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Summer Low Flow Events in the Mackenzie River System

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ABSTRACT. Most northern rivers experience recurrent low flow conditions in the summer (June to September), and rivers of the Mackenzie Basin are no exception. Low flow affects water supply, poses problems for river traffic, and can adversely affect aquatic ecology. Factors that affect summer low flow, which encompasses flows below specified discharge thresholds of concern, include evapotranspiration that leads to water loss from flow-contributing areas, antecedent high flow in which peak discharge is followed by gradual recession to low flow, rainfall and local glacier melt events that interrupt low discharge, replenishments of flow from upstream drainage networks, and arbitrary termination of summer low flow at the end of September. The storage mechanism of large lakes and the regulation effect of reservoirs can produce low flow regimes that differ from those exhibited by rivers without such storage functions. For most rivers, low flow events of longer duration cause larger deficits, and events with large deficits are accompanied by lower minimum discharge. The deficit-to-demand ratio measures the extent to which river flow fails to satisfy water needs. Applying this index to rivers of the Mackenzie drainage shows the hazard of streamflow drought in the basin. Low flow attributes can be summarized by their probability distributions: Gumbel distribution for minimum discharge of events and generalized exponential distribution for event duration. By fitting theoretical distributions to recorded events, one can estimate the probability of occurrence of low flow events that did not occur in the historical past.

Key words: low flow; summer drought; lake storage; regulated flow; duration; deficit; minimum flow; probability distribution; Mackenzie River

RÉSUMÉ. La plupart des rivières du Nord connaissent des conditions récurrentes de faible débit estival (de juin à septembre), et les rivières du bassin du Mackenzie n'y font pas exception. Le faible débit a des incidences sur l'approvisionnement en eau, pose des problèmes sur le plan du trafic fluvial et peut nuire à l'écologie aquatique. Les facteurs qui influencent le faible débit estival, incluant les débits sous les seuils de préoccupation indiqués, comprennent l'évapotranspiration qui entraîne des pertes en eau des segments contribuant à l'écoulement, un antécédent de débit élevé pour lequel le débit de pointe est suivi d'une diminution progressive jusqu'à un faible débit, des épisodes de chutes de pluie et de fontes des glaciers locaux qui interrompent le faible débit, la réalimentation en eau des réseaux hydrographiques en amont et l'arrêt arbitraire du faible débit estival à la fin de septembre. Le mécanisme de stockage des grands lacs et l'effet de régularisation des réservoirs peuvent produire des régimes de faible débit qui diffèrent de ceux présentés par les rivières qui ne possèdent pas de telles fonctions de stockage. Pour la plupart des rivières, les épisodes de faible débit de plus longue durée occasionnent de plus grands déficits et les épisodes assortis de plus grands déficits sont accompagnés de débits minimaux plus faibles. La mesure entre le déficit et la demande indique à quel point le débit fluvial ne réussit pas à répondre aux besoins en eau. Cet indice appliqué aux rivières du bassin du Mackenzie démontre le risque de sécheresse de l'écoulement fluvial dans le bassin. Les caractéristiques du faible débit peuvent se résumer par la distribution de leurs probabilités : une distribution de Gumbel pour les épisodes de débit minimal et une distribution exponentielle généralisée pour la durée de l'épisode. En appliquant ces distributions théoriques aux épisodes enregistrés, il est possible d'estimer la probabilité de l'occurrence des épisodes de faible débit qui n'ont pas eu lieu dans le passé historique.

Mots clés : faible débit; sécheresse estivale; stockage dans les lacs; débit régularisé; durée; déficit; débit minimal; distribution des probabilités; fleuve Mackenzie

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INTRODUCTION

Most northern communities settle along rivers, relying on the waterways not only to supply water, but also to support local economic activities and livelihood. Mining and hydropower generation in the North demand water from rivers and lakes, while in the warmer parts of northern basins agricultural enterprises withdraw water for irrigation. Large northern rivers are also the arteries of north-south transport during the ice-free season, when people and goods are carried by ferries, barges, and other watercraft across and along the rivers.

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Low flows are a natural phenomenon for most rivers. A reduction in flow and an accompanying lowering of water level not only jeopardize river-borne traffic and water supply for community use and resource development, but can have serious consequences for the entrainment of sediments and pollutants (Prowse, 2001) and the distribution of nutrients vital to the health of aquatic and wetland ecology (Peters et al., 2006; Bradford and Heinonen, 2008). Rivers at high latitudes manifest low flow conditions in both summer and winter. This study analyzes major summer low flow characteristics of the Mackenzie River and its principal tributaries, which constitute the largest northern river system in North America. Winter low flows of this river have been investigated (Woo and Thorne, 2014) and this paper is intended to complement that study. Here, we discuss factors that affect summer low flow, analyze low flow characteristics of rivers that are tributaries of the Mackenzie and along its main stem, and consider the probability of low flow events in the Mackenzie drainage system. Understanding and quantifying the temporal and spatial variations of summer low flows offers a sound hydrological basis for planning, decision making, and formulating adaptation strategy and policy in response to natural and anthropogenic changes.

DEFINITION OF SUMMER LOW FLOWS

From the end of the spring freshet until winter ice forms, rivers discharge under open water conditions. For large basins that straddle cold temperate and subarctic latitudes, the time of snowmelt varies considerably among locations. Snowmelt peak flow may arrive in May or June at the southern fringe, but can be delayed until July in the northern mountains of the Mackenzie Basin (Woo and Thorne, 2003). On the other hand, winter comes earlier at higher latitudes, initiating early freeze-up in the north. To provide a common time frame for comparison of summer flow at all stations within the vast Mackenzie Basin, summer is arbitrarily defined as June to September. Low flows that occur within these months are treated as summer low flow.

Low flow is a relative term, suggesting that river discharge falls below a particular level of expectation: there is no one single characterization of low flow that is suitable for all purposes (Riggs, 1980). The several common techniques devised for low flow investigations have been well summarized by Smakhtin (2001). One approach is to study the flow in the dry season or the flows at n-day intervals within the dry season, where n can be 5, 7, 10, or any other number of days (the n-day low flow). For example, Ehsanzadeh and Adamowski (2007) used seven-day low flows to examine the trends in the magnitude and timing of summer and winter minimum flows for 57 stations across Canada. Another approach is to consider the recession rate (the decline from peak flow to low discharge as the dry period progresses). Low flow has also been defined with respect to a certain threshold (QT, in m^3s^{-1}), which is specified according to the demands of economic activities or environmental well-being. Alternatively, the threshold level selected can be the flow at a particular return period (expected time interval between the occurrences of a certain flow magnitude) of daily flow. In this case, a flow below this level is considered low flow, and the difference between expected and actual flow is the flow deficit. This deficit condition may be construed as a hydrological drought (Sen, 1980).

This study applies the threshold approach to low flow analysis. It is equivalent, but opposite, to the analysis of partial duration series, which uses a truncation level to distinguish daily flow into high flow and low flow components (e.g., Todorovic, 1978; Waylen and Woo, 1983; Zelenhasić and Salvai, 1987; Woo and Tarhule, 1994). Figure 1 provides a schematic representation of summer flow and the definitions applied to summer low flow events. Both low flow and deficit conditions are studied in this paper.

Daily discharge (Q in m^3s^{-1}) can be higher or lower than the threshold level. QSH, or the value below QT, is the discharge that falls short of the demand. Its counterpart, or the discharge above QT, is considered to be excessive. Then:

$$\text{If } (Q - QT) > 0,\ QSH = 0, \text{ and excess} = Q - QT \quad (1a)$$

$$\text{If } (Q - QT) < 0,\ QSH = QT - Q, \text{ and excess} = 0 \quad (1b)$$

$$\text{If } Q = QT, \text{ both QSH and excess are zero} \quad (1c)$$

On the day when a deficit occurs (i.e., QSH > 0), low-flow discharge is the same as the measured discharge for that particular day. On other days, when there is no shortage in flow, low flow is zero.

It is meaningful to consider the notion of flow deficit in relation to water use. Flow deficit is the amount of streamflow that fails to meet the demand, but any flow amount that exceeds the threshold would drain away and would not be available for subsequent use. For a given summer day, the demand for river flow is:

$$DEMAND = QT.\Delta t \quad (2a)$$

in which DEMAND is in m^3d^{-1}, and $\Delta t = 86\,400$ s d^{-1} is the number of seconds in a day.

The daily deficit or shortfall below the threshold is DSH (in m^3d^{-1}), which is zero when there is no shortfall:

$$DSH = QSH.\Delta t, \text{ if } Q < QT \quad (2b)$$
$$DSH = 0, \text{ if } Q \geq QT$$

and low flow for the day (in m^3d^{-1}) is:

$$DLF = Q.\Delta t \text{ if } Q < QT \quad (2c)$$
$$DLF = 0 \text{ if } Q \geq QT$$

A low flow event comprises a sequence of contiguous days when discharge falls below the specified threshold. Several low flow events can occur in a summer, or one, or none. A

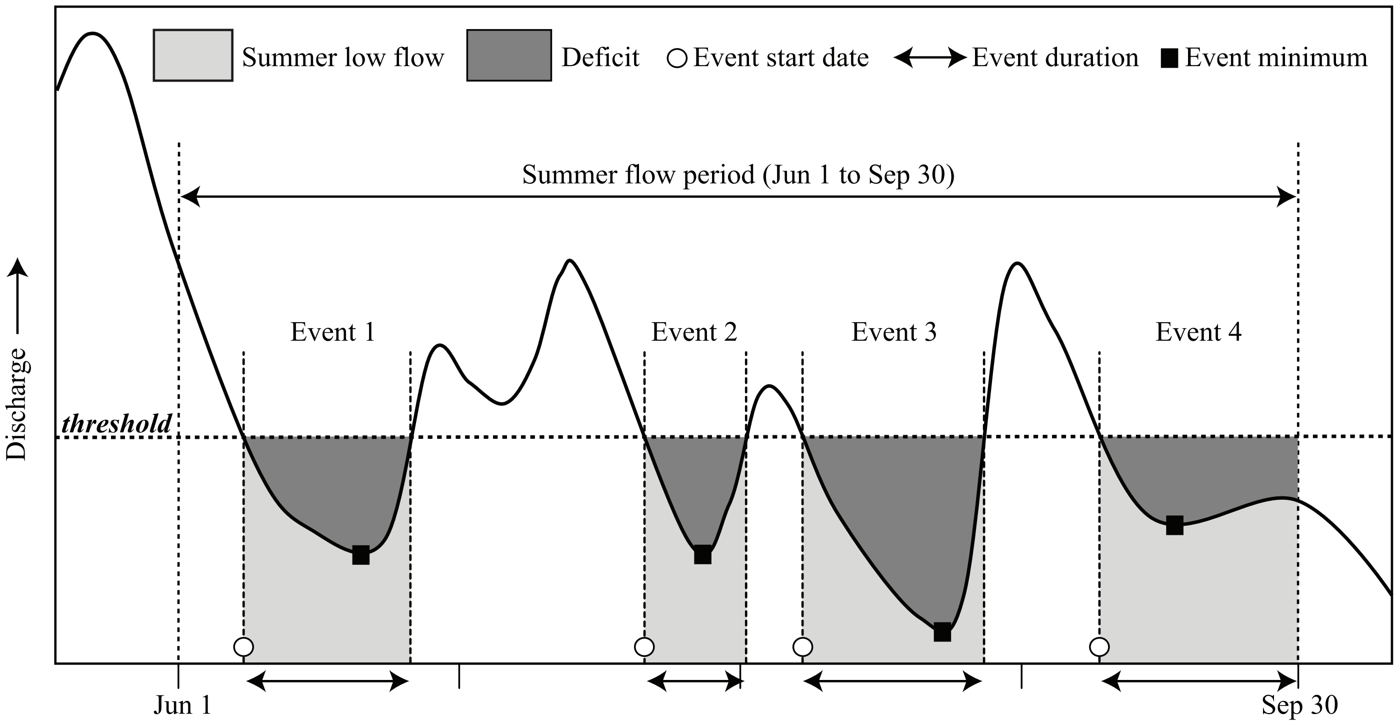


FIG. 1. Definition of summer low flow events and their attributes. Summer is considered to be from June 1 to September 30. The threshold is the discharge below which low flow occurs.

low flow event begins when discharge (Q) first drops below the threshold (or Q < QT) and ends when discharge rises above QT again. Event duration (DUR) is the time between the down-crossing and up-crossing of the threshold. Two additional criteria are attached to this definition, however. When two sequences of low flow occurrence are separated by three days or less, these low flows are considered as parts of the same event and are therefore amalgamated to form one single event. On the other hand, when low flow lasts for three days or less, it is of no practical significance; it is considered a non-event and then eliminated. Within such short intervals of several days, the ignored amount of deficit or surplus would be minimal. Our measure is analogous to the approach adopted by Zelenhasić and Salvai (1987:158–159): to neglect all minor droughts with a deficit less than 0.5% of the maximum deficit, as they are insignificant in comparison with medium or severe droughts.

For a low flow event, the event deficit is the sum of daily deficits (DSHs) for the duration of the event (DUR days), i.e.,

$$SH = \sum_{i=1}^{DUR} DSH(i) \qquad (3a)$$

Here, SH is the total deficit for the event. Each event declines to a lowest discharge that is the event minimum (MIN, in m^3s^{-1}). The lowest discharge attained in a summer is the summer minimum, which is normally, but not always, the lowest among the minima of all low flow events in the summer. A wet year with higher flow than usual may have no low flow event, but will still have a summer minimum that is higher than the discharge threshold.

Total streamflow demand for a specified period of concern is k.DEMAND, where k is the number of days in the specified period and DEMAND (calculated using Equation 2a) is the daily flow requirement under a stated discharge demand level QT. Total deficit for the same period is the sum of daily deficits, i.e.,:

$$\sum_{j-1}^{k} DSH(j) \qquad (3b)$$

A deficit severity index (DSI) is introduced to standardize the ratio of deficit to demand for different stations. This standardization facilitates comparison of the relative severity of deficit among stations. For a particular period of k days, the DSI (a dimensionless ratio) is:

$$DSI = (k.DEMAND)^{-1} \sum_{j=1}^{k} DSH(j) \qquad (4)$$

Two attributes of low flow are also addressed in the realm of probability. The generalized exponential (Pearson Type XI) distribution is applied to the duration (DUR, in number of days), and the cumulative distribution function (Naylor et al., 1966) is:

$$F(DUR) = 1 - [\,(\alpha / (\alpha + DUR)\,]^{k} \qquad (5)$$

Its two parameters can be calculated using the mean (μ) and the variance (σ^2):

$$k = 2\,\sigma^2 / (\sigma^2 - \mu^2) \qquad (5a)$$

$$\alpha = (k - 1)\,\mu \qquad (5b)$$

TABLE 1. Drainage areas and low flow threshold values at non-exceedance probabilities of $p = 0.5$, 0.2, and 0.1 (shown in square brackets as QT_{50}, QT_{20}, and $QT_{10,}$ in m^3s^{-1}) for selected stations in the Mackenzie Basin. Columns 3 to 5 show the correlation (Spearman's r) between total summer flow deficit below the three thresholds and June–September total summer flow (TSF), and Column 6 shows the correlation between spring peak discharge and TSF. Data from 1972 to 2012 were used for most stations. Asterisks denote significance at 0.95 (*) and 0.99 (**) levels.

Station	Area (km^2)	$DEF_{0.5}$	$DEF_{0.2}$	$DEF_{0.1}$	Spring peak discharge vs. total summer flow
Athabasca (Jasper)	3 873	−0.76** [86.4]	−0.48**[115]	−0.42**[192]	0.79**
Athabasca (McMurray)	132 585	−0.90**[563]	−0.56**[672]	−0.26 [963]	0.81**
Peace (Hudson Hope)	73 100	−0.88**[371]	−0.39 [456]	−0.05 [917]	0.53**
Peace (Peace Point)	293 000	−0.82**[1260]	−0.26 [1490]	−0.07 [2210]	0.81**
Clearwater	30 792	−0.78**[74.9]	−0.23 [90]	−0.05 [135]	0.52**
Hay	51 700	−0.86**[24.3]	−0.12 [58]	−0.11 [154]	0.57**
Slave	606 000	−0.92**[3230]	−0.64**[3530]	−0.22 [4560]	0.83**
Liard (Upper Crossing)	32 600	−0.78**[317]	−0.44**[377]	−0.11 [580]	0.69**
Liard (mouth)	275 000	−0.69**[2370]	−0.40**[2800]	−0.17 [4330]	0.60**
Great Bear River[1]	146 400	−0.84**[493]	−0.11 [517]	−0.11 [581]	0.99**
Peel[2]	70 600	−0.89**[587]	−0.79**[696]	−0.42*[1070]	0.47**
Mackenzie (Strong Pt)[3]		−0.90**[4970]	−0.21 [5360]	−0.06 [6150]	0.49*
Mackenzie (Ft Simpson)	1 301 435	−0.90**[7740]	−0.46**[8440]	−0.27 [10700]	0.62**
Mackenzie (Norman)	1 594 500	−0.86**[9850]	−0.54**[10800]	−0.17 [13500]	0.49**
Mackenzie (Arctic Red)[4]	1 679 100	−0.79**[10400]	−0.53**[11700]	−0.06 [14800]	0.48**

[1] Three years with missing data.
[2] Data available only for 1975–2012.
[3] Data available only for 1992–2012.
[4] Data available for 1973–2012.

The extreme-value Gumbel distribution is applied to the lowest discharge of a low flow event (MIN). The probability of a magnitude is less than x (m^3s^{-1}) following the distribution function of:

$$F(MIN < x) = \exp \{-\exp [-\gamma (x - \beta)] \} \quad (6)$$

$$\text{where } \gamma = 1.28 / \sigma \quad (6a)$$

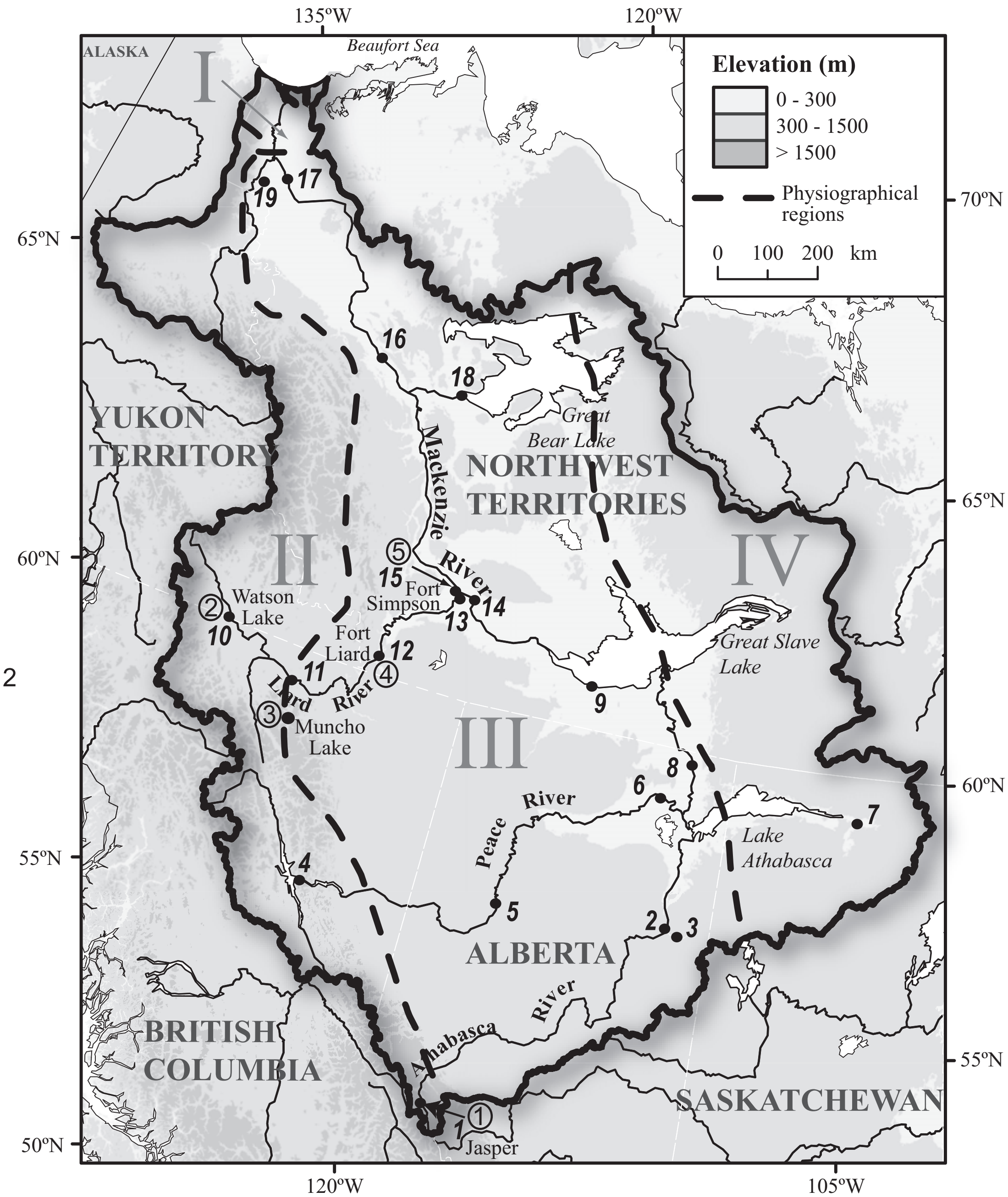
$$\beta = \mu - 0.35 \sigma \quad (6b)$$

In regard to flow thresholds, this study provides as examples three thresholds based on the return periods of daily June–September flows, using the historical records from 1972 to 2012. The examples include discharge levels with non-exceedance probabilities of 0.5, 0.2, and 0.1 (i.e., there is a 50%, 20%, or 10% probability that such a magnitude is not exceeded). and their respective thresholds are represented by the symbols QT_{50}, QT_{20}, and QT_{10}. Here, QT_{50} is the same as the median of daily discharge in the summer months, while the thresholds at the other non-exceedance probability levels catch more extreme events (Table 1). The threshold value varies from station to station within the basin because discharge changes at different rates downstream. Note that the thresholds adopted by our study can be replaced by any other levels appropriate to the user's water demand.

STUDY AREA AND DATA

The Mackenzie Basin extends from the cold temperate to the subarctic regions (52˚ to 69˚ N). With an area of 1.8 million km^2, it covers about one-fifth of the land surface of Canada. The Cordilleran region in the west basin is mountainous, the central Interior Plains are relatively flat, and the eastern region in the Canadian Shield has undulating topography (Fig. 2). The highly diverse hydrological environments give rise to rivers with different streamflow regimes. Briefly, the nival (snowmelt-dominated) regime is the most prevalent, and the proglacial regime exists only in the western mountains. The wetland regime is common on the Interior Plains, while rivers on the Canadian Shield flow through bedrock terrain with chains of lakes and patches of wetlands. Outlets of large lakes exhibit a prolacustrine regime, and the operation of large reservoirs gives rise to a regime with flows regulated by water demands for hydropower generation. Detailed accounts of the basin environment and hydrographs illustrating various typical regimes are given in Woo and Thorne (2003) and are not reproduced here.

Three groups of rivers were selected for this study: headwater rivers, major tributaries, and the main trunk of the Mackenzie River. Their drainage areas range from 10^3 km^2 for headwater basins to 10^6 km^2 for the lower Mackenzie. Headwater rivers that represent different flow regimes include the Upper Liard and Peel (nival), the Athabasca at Jasper (proglacial), the Hay (wetlands and lakes of Interior Plains), the Clearwater (combination of Canadian Shield and Interior Plains), the Great Bear (prolacustrine), and



Hydrometric Stations

1	Athabasca River near Jasper
2	Athabasca River below McMurray
3	Clearwater River at Draper
4	Peace River at Hudson Hope
5	Peace River at Peace River
6	Peace River at Peace Point (Alberta)
7	Fond du Lac River at outlet of Black Lake
8	Slave River at Fitzgerald (Alberta)
9	Hay River near Hay River
10	Liard River at Upper Crossing
11	Liard River at Lower Crossing
12	Liard River at Fort Liard
13	Liard River near the mouth
14	Mackenzie River at Strong Point
15	Mackenzie River at Fort Simpson
16	Mackenzie River at Norman Wells
17	Mackenzie River at Arctic Red River
18	Great Bear River at outlet of Great Bear Lake
19	Peel River above Fort McPherson

Climate Stations (circled)

1	Jasper
2	Watson Lake
3	Muncho Lake
4	Fort Liard
5	Fort Simpson

FIG. 2. Physiographic regions of the Mackenzie River Basin: I – Mackenzie Delta, II – Western Cordillera, III – Interior Plains, and IV – Canadian Shield. Also shown are the locations of hydrometric and climate stations that provided streamflow and climate records for this study.

the Peace at Hudson Hope (regulated). Three major tributary basins (Athabasca, Peace, and Liard) drain into the Mackenzie, each tributary collecting and integrating the flow of headwater rivers from different environments: the Athabasca below Fort McMurray (from southern mountains and Interior Plains), the Peace at Peace Point (with regulated and natural flows), and the Liard near the mouth (from the northern mountains). In addition to these major tributaries, the Mackenzie is fed by lesser rivers of the Canadian Shield, the Interior Plains, and the subarctic mountains in the northwest, as well as by Great Bear Lake outflow in the northeast. Along the Mackenzie main stem are two large lakes, Lake Athabasca and Great Slave Lake. Hydrometric stations are installed on the Slave River at Fitzgerald (Alberta), and on the Mackenzie River at Strong Point, Fort Simpson, Norman Wells, and Arctic Red River.

Figure 2 shows the location of hydrometric stations that provide streamflow data used in this study. Daily discharge and water level data are obtained from the HYDAT database, the National Water Data Archive compiled by Water Survey of Canada (http://wateroffice.ec.gc.ca/). Major rivers chosen for the study (Table 1) offer flow records from 1972 to 2012 that permit extraction of summer (1 June to 30 September) daily discharge information for analysis. Many stations have also collected data over a longer period, and we include these extended records to augment the number of samples of low flow events. In addition to hydrometric data, we obtained temperature and precipitation records from selected stations in the sub-basins from Environment Canada through the Meteorological Service of Canada (http://climate.weather.gc.ca/).

FACTORS AFFECTING SUMMER LOW FLOWS IN THE MACKENZIE BASIN

Burn et al. (2008) listed several dominant processes that influence summer and winter low flows in regions of Canada, including the lack of precipitation and moisture; subfreezing temperatures; slow water release from storages in wetlands, lakes, and soil; and contributions from aquifers and from melting of snow and glaciers. While these are broadly applicable generalizations, certain major factors affecting the occurrence or termination of summer low flows in the Mackenzie Basin warrant particular consideration. These factors can act in concert to reduce water availability, or they can produce contrary effects on low flows.

Evapotranspiration from Flow Contributing Areas

Evapotranspiration from the catchment areas of rivers, including transpiration of vegetation and evaporation from lakes and wetlands, represents a loss in the moisture that feeds river flow. Within the Mackenzie Basin, evapotranspiration rates decrease with increasing latitude and elevation, ranging from almost 500 mm in the south to less than 150 mm in the north (Fisheries and Environment Canada, 1978). The rate also varies among land and vegetation surfaces. Barr et al. (2012), for example, found that in central Saskatchewan for 1999–2009, annual evapotranspiration averaged 427 ± 74 mm for old aspen, 382 ± 26 mm for old black spruce, 306 ± 21 mm for old jack pine, and 447 ± 44 mm for a fen (wetland). Open water surfaces undergo higher evaporation than other surfaces at the same location. Lins et al. (1990) estimated that annual evaporation from lakes in the Mackenzie Basin ranges from more than 500 mm in the south to less than 200 mm in the tundra zone. High evaporation leads to lowering of lake level and consequently, to diminished outflow.

Recession from High Flows

After the spring freshet prominently present in northern rivers, an absence of substantial surface runoff (from snowmelt, rainfall, or river inflow) leaves groundwater as the principal contributor to streamflow. A gradual reduction in groundwater input and a continued water loss to evapotranspiration lead to a decline in river discharge, indicated by recession from high flow to the baseflow. The enduring influence of spring high flow is manifested by a statistical relationship showing that large spring peaks recede to higher post-peak summer flow, whereas lesser spring floods recede to low flow levels within a similar time period (Table 1).

Glacier Melt and Rainfall Events

Large runoff from glacier melt or rainfall can raise streamflow enough to terminate low flow events. An example is from the Athabasca River at Jasper, which is fed by glaciers and by summer rainfall. Figure 3a shows the 1988 hydrograph and the low flow events for QT_{50} (shaded). Figure 3b presents the daily temperature and rainfall at Jasper. The temperature record provides a proxy of glacier melt, with higher temperatures suggesting large melt rates. Rainfall events were accompanied by lower temperatures, but despite reduction in melt rate, runoff was generated by rain. Thus, both the warm spells with large glacier melt and the rainfall events caused hydrograph rises that halted the low flows.

Termination of Summer Season

Since summer ends on 30 September by our definition, all low flow events are terminated artificially on that date even though they may extend into the fall or winter (in the latter case, they are considered as winter low flows). Most low flow events of nival regime rivers do not span a large part of summer, so many events that start in June or July end on or before September 30, whereas a large portion of those events that begin in August or September extend beyond that date. One consequence of the arbitrary cutoff date is to cut short the length of many events that start in late summer.

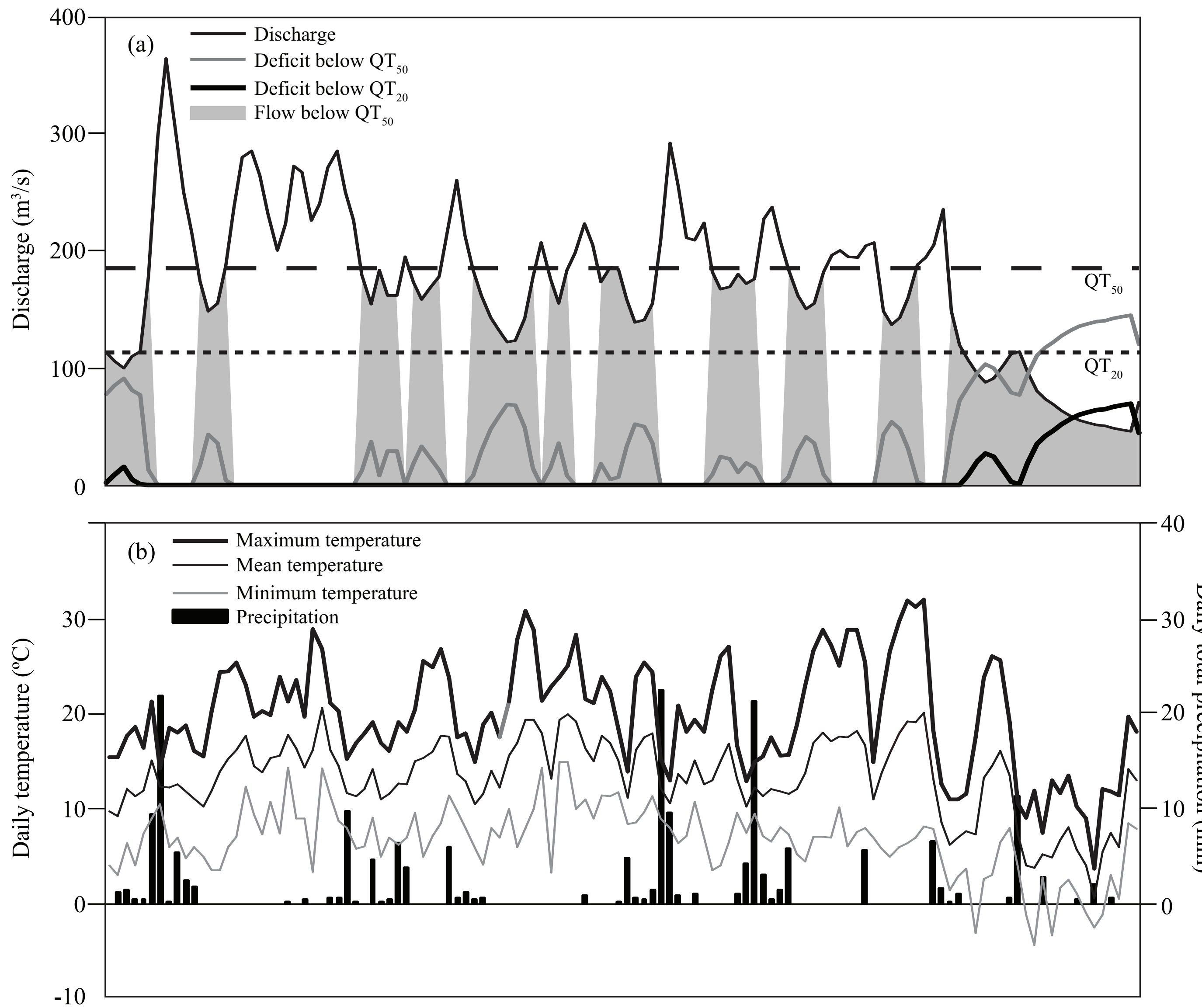


FIG. 3. (a) 1988 hydrograph of Athabasca River at Jasper (a glacierized river) with deficits below two flow thresholds (QT_{50} and QT_{20}) and low flow events as defined by QT_{50}. (b) Temperature and rainfall at Jasper.

Inflow from Upstream Drainage Network

A large pulse of river inflow from upstream can also elevate the discharge of a station sufficiently to suspend its low flow. To illustrate, Figure 4 shows such a surge that propagated down the Liard River. In 10 days (from 14 to 23 July 1977), the climate station of Watson Lake received 54 mm of rain, and the discharge at the Upper Crossing hydrometric station rose steadily (not obvious in the figure because of the plotting scale), while 29 mm of rain recorded at Muncho Lake increased the discharge at the Lower Crossing. High rainfall (84 mm) at Fort Liard caused a steep rise in discharge that ended the low flow at its adjacent hydrometric station. At Fort Simpson, only 8 mm of rain was recorded, a small amount that had negligible influence on the discharge at the nearby hydrometric station. However, the flood pulse that traveled down the river raised the discharge at the Fort Simpson station three days after the hydrograph rose at Fort Liard. It was this inflow, rather than local rain, that curtailed the low flow event at the Liard River mouth.

Storage Effect of Lakes

Lakes provide storage by absorbing the influx of water (including rainfall and inflow, but perhaps not breakup floods that are associated with river ice) and releasing it later at a more gradual rate. The resulting lake outflow, when compared with the inputs to the lake, shows that short-term fluctuations are smoothed and the rhythm of the inflow is attenuated. A comparison of the Slave River flow into Great Slave Lake and the flow of the Mackenzie River at Strong Point below the lake demonstrates the lessening of short-term fluctuations in the latter hydrograph (Fig. 5a). A more uniform flow is exhibited in the hydrograph of the

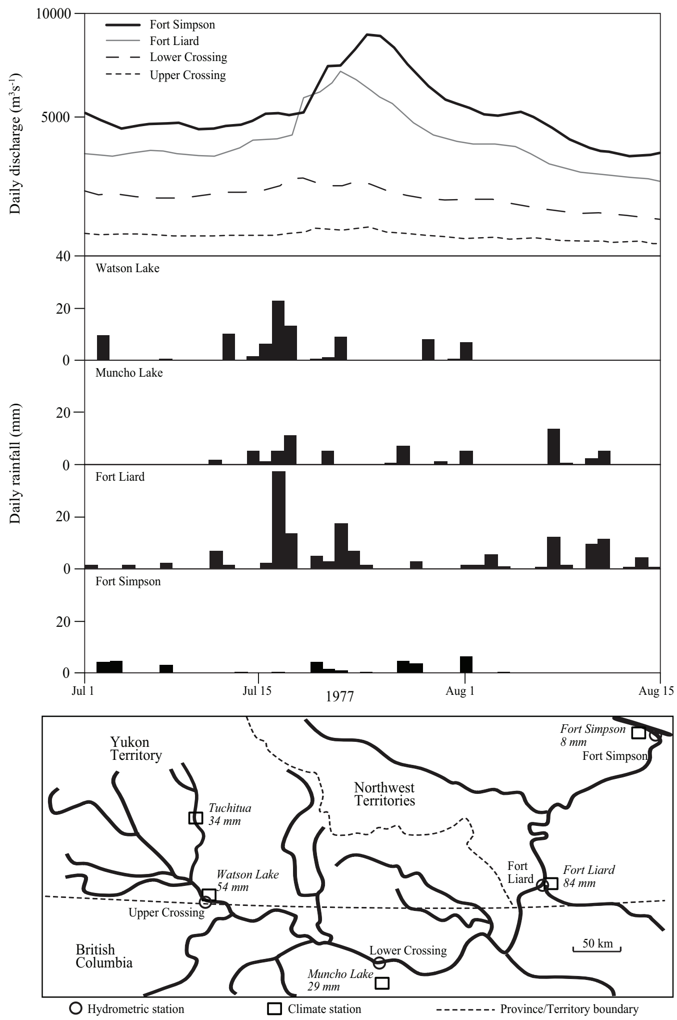


FIG. 4. On the Liard River, a flood pulse from Lower Crossing ending low flow at Fort Simpson. Also shown are the rainfall hyetographs from climate stations in the Liard Basin and their recorded total rainfall during 14–23 July 1977.

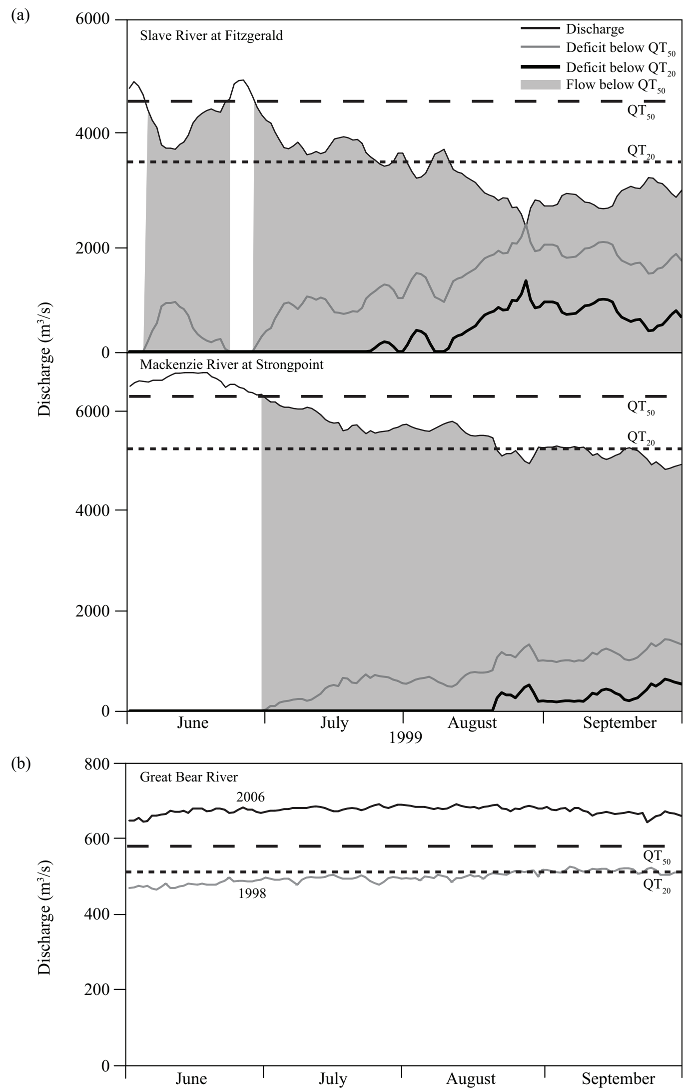


FIG. 5. (a) Dampening of flow variations due to the storage effect of Great Slave Lake as shown by the 1999 hydrographs, which indicate that outflow from the Lake to Mackenzie at Strong Point is smoother than the inflow from Slave River to the Lake. (b) The relative evenness of outflow from Great Bear Lake gives rise to an entire summer under low flow condition (1998) or a summer without low flow events (2006) except for very low flow thresholds

Great Bear River, which is fed by Great Bear Lake. This lake integrates inputs from its catchment and releases outflows with noticeable delay. The relatively gentle seasonal rise and fall in discharge results in flows entirely above a specified threshold (i.e., no low flow at all) in certain summers, while some other summers have all flows below the threshold (Fig. 5b). For example, no low flow event occurred in 2006, but in 1998, the whole summer experienced flows below the thresholds of QT_{50} and QT_{20}, and the flow rose above QT_{10} on only a few occasions.

Human Modification of Natural Flow Regime

Reservoir operation (notably that of Williston Lake on the Peace River) is the main human interference with river flow in the Mackenzie Basin. In the upper Peace River, summer has lower flow than winter, a condition that is contrary to the nival streamflow regime of most other rivers in the basin. The flow is dictated by the demand for hydropower production: regardless of the natural flow rhythm, it fluctuates in accordance with the amount of water released. For example, the 1993 summer hydrograph of the Peace River at Hudson Hope exhibits features attributable to reservoir operation. Compared with daily rainfall, the discharge remained low in June to early July, but it rose in September when rainfall was minimal (Fig. 6). Low flow during early summer was due to rainfall being stored in the reservoir, but high flow in late summer was caused by water release. Farther down below the dam, the natural rhythm of flow diluted the effect of reservoir regulation, and the natural regime was progressively restored downstream, as seen by comparing the hydrograph response to rainfall at the hydrometric station at the town of Peace River. The anthropogenic influence is conveyed by the Peace River to the Slave River, which also receives inputs from Lake Athabasca but below two weirs that modify the lake

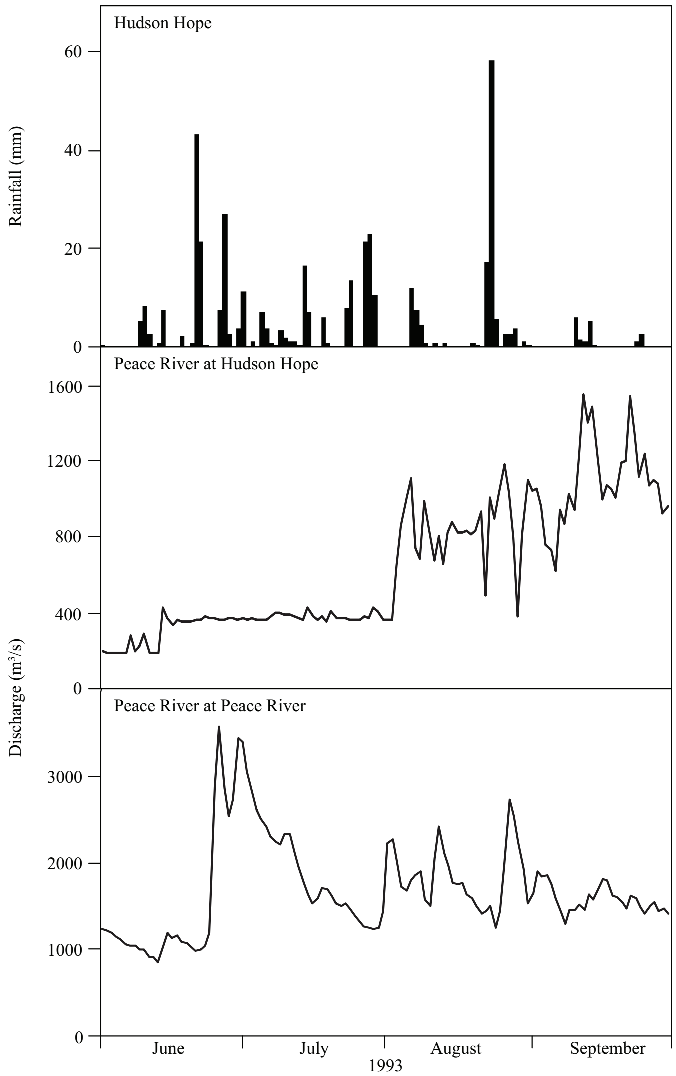


FIG. 6. Discordance between rainfall events and hydrograph of regulated discharge of Peace River at Hudson Hope. Response of streamflow to the rainfall pattern is gradually restored downstream, as shown by the hydrograph at the town of Peace River.

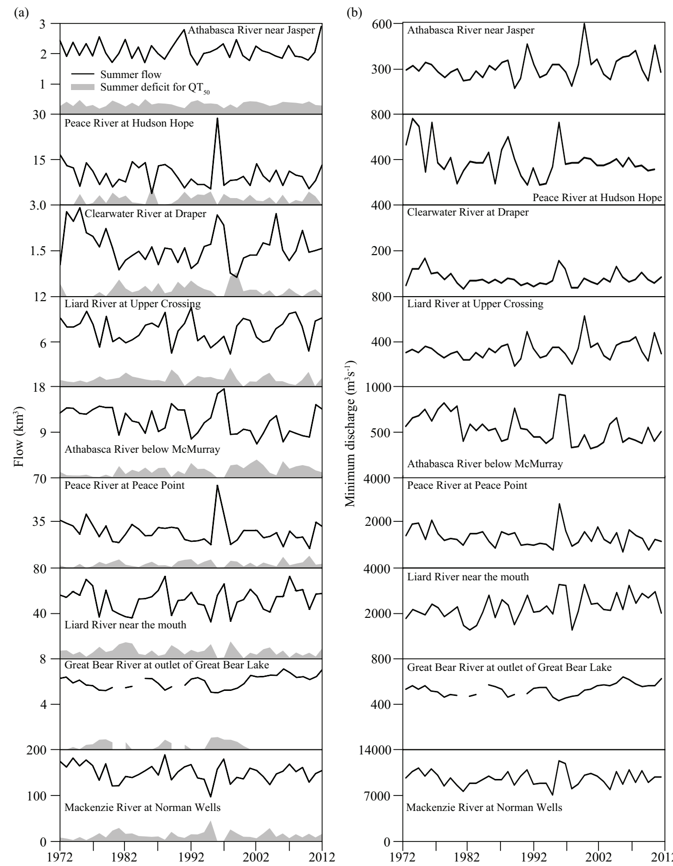


FIG. 7. (a) Total summer flow and deficit below discharge threshold of QT_{50}, and (b) summer minimum discharge for selected rivers in the Mackenzie Basin: headwater rivers of the Athabasca at Jasper, the Peace at Hudson Hope, the Liard at Upper Crossing, the Clearwater, and the Great Bear; major tributaries of the Athabasca at Fort McMurray, the Peace at Peace Point, the Liard near the mouth; and the Mackenzie at Norman Wells.

outflow (Prowse and Lalonde, 1996). However, the effect of the weirs on the Slave River is masked by the substantial influx from the Peace River, as is illustrated by the similarity of relationship between summer flow and summer flow deficit of the Slave River when including and excluding the data from the pre-weir years (Table 1).

SUMMER MINIMUM DISCHARGE

One commonly used indicator of the severity of low flow is the summer minimum discharge, defined as the lowest value recorded for the summer season. For most rivers, this seasonal minimum usually arrives late, long after the spring snowmelt freshet has waned and after days of prolonged evaporation. Exceptions are rivers fed by large lakes or reservoirs that can experience minimum discharge at other times of the summer. The time series of minimum summer discharge generally resembles the year-to-year variations of total summer flow, but both summer flow and the summer minimum display tendencies opposite to that of the summer deficit (Fig. 7). Thus, minimum discharge falls to lower magnitudes in the years with a large flow deficit.

The year-to-year variations of minimum discharge differ considerably among rivers, as indicated by the coefficient of variation (CV), the standard deviation divided by the mean. The values for minimum discharge commonly lie between 20% and 30% (Table 2), but are anomalously small for the Great Bear River, which receives outflow from Great Bear Lake, and for the Mackenzie River at Norman Wells, where inflows from most tributaries of the basin have coalesced to produce an integrated nival flow regime with small interannual deviance in its summer minimum discharge. Some rivers exhibit an anomalously large CV at about 40% or higher. They include CV = 38% for the Peace River at Hudson Hope, which receives irregular releases from the reservoir above the station, and an exceptionally large CV of 79% for the minimum discharge of the Hay River, which drains wetlands and lakes on the Interior Plains that are subjected to the vagaries of summer rain and evaporation depending on the direction of regional air flow over the

TABLE 2. Summer minimum discharge statistics (mean ± SD and coefficient of variation) for selected rivers that are representative of different hydrological conditions in the Mackenzie Basin. Column 3 shows the ratio of deficit to summer demand (%) at three discharge thresholds (QT_{50}, QT_{20}, and QT_{10}).

	Minimum discharge		Deficit/demand ratio (%)		
	(m^3s^{-1})	CV (%)	QT_{50}	QT_{20}	QT_{10}
Athabasca (Jasper)	61 ± 13	21	19.0 ± 3.8	5.3 ± 2.3	2.0 ± 1.6
Athabasca (McMurray)	537 ± 163	30	14.3 ± 9.5	4.3 ± 4.6	2.0 ± 2.7
Peace (Hudson Hope)	388 ± 148	38	19.5 ± 16.6	3.8 ± 6.6	1.5 ± 4.3
Peace (Peace Point)	1328 ± 408	31	13.7 ± 9.5	2.8 ± 4.3	1.1 ± 1.4
Clearwater	94 ± 38	40	14.7 ± 13.7	4.3 ± 7.7	2.0 ± 5.0
Fond du Lac	310 ± 70	23	6.1 ± 7.4	1.4 ± 3.4	0.5 ± 1.7
Hay	81 ± 64	79	22.5 ± 25.3	9.6 ± 16.0	2.6 ± 6.3
Slave	3232 ± 724	22	12.0 ± 9.2	3.0 ± 4.6	1.4 ± 3.1
Liard (Upper Crossing)	321 ± 85	26	16.5 ± 9.0	3.8 ± 5.5	1.6 ± 3.5
Liard (mouth)	2264 ± 534	24	15.1 ± 8.5	3.7 ± 4.4	1.5 ± 2.3
Great Bear River	528 ± 52	10	5.1 ± 6.2	1.0 ± 2.1	0.3 ± 0.9
Peel	545 ± 135	25	16.1 ± 10.7	5.0 ± 7.3	3.0 ± 6.3
Mackenzie (Norman)	9595 ± 1154	12	9.4 ± 6.1	2.4 ± 3.3	1.1 ± 2.1

Mackenzie Basin (Szeto et al., 2008). The Clearwater River passes through both the Interior Plains and the Canadian Shield, but the CV of its summer minimum is moderated to 40% by the generally less variable summer flow of its tributaries in the Shield. Other Shield rivers also exhibit flow variability of low magnitude (e.g., CV = 23% for the Fond du Lac River).

LOW FLOW EVENTS

A sequence of days when discharge falls below a specified threshold constitutes a low flow event. The number of events in summer influences the frequency of cyclical build-up and flushing of pollutants and sediments in rivers. A high threshold gives rise to more low flow events than a lower threshold (e.g., there are more events under QT_{50} than under QT_{20}) and the latter threshold can have more years without a summer low flow condition. Frequent fluctuation of discharge close to the threshold value can produce many low flow events too brief to be significant. Several characteristics of low flow events that occur below three selected discharge thresholds are examined for their starting time, duration, deficit, and the minimum to which the discharge falls.

TIMING AND DURATION OF EVENTS

Most basins become progressively drier as summer advances, unless dry conditions are ameliorated by lake outflow, ample rain in some years or by glacier melt runoff. Consequently, summer flow often reaches lower levels in mid and late summer, and severe low flow events like those that fall below QT_{10} usually begin later in the summer than those below QT_{20}, which in turn occur later than the low flows defined by QT_{50}. Of course, some protracted events can begin with flow below a high threshold but worsen to more intense low flows as the event period continues.

The length, or duration, of events that start on different days of the summer for several headwater and downstream stations in the Mackenzie Basin is presented in Figure 8. One common feature is that events delineated by a low threshold (e.g., QT_{10}) are shorter than those defined under higher thresholds (e.g., QT_{50}). Another feature is that events that extend to the end of summer are aligned onto an upper enveloping line in each plot.

The timing and duration of low flow events at different stations are influenced by regional setting and local conditions, including latitude and elevation, and by the presence of lakes or glaciers and late-lying snowbanks. In southern latitudes and on most of the Interior Plains, the spring freshet begins earlier than in the uplands farther north, and so does the post-melt recession of discharge. Stations on the Athabasca River produce mild low flow events (discharges of < QT_{50} but seldom < QT_{20}) starting from June, but the June events last less than 20 days, while later events can stretch to the end of summer. Severe low flows (discharges < QT_{10}) become more frequent after July. Above Jasper, the Athabasca River flow is augmented by glacier meltwater that interrupts low discharges, and events longer than 30 days appear only after July.

Within comparable latitudes, spring arrives sooner at low elevations, and lowland rivers recede to low discharges before the upland streams do. Low flows can occur any time during the summer and can be terminated by erratic rain events. The Hay River on the Interior Plains and the Clearwater River that crosses the Plains and the Canadian Shield are examples that have both long and short events (from several days to more than three months) spread throughout the summer. Interestingly, the Clearwater has some summers without low flow, which is likely the effect of the many headwater lakes in the Canadian Shield. When linked up with the rest of the drainage network, these lakes offer steady outflow, but flow connectivity can be severed in those years when the level of some lakes in the network chain falls below their outlet levels (Spence, 2006; Woo and Mielko, 2007). The disruption of outflow then leads to low discharge downstream.

The influence of a large lake is particularly pronounced for the Great Bear River with its flow regime controlled by

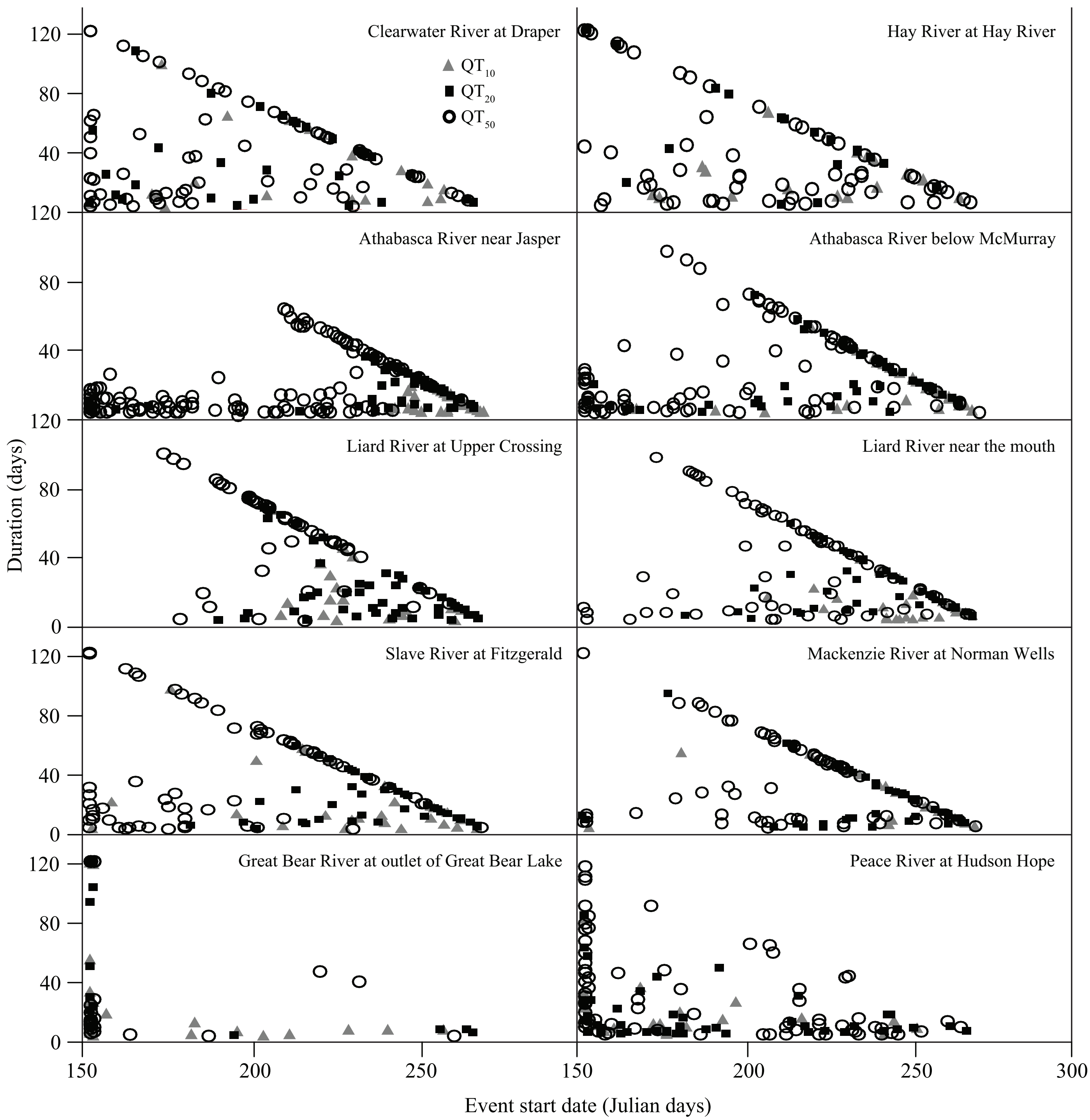


FIG. 8. Duration and starting date of events below low flow thresholds of QT_{50} (○), QT_{20} (■), and QT_{10} (▲) for the Athabasca River at Jasper and Fort McMurray, the Peace River at Hudson Hope, the Clearwater, Hay, Slave, Great Bear, and the Liard Rivers at Upper Crossing and near the mouth, and the Mackenzie River at Norman Wells.

outflow from the large Great Bear Lake. Most low flow events begin in June or earlier, as a continuation of the lengthy winter low discharge. Owing to the relatively uniform discharge, there are years that have either no low flow or entire summers under low flow condition (Fig. 5b), yet there are also many short events that fall not far below the thresholds.

Regulated discharge for hydroelectric production from the large artificial lake on the upper Peace River above Hudson Hope usually results in short low flow episodes, but sometimes produces long low flow events that span several months. The effect of such periodic release and retention of flow is diluted downstream and often becomes undetectable at Peace Point. There, in the lower Peace River, the timing and duration of low flow events resemble those of the Liard River at Upper Crossing. That area lies within the mountains in the middle section of the Mackenzie Basin, where

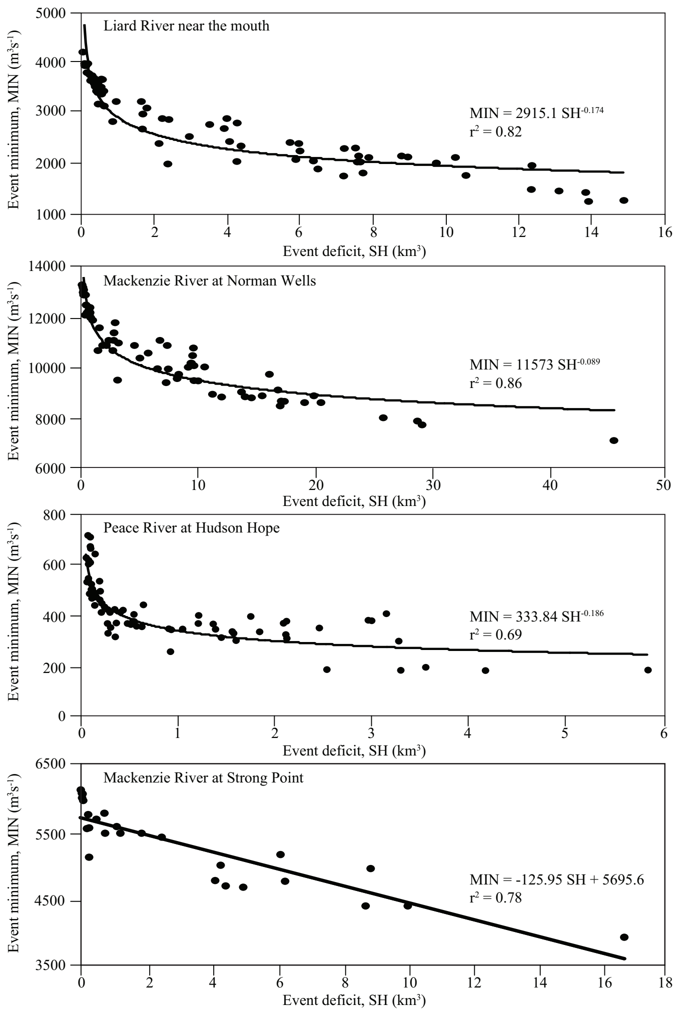


FIG. 9. Relationship between deficit (SH) and the minimum (MIN) of low flow events below QT_{50}. The common pattern is exemplified by the power relationship of the Liard near the mouth and the Mackenzie at Norman Wells. Departures from this pattern are shown by the considerably larger scatter at the Peace at Hudson Hope, which receives regulated flow from a reservoir, and by the linear relationship for the Mackenzie at Strong Point below Great Slave Lake.

snowmelt is delayed by altitude so that recessions seldom fall to low levels until July. Low flows are unusual in early summer, but in those occasional years with an early spring, an early start of recession from high flow can lead to the occurrence of low flow events at the beginning of June.

The Mackenzie River at Norman Wells integrates the flow from about 90% of the basin, but the timing (and to some extent, the duration) of its low flow events follow those of the Liard River mouth at Fort Simpson. This pattern indicates that the flow rhythm of the Liard, and of the northern mountain rivers like the Peel, exerts prominent influence on the low flows of the main Mackenzie River. Whitfield (2008) has also mentioned the allogenic behaviour of the main stem flow (i.e., the flow is attributed to runoff generated elsewhere, rather than being produced in the area where the main river runs).

SUMMER FLOW DEFICIT

Deficit is an important consideration for water supply and for filling of reservoirs. It can be interpreted as the demand that cannot be satisfied by river discharge. In the absence of storage facilities, any flow that exceeds the demand threshold runs off and is not available to relieve future water shortages. Thus, deficits can occur even in years when total summer flow is larger than usual because the amount that exceeds demand drains away before the onset of dry periods. Conversely, high flow days occur even in years when the total summer flow is below normal.

Total amount of summer deficit, incurred below discharge thresholds QT_{50}, QT_{20}, and QT_{10}, can be placed in the context of total summer flow from June to September (Table 1). At the threshold of QT_{50}, all the rivers examined yield a strong correlation between summer flow and summer deficit, suggesting that more severe deficits occur in dry summers while deficits are small in years with large summer flow (Fig. 7a). When the discharge threshold is dropped to lower levels, however, the correlation weakens. The diminished correlation is mainly the consequence of an increased number of summers that have zero deficits below such low thresholds.

LOW FLOW EVENT DEFICIT

In addition to the total amount of deficit for the entire summer, deficits created by individual low flow events within the summer can have socioeconomic and environmental consequences: they can lead to short-term droughts that curtail economic activities, interrupt river traffic, and cause damage to the ecosystem.

Event Deficit and Event Minimum

As an indicator of the severity of low flow, the event minimum is expected to worsen for those events that produce large deficits. This co-varying relationship arises because the amount of deficit increases as the low flow event lengthens, while the discharge continues to decline to a minimum before the hydrograph rises to terminate the event. In detail, the relationship can take on different forms (Fig. 9). For most stations, event minimum has a power relationship with deficit, as shown by the deficit events below QT_{50} for the Liard River at its mouth and for the Mackenzie at Norman Wells. This relationship is attributable to the manner of flow recession, which usually approximates an exponential curve as discharge declines. However, recession departs from this general pattern for the Peace River at Hudson Hope, where the rise and fall of discharge is artificially controlled, and the result is greater scatter of data. Another situation arises at stations below large lakes. For the Mackenzie at Strong Point below Great Slave Lake, for example, the minimum flow has an approximately linear relationship with event deficit, and it is similar for the

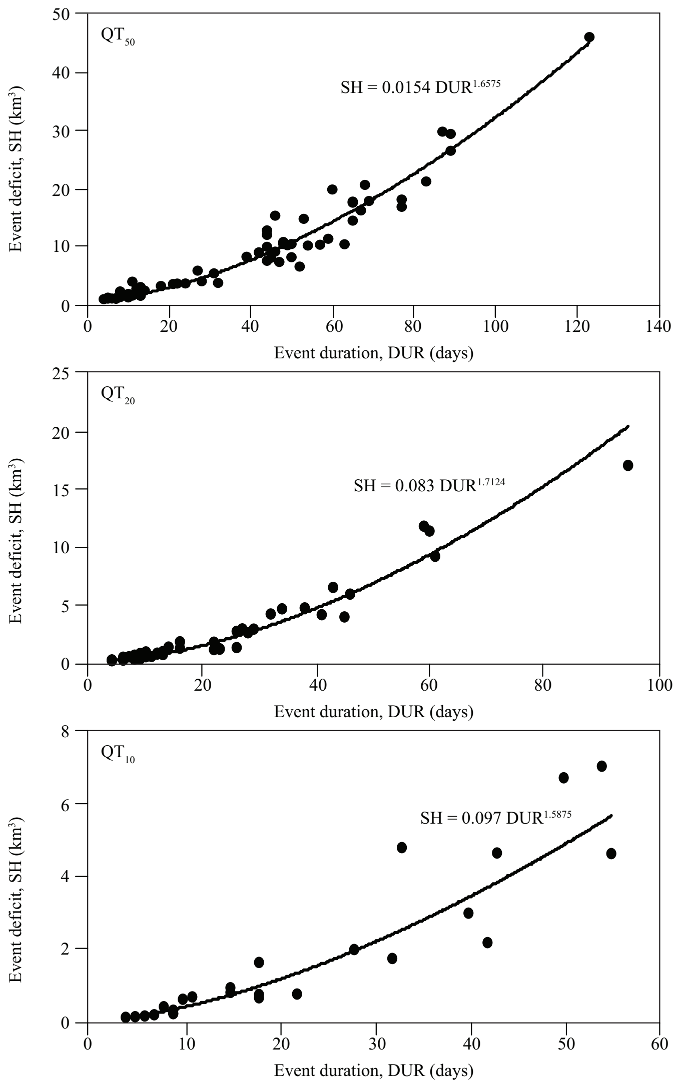


FIG. 10. Relationship between deficit and duration of low flow events as defined by three thresholds (QT_{50}, QT_{20}, and QT_{10}) for the Mackenzie River at Norman Wells.

Great Bear River. Such a departure from the usual power relationship is likely the result of relatively uniform outflow from large lakes that differs from the commonly exponential decline of recession flow.

Duration and Deficit

The amount of deficit is expected to increase when event duration is extended. Clausen and Pearson (1995) noted a linear relationship between annual maximum drought deficit and duration (i.e., for the largest drought event of a year). Here, we adopt a power relationship between event deficit (SH) and event duration (DUR) to accommodate the artificial termination of some low flow events at the end of September, particularly those of longer duration that start in mid-summer.

$$SH = a\ DUR^{b} \qquad (7)$$

where a and b are empirical coefficients. Figure 10 provides an example for the Mackenzie River at Norman Wells, for events below three thresholds. Table 3 lists the correlation coefficients and the number of sample events used to obtain the coefficients for selected stations in headwater areas, at the mouth of principal tributaries, and along the main Mackenzie River. All correlations are statistically significant at the 0.95 level or higher. Equation 4 thus offers a practical way to estimate a low flow event deficit from its duration.

Deficit and Demand

The deficit severity index (DSI), the ratio of deficit to streamflow demand, is calculated using Equation 4. Its complement (1.0 − DSI) indicates the fraction of flow demand that is satisfied by river discharge. Variations of the DSI reflect the risks associated with water shortage between years and among stations at three flow demand thresholds (QT_{50}, QT_{20} and QT_{10}). The ratios are converted into percentages for ease of reading (Table 2). The summary statistics indicate several features.

(1) The index is larger for flows below QT_{50} than for those below QT_{20} and QT_{10} because it is less frequent for discharge to reach the more extreme low levels. For individual years, the index ratio tends to be large when summer flow is low, and vice versa. On the other hand, years with ample summer flow can result in no deficit or the ratio can drop to zero. For all stations, both the 40-year mean and its accompanying standard deviation fall to lower values as the demand level drops.

(2) For the principal tributaries that enter the Mackenzie (the Slave, the Peace at Peace Point, and the Liard at its mouth), the mean deficit index for QT_{50} lies within 12%–16% with a standard deviation of about 9%. The mean decreases for QT_{20}, lying around 3%–4% with a standard deviation of 4%–5%.

(3) The coefficient of variation (CV), indicative of interannual variation relative to the multi-year mean, tends to increase as the demand level falls. Thus, while the demand is reduced to a lower level, the corresponding deficit index becomes relatively more variable between years.

(4) Noticeably high or low indices, particularly those presented by headwater rivers, may be the consequence of several identifiable physical processes. The Athabasca at Jasper is fed by rainfall and glacier melt in the summer, sustaining a moderate to high level of discharge in most years, thus dampening interannual variability of low flow to maintain a small standard deviation. In contrast, the Hay River on the Interior Plains has wide fluctuations in flow in response to the considerable year-to-year differences in rainfall, thereby driving up both the mean deficit and the standard deviation of the deficit ratio. The Clearwater River straddles two physiographical provinces and derives its water from the Interior Plains and from the Canadian Shield with numerous lakes. The different water sources apparently affect the interannual fluctuation in flow, oscillating between large and small deficits in different years.

TABLE 3. Deficit of low flow event (SH) is correlated with event duration (DUR) through the relationship: SH = a DUR^b, for various discharge thresholds (QT) at non-exceedance levels of 10%, 20%, and 50%, for major tributaries of the Mackenzie River and on its main stem. All correlations as shown by r^2-values for n samples are statistically significant. The standard errors are given as s_y.

	QT_{10}					QT_{20}					QT_{50}				
Stations	a	b	r^2	s_y	n	a	b	r^2	s_y	n	a	b	r^2	s_y	n
Athabasca (Jasper)	0.0005	1.44	0.54	2.13	46	0.0005	1.56	0.82	1.61	56	0.0008	1.55	0.93	1.47	109
Athabasca (McMurray)	0.0008	1.70	0.89	1.62	28	0.0015	1.57	0.89	1.54	45	0.0016	1.70	0.91	1.66	87
Peace (Hudson Hope)	0.0004	1.71	0.82	1.86	20	0.0015	1.50	0.88	1.58	46	0.0102	1.29	0.96	1.32	69
Peace (Peace Point)	0.0011	1.87	0.90	1.55	28	0.0028	1.53	0.86	1.64	33	0.0067	1.51	0.91	1.52	57
Clearwater	0.0000	2.07	0.96	1.58	17	0.0000	1.80	0.94	1.60	27	0.0001	1.81	0.94	1.59	65
Hay	0.0000	1.81	0.96	1.26	17	0.0000	1.86	0.96	1.45	16	0.0002	1.87	0.92	1.71	61
Slave	0.0017	1.80	0.93	1.58	25	0.0029	1.66	0.93	1.54	54	0.0038	1.73	0.93	1.68	64
Liard (Upper Crossing)	0.0004	1.67	0.95	1.39	21	0.0003	1.76	0.91	1.62	46	0.0007	1.75	0.96	1.34	46
Liard (mouth)	0.0015	1.94	0.90	1.61	32	0.0043	1.66	0.88	1.56	43	0.0090	1.63	0.95	1.45	66
Great Bear River	0.0002	1.48	0.90	1.78	14	0.0005	1.30	0.97	1.39	15	0.0001	1.72	0.94	1.70	35
Peel	0.0007	1.77	0.90	1.57	32	0.0014	1.64	0.86	1.62	52	0.0038	1.56	0.94	1.40	97
Mackenzie (Strong Pt)	0.0040	1.54	0.99	1.19	5	0.0018	1.75	0.93	1.52	10	0.0036	1.64	0.88	2.05	24
Mackenzie (Simpson)	0.0022	1.95	0.85	1.96	31	0.0048	1.77	0.91	1.53	36	0.0224	1.48	0.90	1.53	50
Mackenzie (Norman)	0.0097	1.59	0.93	1.43	23	0.0083	1.71	0.94	1.46	43	0.0148	1.67	0.94	1.48	66
Mackenzie (Arctic Red)	0.0099	1.65	0.93	1.56	20	0.0072	1.78	0.92	1.67	38	0.0118	1.75	0.93	1.54	57

Another river that shows a large mean and standard deviation is the Peace River at Hudson Hope, where the retention and release of reservoir water are regulated to produce large variations in the deficit ratio. In contrast, the Great Bear River is fed by Great Bear Lake with relatively even outflow. Instead of declining, the discharge of Great Bear River actually rises gradually during the summer because lake storage continues to maintain moderate discharge after the spring. Since 2000, this river has shown no deficit. Below the Great Bear River, the main stem of the Mackenzie River at Norman Wells integrates the flows of its tributaries and likewise has a small mean deficit ratio (< 10%) and standard deviation.

Downstream Variation of the Deficit Severity Index

We examined downstream variation of the DSI for each month. In Equation 4, we used the number of days for a given month instead of the total number of days in the summer season (i.e., we re-set k in the equation). This index that represents failure to satisfy the demand may be considered as an indication of the severity of streamflow drought, with higher values suggesting droughts of greater intensity. The index is examined between 1972 and 2012 for selected stations along the major tributaries and down the main stem of the Mackenzie River, with the deficit defined at two threshold levels (QT_{50} and QT_{20}) for individual stations. The threshold discharge values are station-specific, though fluctuation in the seasonal pattern of DSI for an upstream station may be similarly encountered in the monthly rhythm of DSI for the station downstream if both stations suffer the same droughts.

As shown in Figure 11, the index is lower and exhibits less interannual variation for flows under QT_{20} than for those under QT_{50}, suggesting that on a monthly time scale, intense low flow events are less frequent and are of shorter duration so that smaller total deficits are incurred than for events delineated below a higher threshold. Regarding timing, the DSI for most stations is often lower for June, and for July in some cases, than for August and September. This is an expected outcome because most low flow events cluster in the latter part of summer. Months with high DSI also show more interannual variation in the index. When there are basin-wide dry or wet years, DSI values are prevalently high or low across the Mackenzie Basin. Widespread dry conditions in the summer of 1995, for example, gave rise to high DSI at most stations (other than those benefiting from direct lake or reservoir outflows). On the other hand, the wet summer of 1996 led to low DSI for many stations across the basin.

Headwater rivers best reflect the hydrological influence of their basin environments. The index for mountain headwaters, like the Athabasca at Jasper or the Liard at Upper Crossing, is less variable than that for lowland rivers that traverse the foothills and plains. However, reservoir operation on the Upper Peace totally distorts the natural flow of this mountain river so that the DSI at Hudson Hope is highly variable. For a different reason, many rivers on the Interior Plains, such as the Hay River, are prone to much variability. This variability is due to interruptions of low flow by sporadic convective rainstorms engendered by local heating, as well as the many reversals in airflow (relatively cool, dry conditions prevail when air flow is from the north, but air flow from the southeast brings warm, wet conditions that raise the river discharge, as described by Szeto et al., 2008). On the other hand, glaciated and thermokarst landscape on the Plains has many depressions, and where these are filled with water, the frequent presence of lakes and wetlands reduces fluctuations in discharge, as indicated by the low DSI for the river that flows out of Lac La Martre.

The Canadian Shield is occupied by numerous lakes. The lake storage effect dampens unevenness of flow, so the rivers (e.g., Fond du Lac, Camsell) tend to have low DSI. An extreme is the Great Bear River: fed by a large lake, it has remarkably uniform flow and low DSI because lake storage tempers interannual flow variation. When a Shield river is joined by one from the Plain, like the tributaries of

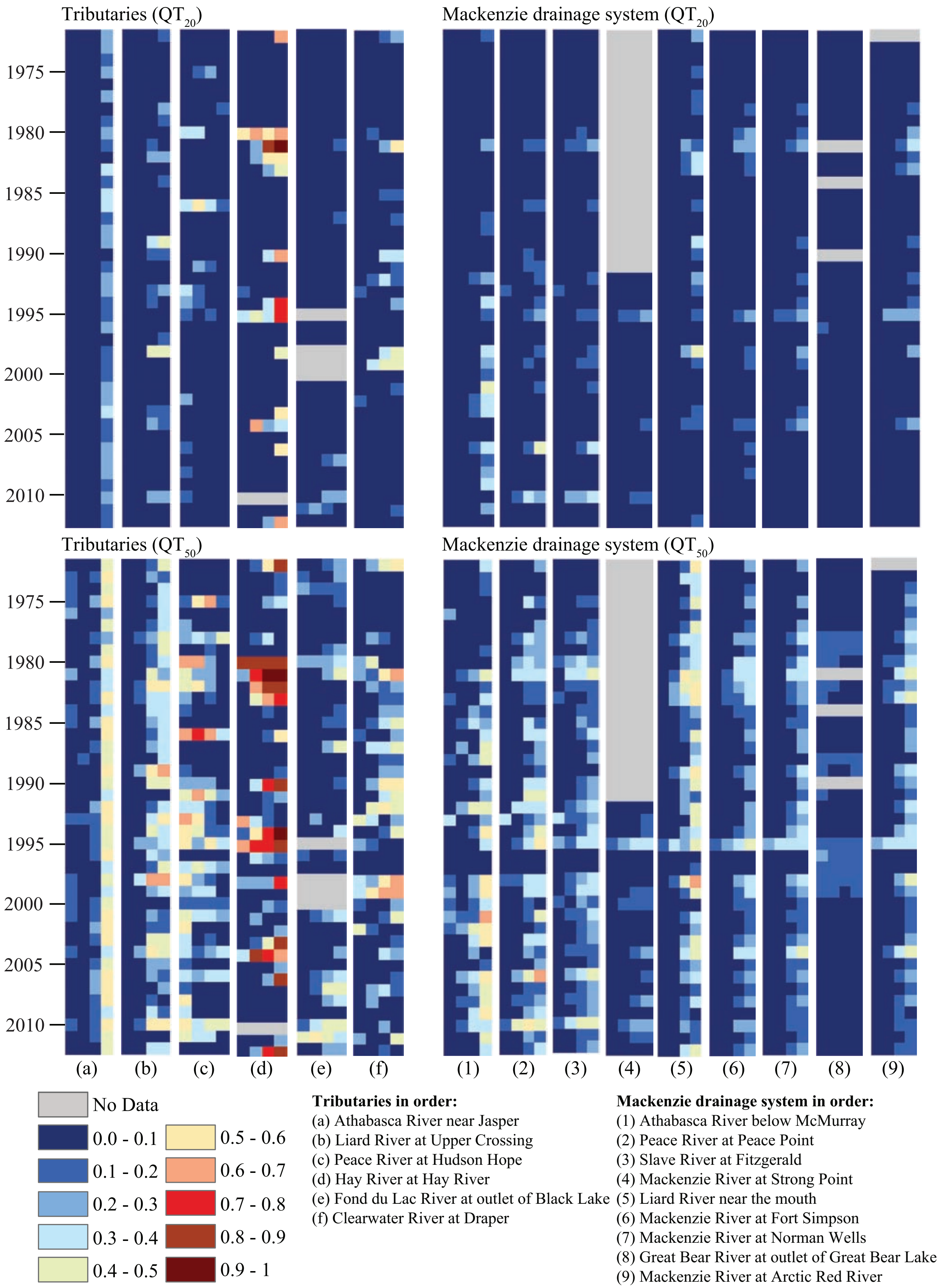


FIG. 11. Monthly (June to September) variations of the deficit severity index between 1972 and 2012 for selected stations in the Mackenzie drainage system, with deficit defined at two threshold levels (QT_{50}, QT_{20}) for individual stations.

the Clearwater River, the resultant DSI is a compromise of the effects of the two environments.

Principal tributaries of the Mackenzie River experience less fluctuation in DSI between years because headwater flows are systematically integrated downstream. For the Peace River, increasing contribution from unregulated tributaries restores the summer flow natural to mountain streams, and at Peace Point, the river exhibits a DSI similar to that of the Liard River. The Peace River and the Athabasca River constitute two principal branches of the Slave River, and there is a weak correspondence in the DSI patterns of the Slave River with these two branches. However, the Mackenzie River at Strong Point does not follow the pattern of the Slave River, possibly because the intervening Great Slave Lake modifies the Slave River input before issuing its outflow to the Mackenzie. The Liard River follows a similar DSI pattern from its headwater at Upper Crossing to its mouth at Fort Simpson, reflecting a high degree of parallelism in hydrograph fluctuation down the river. A general resemblance of the DSI between the Liard River and the Mackenzie River from Fort Simpson to downstream indicates that the monthly rhythm of low flow, hence the deficit, of the Liard River plays a strong role in affecting the deficit pattern of the Mackenzie.

PROBABILITY ANALYSES OF LOW FLOW EVENTS

Pertinent characteristics of historical low flow events can be conveniently summarized by their probability distributions. Since event occurrence has an inherent element of randomness, the application of probability analysis facilitates the assessment of risks. Characteristics associated with low flow events include event duration, the amount of event deficit, and the magnitude of the event minimum. For this investigation, several comments are in order.

1) It is recognized that some events are terminated by the arbitrary end of the summer season, rather than by an actual rise of discharge back above the low flow threshold, but these events have to be included for practical considerations because of the limited number of available samples. For the same reason, it is necessarily assumed that all events are drawn from a homogeneous population.

2) There is no definitive measure to determine whether one type of probability distribution is superior to another, and the Kolmogorov-Smirnov goodness-of-fit test is used to show that the chosen distribution cannot be rejected on statistical grounds. We prefer distributions with parameters that can be obtained by the method of moments, specifically the mean and the variance, so that these parameters can be manipulated to explore the effect of increase or decrease in the average and in variability.

3) Fitting probability distribution curves to the data permits interpolation and extrapolation of occurrence probabilities for events not manifested in the historical time series, which effectively extends the range of the available data.

Event Duration and Deficit

On theoretical and empirical grounds, as implied in Zelenhasić and Salvai (1987), event duration and deficit are closely related because of the steady recession in the hydrographs from high to low flows. These variables are expected to have distributions belonging to the Poisson and its associated exponential family of distributions.

Figure 12a gives examples of applying a generalized exponential distribution (Equation 5) to fit the event duration for stations at a headwater river (Clearwater River), at the mouth of a major tributary (Liard River), and on the main stem of the Mackenzie River at Arctic Red River station. The Kolmogorov-Smirnov goodness-of-fit test indicates that the observed and fitted values do not differ significantly for any of the three thresholds. For the headwater rivers, the generalized exponential distribution may or may not apply. Table 4 summarizes the means, standard deviations, estimated parameters, and root-mean-square differences between the observed and fitted values for all the cases in which the test does not reject the assumed theoretical distribution. Where the fit is poor (i.e., rejected by the test), only the means and standard deviations are listed. These cases include such situations as a limited number of available events (e.g., Great Bear River with a short record) and the arrival of low flow events that possibly does not follow the exponential assumption (such as the Peace River at Hudson Hope subject to flow regulation, or Athabasca River at Jasper with mixed flow contributions from glacier and rain that have different likelihoods of arrival).

The generalized exponential distribution is applied to the event deficit. The results (not shown here) are similar to those for the event duration, with the generalized exponential being appropriate for all the major tributaries and the main trunk of Mackenzie River. The fit is satisfactory for the headwater rivers, except for those same stations with poor fit for the event duration. This outcome is expected because of the close relationship between the duration and deficit of events.

Event Minimum

The Gumbel distribution (Equation 6) is applied to the lowest discharge of low flow events. Examples of using this distribution to fit the event minima are presented in Figure 12b. Kolmogorov-Smirnov tests indicate that the observed and fitted values do not differ significantly for most stations and for the three thresholds. Values of the fitted parameters are given in Table 4. Poor fit results from a limited number of available events (e.g., the Liard River at Upper Crossing with few events below its QT_{10}). The

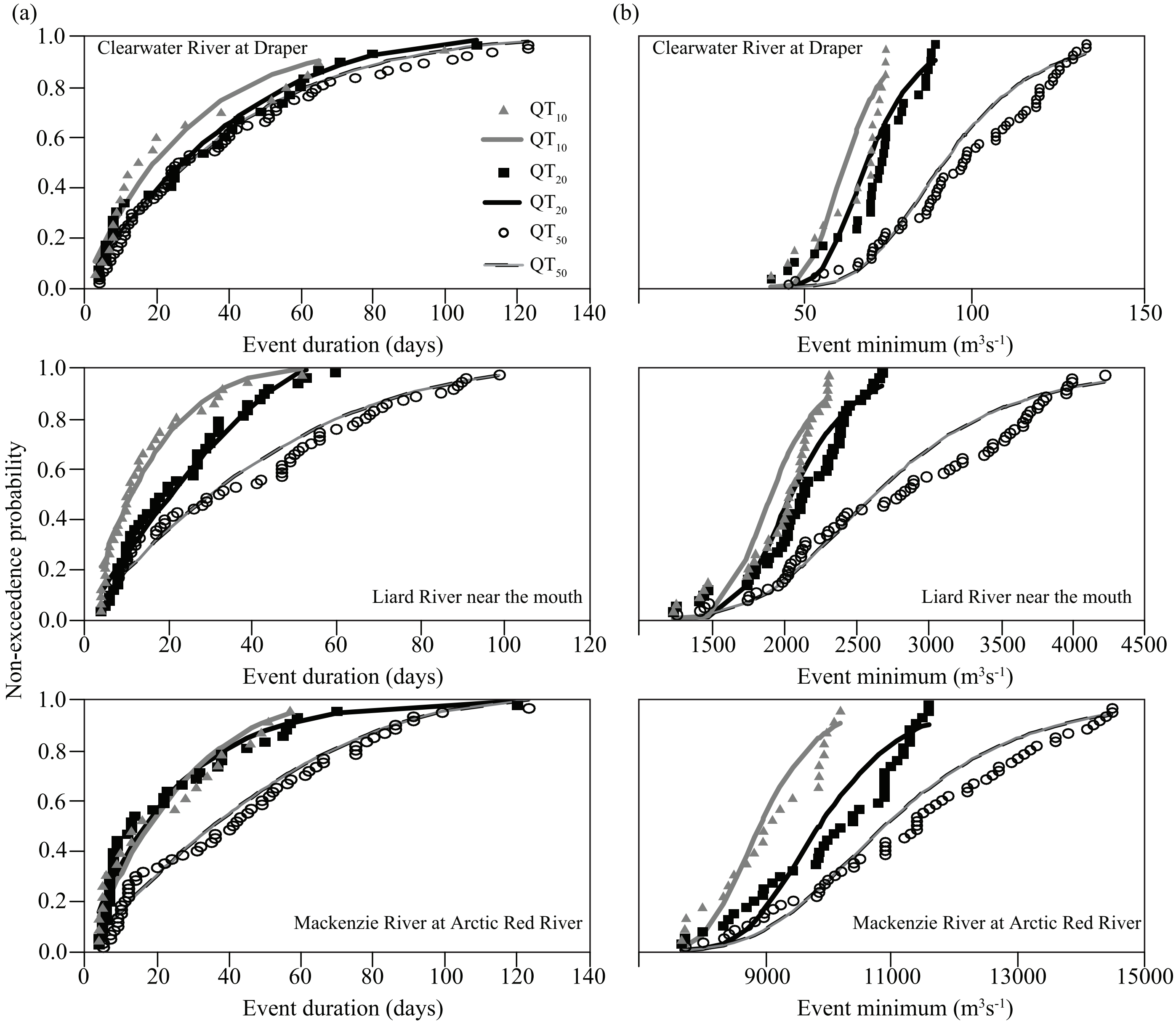


FIG. 12. (a) – left panels: Examples of fitting the generalized exponential distribution to low flow event duration and (b) – right panels: Examples of fitting the Gumbel distribution to event minimum, for events defined by three flow thresholds. The Clearwater is a headwater river, the Liard River near the mouth is a major tributary, and the lower course of the Mackenzie River is gauged at Arctic Red River station.

reduced availability of events for the lower thresholds often gives rise to larger root-mean-square errors.

CONCLUSIONS

After the snowmelt freshet in spring, discharge in the Mackenzie River system generally recedes in the summer toward low flow conditions. With practical application as a consideration, low flow is defined by the discharge that drops below a specified level of concern or interest. Such an approach provides the flexibility that water users and resource managers need to perform similar analyses, using their stated discharge level to assess the attendant attributes of low flow.

This paper fulfills three main purposes:

1) It assesses the mechanisms associated with summer low flow, which include local atmospheric conditions that influence moisture input and loss (through rainfall, snow and glacier melt, evaporation); rate of recession from high flows, reflecting groundwater contribution during the low flow period; surface (river) inflow from the upstream drainage network; the storage effect of large lakes, which modifies the retention and release of inflow; human alteration of the natural flow regime, notably below Bennett Dam on the Peace River; and termination of the summer season.

TABLE 4. Means (μ) and standard deviations (σ) of duration and minimum of events below three thresholds for selected river stations in the Mackenzie Basin. Also shown are parameters (k and α) and root-mean-square errors (RMS) for fitting the observed data with the generalized exponential and the Gumbel distributions.

		Event duration, days (Generalized exponential)					Event minimum, m^3s^{-1} (Gumbel)				
		μ	σ	k	α	RMS	μ	σ	γ	β	RMS
Athabasca (Jasper):	QT_{50}	19.3	17.4	–[1]	–	–	110.7	42.8	–	–	–
	QT_{20}	16.1	9.2	−0.965	−31.7	0.046	69.0	18.3	1.281	60.7	0.042
	QT_{10}	9.5	5.7	−1.104	−19.9	0.086	61.1	11.0	0.116	56.2	0.048
Athabasca (McMurray):	QT_{50}	28.6	24.1	4.895	−168.4	0.047	658.3	180.4	–	–	–
	QT_{20}	22.6	16.4	−2.252	−73.4	0.039	496.6	96.8	0.013	453.0	0.094
	QT_{10}	18.5	13.6	−2.307	−61.3	0.047	436.4	69.4	0.018	405.2	0.067
Peace (Hudson Hope):	QT_{50}	30.9	30.4	−62.14	−1953	0.055	408.1	123.5	0.010	352.5	0.036
	QT_{20}	16.7	17.4	24.49	391.0	0.077	342.8	67.3	0.019	312.5	0.118
	QT^{10}	18.1	17.0	−16.55	316.6	0.070	295.4	66.8	–	–	–
Peace (Peace Point):	QT_{50}	40.6	27.8	−1.776	−112.6	0.033	1432	357.4	0.004	1271.3	0.069
	QT_{20}	25.4	19.1	−2.606	−91.7	0.046	1137	196.0	0.007	1048.8	0.081
	QT_{10}	12.6	11.5	−10.86	−149.0	0.095	1054	145.9	0.009	988.2	0.107
Clearwater:	QT_{50}	37.8	32.1	−5.121	−231.6	0.027	95.1	24.2	0.053	84.2	0.005
	QT_{20}	34.1	27.2	−3.481	−153.0	0.046	70.6	13.3	0.097	64.6	0.102
	QT_{10}	27.8	27.0	−33.04	−945.9	0.062	63.6	10.9	0.118	58.7	0.148
Hay:	QT_{50}	35.2	34.5	−48.86	−1754	0.042	89.6	46.8	–	–	–
	QT_{20}	49.4	33.4	−1.673	−132.2	0.048	22.6	14.5	0.088	16.1	0.076
	QT_{10}	22.3	14.8	−1.573	−57.3	0.074	16.2	4.3	0.297	14.3	0.103
Slave:	QT_{50}	43.9	35.5	−3.753	−208.8	0.041	3440	631.1	0.002	3156.7	0.050
	QT_{20}	22.4	22.8	49.01	1073.4	0.049	3067	367.8	–	–	–
	QT_{10}	22.8	22.9	138.8	3139.6	0.058	2806	323.1	0.004	2660.1	0.103
Liard (Upper Crossing):	QT_{50}	30.9	30.4	−62.14	−1953	0.255	408.1	123.5	0.010	352.5	0.036
	QT_{20}	16.7	17.4	24.49	391.0	0.077	342.8	67.3	0.019	312.5	0.118
	QT_{10}	18.1	17.0	−16.55	−316.6	0.070	295.4	66.8	–	–	–
Liard (mouth):	QT_{50}	36.9	28.0	−2.751	−138.2	0.047	2785	814.5	0.002	2418.3	0.070
	QT_{20}	22.6	14.6	−1.422	−54.7	0.041	2126	367.9	0.003	1960.9	0.083
	QT_{10}	14.4	11.7	−3.925	−70.8	0.060	1973	301.0	0.004	1837.5	0.121
Great Bear River:	QT_{50}	65.0	54.9	–	–	–	523.5	43.5	0.029	503.9	0.117
	QT_{20}	58.0	51.9	−8.095	−537.5	0.113	475.9	20.2	0.063	466.8	0.064
	QT_{10}	27.7	38.0	4.273	90.6	0.079	471.5	16.5	0.078	464.1	0.093
Peel:	QT_{50}	22.6	21.8	−26.67	−625.8	0.057	698.1	180.7	0.007	616.8	0.084
	QT_{20}	17.3	14.7	−5.276	−108.4	0.073	528.7	95.2	0.013	485.9	0.083
	QT_{10}	13.6	12.9	−26.41	−369.2	0.076	471.9	76.0	0.017	437.6	0.108
Mackenzie (Simpson):	QT_{50}	47.4	28.0	−1.073	−98.2	0.039	8022	1160.5	0.001	7500.1	0.061
	QT_{20}	27.1	17.5	−1.447	−66.3	0.038	7283	634.2	0.002	6998.0	0.066
	QT_{10}	17.7	15.8	−7.889	−157.3	0.067	7066	478.4	0.003	6850.8	0.079
Mackenzie (Norman Wells):	QT_{50}	37.3	27.6	−2.410	−127.2	0.054	10497	1586.7	0.001	9783.1	0.059
	QT_{20}	22.4	19.5	−6.387	−165.1	0.044	9411	866.1	0.001	9020.9	0.090
	QT_{10}	22.4	16.5	−2.345	−75.1	0.051	8696	620.9	0.002	8416.2	0.103
Mackenzie (Arctic Red River):	QT_{50}	41.4	30.0	−2.188	−132.1	0.038	11236	1911.6	0.001	10376	0.059
	QT_{20}	24.4	24.5	198.7	4832	0.064	10071	110.7	0.001	9543.9	0.099
	QT_{10}	22.3	17.9	−3.645	−103.4	0.064	9066	838.7	0.002	8688.9	0.085

[1] Parameters are not listed for those cases where goodness of fit is rejected by the Kolmogorov-Smirnov goodness-of-fit test.

2) It analyzes low flow characteristics, including timing, duration and magnitude, for the main stem and selected tributaries of the Mackenzie River. Most low flow events, especially those that encompass discharge that drops below very low threshold levels, occur in late summer. Event duration is related to deficit, and the latter is also correlated with minimum discharge of the event. The ratio of deficit to demand, or the deficit severity index, tends to be more seasonally variable for headwater streams than for the large tributaries of the Mackenzie, though in very dry summers, the index value is high for the entire Mackenzie Basin.

3) Probability studies allow interpolation and extrapolation of the probability of occurrence of minimum discharge, duration, and deficit of low flow events, thus offering a tool for water resource planning and management applications.

As the main northern river in North America, the Mackenzie is a chief provider of water resources and the main artery for water transportation. An understanding and a characterization of summer low flows will facilitate policy making, planning, jurisdiction, and management of streamflow droughts in northern territories.

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