common outcome is a reduction of flow in summer and an increase of flow in winter. For the Peace River, regulated release from Williston Lake after the reservoir came into operation in 1972 has remarkably increased the winter flow below the dam, which jumped from 4.3 km^3 in 1951–69 to 18.2 km^3 in 1972–2011. Along the Peace River, discharge at Hudson Hope, not far below Bennett Dam, attains a mean winter low flow of 18.2 ± 2.7 km^3, which is particularly substantial from a drainage area of only 73 100 km^2. This magnitude contrasts with the mean natural flow of 4.3 ± 1.0 km^3 (1951–70 data) for this mountainous section of the river prior to construction of the reservoir.

Groundwater

(1) Runoff Contribution: In the absence of external water sources from the atmosphere and from surface runoff, groundwater is the chief external supply of water into the drainage network during the winter. Groundwater input, together with internal changes in storage described previously, govern the magnitude of winter low flow. The difference in flow (ΔTFw) between two adjacent hydrometric stations along a river indicates runoff contribution from within the section. The map in Figure 10a shows the winter flow contribution from areas between two neighbouring hydrometric stations (Δarea). These flow amounts are also converted into runoff (expressed in mm per unit area and obtained by ΔTFw/Δarea) in Fig. 10b.

Major tributaries of the Mackenzie traverse various physical provinces, and their low flows reflect the hydrologic influence of the regions. Under natural flow situations, but without inflow from large lakes and reservoirs, the input to Mackenzie River flow is larger for rivers in the higher and more rugged headwater zones than for those that drain the flatter plateaus, plains and rolling terrain of the Canadian Shield. Thus, the mountainous terrain of the Western Cordillera yields high winter runoff (e.g., the upper parts of the Athabasca basin down to Hinton yield more than 50 mm runoff, and the upper Liard basin to the Lower Crossing produces more than 40 mm runoff). The presence of glaciers in the upper catchment of the Athabasca River near Jasper probably has no obvious effect on winter flow because low temperatures inhibit glacier melt during the cold season. The yield is moderate from the plateaus and upland areas of subdued relief (e.g., lower Athabasca basin around Athabasca and Fort McMurray, with about 15–20 mm runoff), while flatlands that contain a large proportion of wetlands (frozen in winter) produce the lowest flow per unit area (e.g., the Mackenzie valley downstream from Fort Simpson provides 7 mm, and Hay River gives a runoff of only 4 mm). The overall pattern of groundwater contribution is similar to that of the Yukon River Basin, which rises from the mountainous regions of Yukon, is fed further by tributaries from the highlands of central Alaska, and flows through low-lying areas before entering the Bering Sea. Walvoord and Striegl (2007) found that the upland areas produce the largest proportion of groundwater, which decreases downstream in the lowlands that are also underlain by continuous permafrost.

(2) Recession Flow: Recession refers to a gradual decline in flow due to reductions in groundwater and surface runoff. For rivers in the Mackenzie Basin, discharge follows a general decline or recession that begins in late

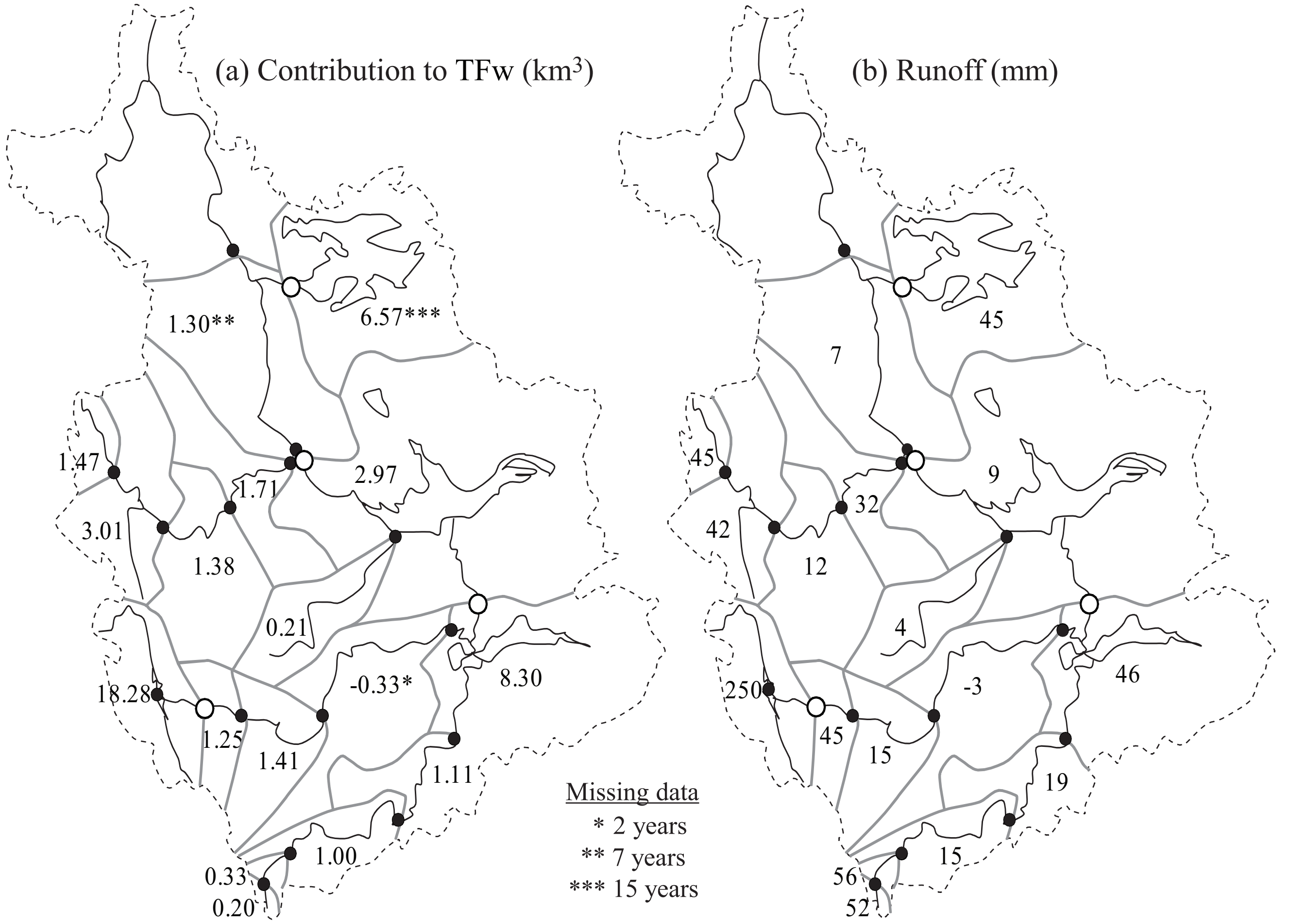


FIG. 10. Maps showing (a) the amounts of flow supplied by areas between two principal hydrometric stations and (b) spatial variation of runoff from various between-station areas. Open circles indicate stations that receive significant flow contribution from lake and reservoir releases.

autumn. The decline in winter flow is conditioned by the pre-winter groundwater storage status and by lake release, which in turn depends on lake storage.

Adopting 15 October as a common date to represent late autumn for all stations in the Mackenzie Basin, we took the discharge on this date (Qoct15) as an approximate surrogate of pre-winter storage status, used for comparison with TFw (Fig. 11). A close relationship between Qoct15 and TFw would suggest that autumnal discharge exerts influence on winter flow. Table 4 provides values of r^2 and the standard error of estimate for regression of TFw (dependent variable) and Qoct15 (independent variable):

$$TFw = a + b\ Qoct15 \qquad (4)$$

Correlation is significant for many rivers, and the corresponding standard errors are not too large. However, for the southern rivers where freeze-up occurs much later than 15 October (e.g., the Athabasca River), Qoct15 is a less satisfactory indicator of the flow condition at freeze-up, and it yields a weak correlation with the winter flow. Some of the statistical correlations are enhanced erroneously by the presence of outliers (exceptionally large winter flow in one or two years). When we remove the large flow shown on the right hand side of the graph for the Athabasca River near Jasper (Fig. 11), for instance, the r^2 value drops from 0.15 to 0.04, which is statistically insignificant. No relationship is expected for the Peace River, where winter release from the reservoir is managed. On the other hand, for rivers with a high correlation between total winter flow and the discharge on 15 October, such a simple relationship enables rudimentary forecast of winter flow when the discharge in late autumn is known.

INFLUENCE OF THE PEACE RIVER ON THE MACKENZIE SYSTEM

Winter flow of the Mackenzie drainage system varies greatly among the major tributaries. Quantification of the magnitude has application for planning and management of water resources of the Mackenzie Basin. The Peace River has a disproportionately large contribution to the winter flow of the entire Mackenzie system, as seen in Table 1, which presents the drainage areas and total winter flow recorded at stations along the Athabasca, Liard, and Peace Rivers, as well as at several stations along the Mackenzie River. Expressed as runoff per unit area, the yield of

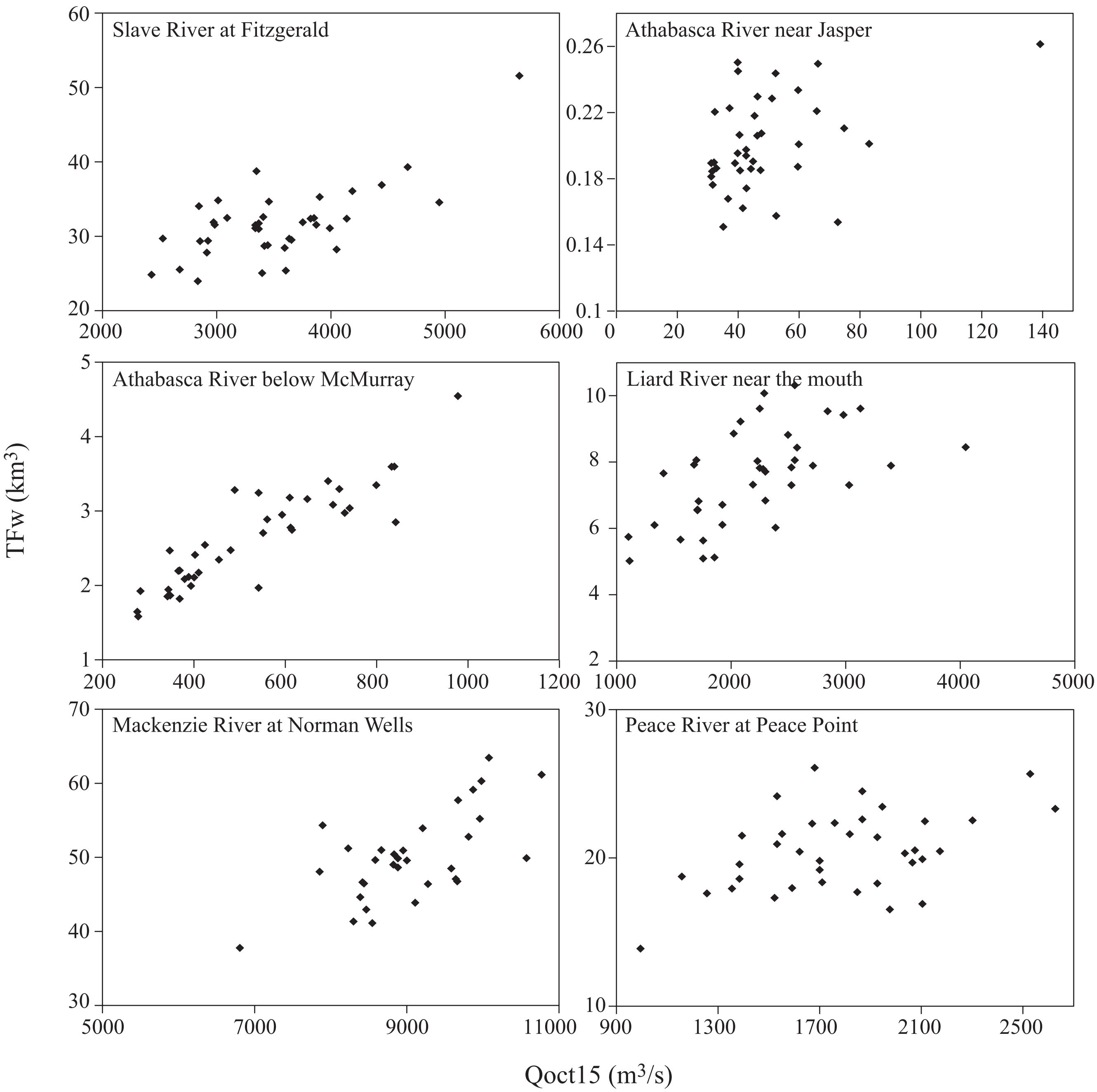


FIG. 11. Relationship between the discharge on 15 October (Qoct15) and total winter flow (TFw) for selected rivers.

the regulated Peace River is about 250 mm from Williston Lake reservoir. The upland terrain below the dam produces a high runoff of 45 mm between Hudson Hope and Taylor, then 15 mm between Taylor and the village of Peace River. Below that, the lower basin has a negative contribution that infers runoff loss between Peace River village and Peace Point. This downstream reduction in flow may be attributed to a difference in the timing of freeze-up between the two stations (freezing often occurs earlier at the lower than at the higher station along the river, as previously noted).

The release of water from Williston Lake not only augments the winter low flow of the Peace, but it also raises the flow of the Slave River, into which the Peace enters. Expressed as a percentage of total winter flow of the Slave at Fitzgerald, the Peace at Hudson Hope below the reservoir provides 58% ± 9% (max. 79%, min. 41%); the Peace between Hudson Hope and Peace Point before it enters the Peace-Athabasca Delta contributes 9% ± 3% (max. 17%, min. 3%); and the Athabasca at Fort McMurray is responsible for only 8% ± 2% (max. 13%, min. 5%). The year-to-year variations in flow contributions from these river sections are illustrated in Figure 12.

The Athabasca River enters Lake Athabasca, and together with the Peace River, discharges to the Slave River. The Athabasca delivers only a small amount of flow to the Slave River (about 3 km^3 from the Athabasca vs

TABLE 4. Relationship between the 1 November – 31 March flow (TFw as the dependent variable) and discharge on 15 October (Qoct15 as the independent variable) for selected stations in the Mackenzie Basin. Also shown are the intercept (a) and slope (b) in the regression equation: TFw = a + b Qoct15, as well as the standard error and degrees of freedom. Asterisks indicate statistical significance at the 0.95 (*) or 0.99 (**) confidence level.

Station	Intercept (a)	Slope (b)	r^2	Standard error	Degrees of freedom
Athabasca River					
Jasper	0.174	0.001	0.15*	0.026	37
Hinton	0.440	0.001	0.13*	0.064	37
Athabasca	0.654	0.003	0.63**	0.231	37
Fort McMurray	0.928	0.003	0.80**	0.305	37
Hay River	0.012	0.002	0.80**	0.080	37
Peace River					
Hudson Hope	16.633	0.001	0.03	2.650	37
Peace River	20.034	0.001	0.01	2.670	36
Peace Point	14.487	0.003	0.20**	2.492	35
Liard River					
Upper Crossing	0.688	0.0023	0.69**	0.160	37
Lower Crossing	2.495	0.0019	0.42**	0.600	37
Fort Liard	2.918	0.0017	0.44**	0.837	35
Liard mouth near Ft. Simpson	4.612	0.0014	0.34**	1.207	37
Great Bear River	1.198	0.010	0.69**	0.319	23
Mackenzie River					
Fitzgerald (Slave River)	13.963	0.005	0.46**	3.712	37
Strong Point	1.508	0.006	0.88**	2.585	15
Fort Simpson	4.815	0.005	0.65**	3.889	37
Norman Wells	7.659	0.005	0.43**	4.650	39

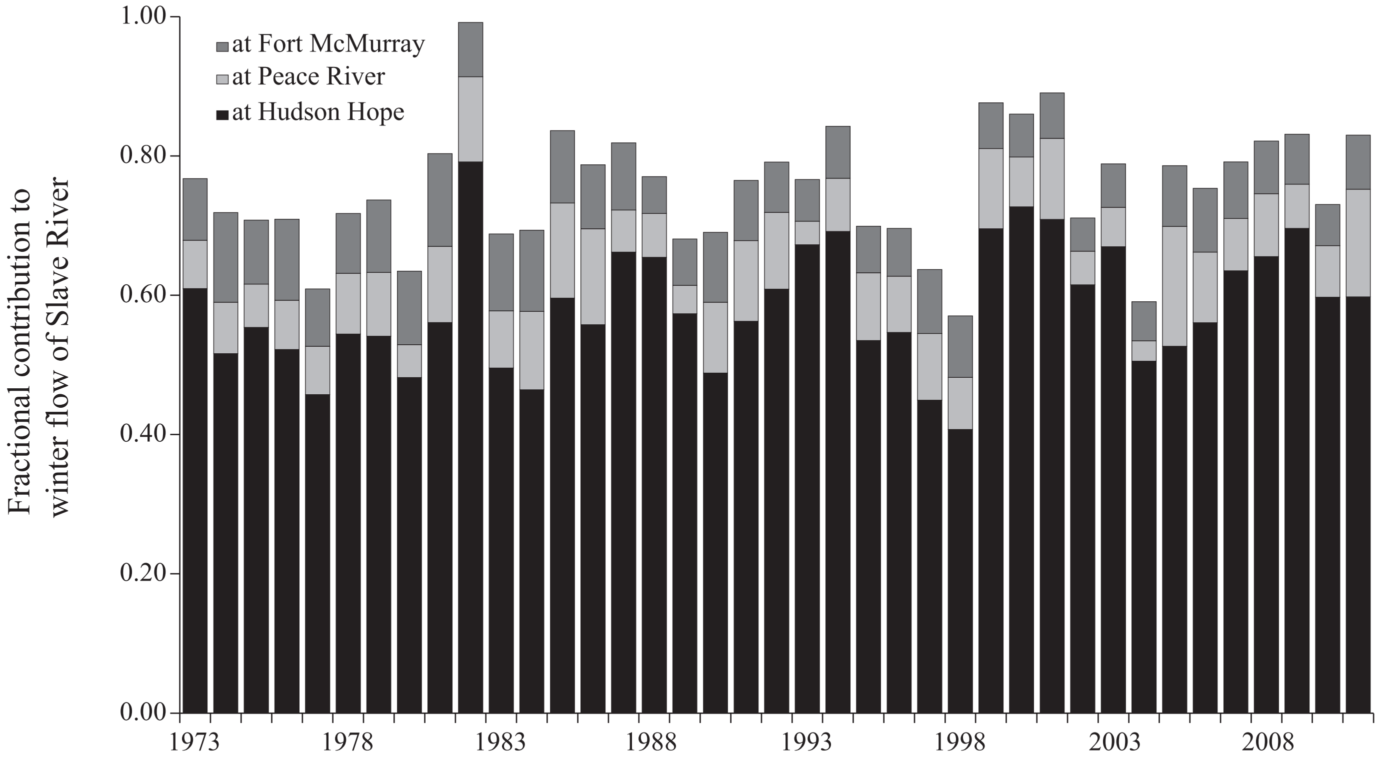


FIG. 12. Year-to-year variation in winter flow contribution (expressed as a fraction of Slave River flow at Fitzgerald) from the Williston Lake outflow (represented by Hudson Hope discharge), from the Peace River below the reservoir (at the village of Peace River), and from the Athabasca River at Fort McMurray.

21 km^3 from the Peace). The discharge pattern of the regulated Peace River is frequently asynchronous with the natural regime of the other tributaries that flow into the Slave River. In 1981 – 82, for example, when the Slave River had the lowest winter flow (23.4 km^3) since 1972, the Peace River provided 21.6 km^3 of the flow, but only 1.34 km^3 came from the other tributaries. Yet, in 1997 – 98, when the Slave River had the largest winter flow of 51.8 km^3, the Peace yielded 25.8 km^3, and 26 km^3 came from the remaining tributaries of the Slave River. When a reduction in reservoir release was accompanied by a decline of inflow from non-Peace rivers, as in 2010 – 11, the Slave River had a flow

TABLE 5. Winter flow in the Mackenzie River and flow contributions from its principal tributaries for winters with low, medium, and large flow at Norman Wells. Total winter flow (TFw) is expressed in km^3. The fraction of flow contribution from tributaries is shown in parentheses.

Basins	Basin area (km^2)	Winter with low flow (1978–79)	Winter with medium flow (1984–85)	Winter with large flow (1974–75)
Great Bear	146 400	5.74 (0.137)	7.24 (0.146)	6.61 (0.108)
Liard mouth near Ft. Simpson	275 000	5.07 (0.120)	6.10 (0.123)	7.32 (0.119)
Peace (Peace Point)	293 000	21.61 (0.511)	19.89 (0.401)	22.56 (0.368)
Athabasca (Ft. McMurray)	132 585	3.35 (0.079)	2.97 (0.080)	3.16 (0.050)
Hay River	51 700	0.18 (0.004)	0.26 (0.005)	0.11 (0.002)
Other basin areas	695 815	(0.15)	(0.27)	(0.35)
Mackenzie (Norman Wells)	1 594 500	41.26	45.21	46.72

of only 24.6 km^3 (with 16 km^3 from the Peace), the second lowest on record since 1972.

The effect of reservoir operation decreases going down the Mackenzie River system. This is in accord with the finding of McClelland et al. (2004) who, in examining the influence of dam operation on the flow of large Russian rivers, noted that the changes relative to the average flow are large near the dam site, but become progressively smaller as a percentage of the average flow downstream. Nevertheless, in terms of winter flow of the Mackenzie system, the amount of water released from Williston Lake (represented by the flow of Peace at Hudson Hope) remains the largest portion (average about 40%) of total winter flow at Norman Wells in the lower Mackenzie Basin, far exceeding the percentage contributions from the Liard River (15%) and Great Bear River (13%).

To further explore the between-year variations in sub-basin contribution to the Mackenzie River, Table 5 provides examples of years with low (1978–79), medium (1984–85), and high (1974–75) winter flows at Norman Wells. In all three winters, the Peace River provided the largest amount of flow to the Mackenzie, followed by the Great Bear River or Liard River as a distant second in different years. However, in the year when the Mackenzie had large winter flow, the fractional contribution from these two sub-basins with steady lake outflow decreased, while more runoff came from those areas not drained by the major tributaries. These latter areas encompass parts of the Canadian Shield and northern plains. Their percentage flow contributions rose from 15% in the low flow winter to 35% in the winter with high flow.

REGIONAL CLIMATIC SIGNALS AND TRENDS

Teleconnection has a possible influence on winter low flow through such climatic variables as temperature and precipitation. Climatic signals may be transmitted to streamflow, leaving their marks as interannual variability and trends in the flow. We first compare climatic indices like the SOI (Southern Oscillation Index) and PDO (Pacific Decadal Oscillation) with winter air temperature and precipitation for a number of climatic stations that cover different parts of the Mackenzie Basin. The results are mixed (Table 3), with air temperature at some stations showing significant correlation with the PDO but not with the SOI. Overall, there is weak to no significant correlation between the indices and winter precipitation.

With respect to winter flow, changing intensity of atmospheric coldness does not have a noticeable effect, as indicated by the lack of significant correlation between TFw of various hydrometric stations with the November–March air temperature of their nearby climate stations. Similarly, TFw, freeze-up, and breakup dates do not show significant correlation with SOI, PDO, and AO (values not presented here), except for a few isolated cases involving very few stations. Thorne and Woo (2011) studied the Fraser River basin in British Columbia and found that even in regions where teleconnection signals are pronounced, local conditions such as topography, geology, and vegetation can negate, distort, or delay the response of streamflow to the large-scale climatic signals. For the Mackenzie and its tributaries, river ice is one additional local factor that seasonally blunts the influence of the climate on winter low flow.

Previous studies have noted rising trends in winter flow for a number of rivers in Western Canada. Burn et al. (2004b) found that the January, February, and March flows at the Liard River stations (1960–99 period) are related to the winter temperature and suggested that larger flows during this period arose from increased temperature. In our present study, Mann-Kendall tests performed on the 1973–2011 winter (1 November–31 March) flow series detected statistically significant rising trends in the winter flow of the Liard River, as well as the Peace River (Fig. 13). The Peace River trend cannot be accepted because the natural flow has been altered for hydropower production. In contrast to these two rivers, the lower Athabasca River in the south showed a decreasing trend in winter flow. Abdul Aziz and Burn (2006) reported similar trends. Regarding the winter minimum (QMINw), our Mann-Kendall tests yielded trending patterns that generally resemble those of the total winter flow. The upper Liard basin and Hay River show a positive tendency in QMINw, while the lower Athabasca presents a decreasing one, and no trend is apparent for the other rivers. However, any statistical trend manifested in QMINw should be interpreted with caution because the occurrence of the winter minimum is attributed

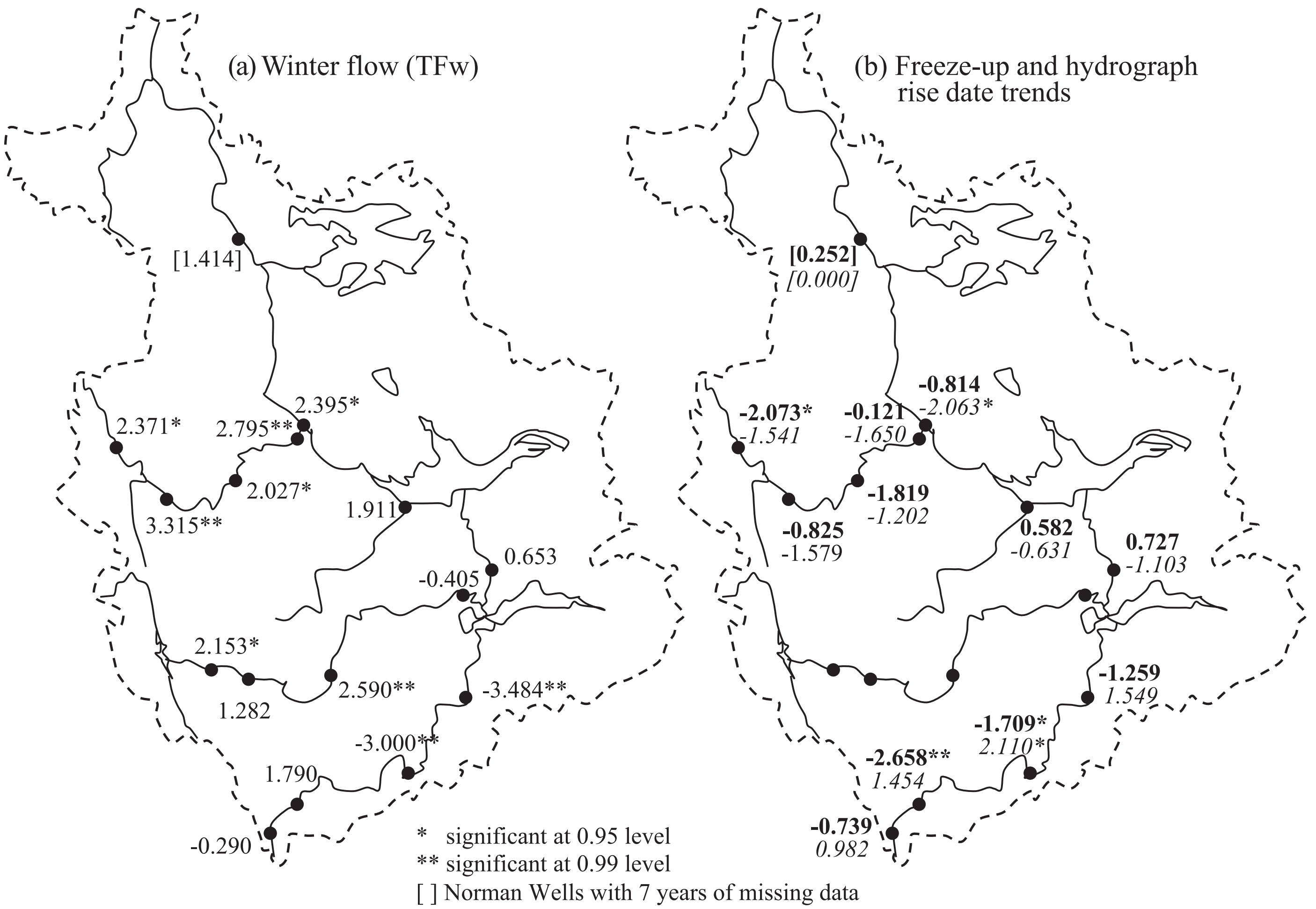


FIG. 13. Mann-Kendall statistics for trends in (a) winter flow and (b) dates of freeze-up (bold) and spring hydrograph rise (italics) for selected hydrographic stations in the Mackenzie basin, 1972–2011.

to two separate processes: hydraulic storage in some years and continued recession in winter flow in other years.

Burn and Hag Elnur (2002: Fig. 3) found a trend toward earlier termination of ice conditions during the 1960–97 period for the headwaters of the Liard River and the Athabasca River at Fort McMurray. Woo and Thorne (2003) likewise noted significantly earlier rise in the end-of-winter hydrographs for the Slave and Mackenzie main rivers in the 1973–99 data, but these trends become insignificant when longer time series are used, as indicated by a lack of significance in the Mann-Kendall statistics (Fig. 13). The case of spring hydrograph rise in the Slave River is presented in greater detail (Fig. 14). A statistically significant downward trend or earlier hydrograph rise is detected when the 1972–99 data are used (Spearman's $r^2 = 0.16$, significant at $p = 0.05$). However, this trend vanishes in the extended (1972–2010) time series ($r^2 = 0.04$, statistically insignificant). This example points to the need for long data series to perform trend analysis and forces us to question the validity of applying a monotonic linear trend to records that exhibit jumps or cyclical patterns (Burn et al., 2004a).

Several comments are pertinent to the investigation of winter flow trends of the Mackenzie drainage.

1) Foremost is the artificial pattern of reservoir release to the Peace River, which is transmitted down the Mackenzie system. Since the Peace provides about 40% of total winter flow of the Mackenzie (Tables 1 and 5), its considerable magnitude relative to the flow contribution from the non-regulated tributaries can significantly mask any natural flow trend that may exist along the main stem of the Mackenzie River.
2) A long-term trend in winter flow is superimposed by medium-term variability. The flow record used in statistical analysis may manifest only part of an oscillation and does not necessarily reveal the true trend. Furthermore, the statistical techniques used by many studies are predicated on the assumption that the trend is monotonic and linear, an assumption that should be verified, but seldom is.
3) Permafrost thaw has been advanced as a possible mechanism that raises winter flow (Walvoord and Striegl, 2007; St. Jacques and Sauchyn, 2009), either through the melting of ground ice or by enhanced connectivity of the talik network (unfrozen zones in permafrost) to facilitate greater groundwater movement. Such inferred permafrost-hydrology linkages await conclusive field

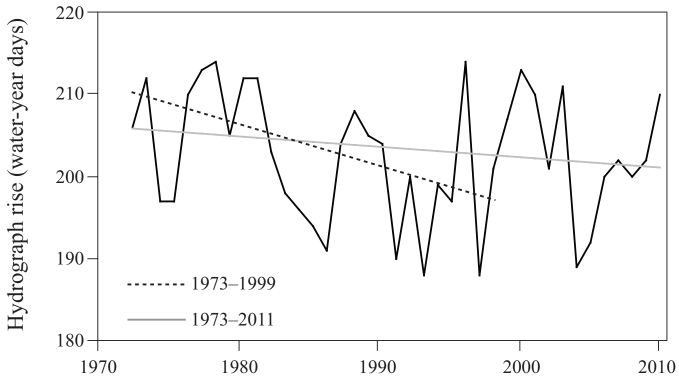


FIG. 14. Time series of hydrograph rise dates for the Slave River at Fitzgerald. The graph shows the apparent presence of a downward (earlier rise) trend from 1973 to 1999 (Spearman's $r^2 = 0.16$). However, the trend is not evident when a longer time series (1973 to 2011) is used (Spearman's $r^2 = 0.04$).

verification. Furthermore, owing to the effect of storage, the magnitude of winter low flow cannot be considered in isolation from the flow in other seasons, during which storage is recharged by rainfall, snowmelt, and inflow from upstream, as evidenced by the observed relationship between Qoct15 and TFw for many stations. Burn et al. (2004b) noted an increasing trend in October rain for Fort Nelson in the lower Liard basin. Perhaps that trend plays a role in raising the winter flow of the Liard.

CONCLUSIONS

Two definitions of winter low flows are proposed: (1) the flow between river freeze-up and steep hydrograph rise in the spring and (2) the flow during the period from 1 November to 31 March. The latter, considered as winter flow, allows comparison of flow attributes among all rivers in the extensive Mackenzie drainage system, which spans over 15˚ of latitude in northern Canada. For rivers that acquire a winter ice cover for five or more months, there is a strong statistical correlation of the low flows defined by these two criteria.

Low flows occur during the long cold winters, when subfreezing temperatures prevent rainfall, snowmelt, and surface runoff from replenishing the river flow, leaving groundwater as the main external water source that supports discharge in the Mackenzie River Basin. Considerably more winter runoff is generated from mountainous areas than from flat and low-lying terrains.

Storage is another factor that affects winter flow. River ice formation abstracts water at the expense of river flow, and ice is held in storage, rendering much of this stored water unavailable for flow until the next spring. This form of storage change is small in magnitude compared with the amount of water released from the large lakes that constitute parts of the drainage system. The managed discharge of the Williston Lake reservoir plays an especially significant role in modifying winter flow in the Mackenzie system. Not only does the discharge eliminate the low flow of the Peace River, but the effect propagates down the drainage system so that the release from this reservoir provides 30%–50% of the Mackenzie winter discharge.

Statistical analyses of winter flow data for 1972–2011 show a lack of teleconnection with several climatic indices (SOI, PDO, and AO). A negative trend is detected in the Athabasca River flow and a positive trend for the Liard River. However, attention should be paid to the length and the particular segment of flow record used in the analysis, the influence that regulated flow exerts on the low flow downstream, and the need for evidence that supports physical interpretation of the identified trend.

Most large northern river basins possess hydrological settings similar to that of the Mackenzie: long and intensely cold winters and large latitudinal and altitudinal extents with diverse topography, often with large lakes and regulated discharge. A study of winter low flow in the Mackenzie River system enables understanding of the hydrologic processes, and the general conclusions obtained are applicable to other large rivers in the circumpolar Arctic.

ACKNOWLEDGEMENTS

This study was supported by contract A7221-11-2172 from Aboriginal Affairs and Northern Development Canada. We thank Shawne Kokelj of the Department's Yellowknife office for her encouragement and valuable assistance. We thank the anonymous reviewers for their detailed comments and helpful suggestions.

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