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Streamflow in the Mackenzie valley

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Abstract: Rivers in the Mackenzie valley generally exhibit a spring-snowmelt dominated mean monthly flow pattern classified as a subarctic, nival flow regime. Along the Mackenzie River, ice jamming during spring breakup is an important process since it can obstruct flow locally and elevate river stage to flood levels. Flow along the large tributary rivers draining the Mackenzie Mountains to the west of the Mackenzie River can rise and fall rapidly in response to rain storms and diurnal snow melt. Global climatic change may result in an increase in the magnitude and frequency of extreme floods, in common with mid-latitude rivers. Some hydraulic modelling suggests that precipitation, and therefore runoff, will increase, but other models indicate that the increased precipitation will be offset by greater evapotranspiration. Considerably more immediate and drastic changes to the flow regime of a given river could arise from dam construction for hydroelectric generation.

Résumé : Les rivières de la vallée du Mackenzie affichent généralement un débit mensuel moyen qui montre l'effet prédominant de la fonte nivale printanière, définissant un régime d'écoulement que l'on qualifie de nival subarctique. Tout le long du fleuve Mackenzie, la formation d'embâcles de glace durant la débâcle printanière est un phénomène important puisque l'obstruction de l'écoulement local par les glaces produit une élévation des eaux du fleuve jusqu'aux niveaux d'inondation. Le débit des principaux affluents qui drainent les monts Mackenzie à l'ouest du fleuve Mackenzie peut fluctuer rapidement suite à des pluies torrentielles ou en raison de la fonte diurne de la neige. Le réchauffement climatique à l'échelle planétaire se traduit par des crues extrêmes plus intenses et plus fréquentes, comme sous les latitudes moyennes. Certains modèles hydrauliques indiquent que les précipitations et, par conséquent, le ruissellement, augmenteront, alors que d'autres modèles laissent entendre qu'une augmentation des précipitations sera compensée par un accroissement de l'évapotranspiration. La construction de barrages pour la production d'électricité pourrait causer des changements considérablement plus rapides et importants au régime d'écoulement d'un cours d'eau donné.

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INTRODUCTION

The Mackenzie River network represents an integral component of the geomorphic landscape in the Mackenzie valley and functions as an important transportation network for communities and economic activities in the region. The purpose of this paper is to review the general streamflow characteristics of Mackenzie River and its major tributaries and to discuss the possible implications on streamflow of global climatic change and flow regulation by hydroelectric dam construction.

DATA

Streamflow in the Mackenzie valley is measured routinely by the Water Survey of Canada (Water Survey of Canada, 1992). For such a large area, the density of stations is very low compared to southern Canada, and many large rivers are ungauged (e.g. Hare Indian River, North Nahanni River). Except for several stations along Mackenzie River and its most important Mackenzie valley tributary, Liard River, streamflow records are of relatively short duration, beginning in the early 1970s or later (Table 1). For some stations, only partial records exist for the initial several years. Many of these stations were established in response to proposed pipelines, highways, and hydroelectric power projects along the Mackenzie valley, most of which were not built.

FLOW REGIME

Generally, rivers in the Mackenzie valley exhibit a spring-snowmelt-dominated mean monthly flow pattern classified as a subarctic, nival flow regime (*see* Church, 1974, 1977). The maximum mean monthly discharge occurs in the May to July period, mainly due to snowmelt. As the snow pack wanes, flow gradually becomes dependent upon base flow and discharge generally decreases slowly through the summer months. This decrease in flow continues throughout the fall and into the winter as ground temperatures decline and freeze-up begins. Storm-induced flows cause periodic increases in discharge that may significantly exceed the

Table 1. Background information about steamflow recording stations.

Station	Station number	Record	Location (lat./long.)	Drainage area (km^2)	River stage[a] (m) At mean annual discharge (m^3/s)	At maximum mean monthly discharge (m^3/s)	At maximum historic daily discharge (m^3/s)
Mackenzie River at Arctic Red River	10CL014	1972–1992	67°27′30″N 133°44′41″W	1 660 000	3.45 (9140)	6.48 (21 400)	8.30 (35 000)
Mackenzie River at Norman Wells	10KA001	1943–1992	65°16′21″N 121°21′25″W	1 570 000	3.94 (7760)	6.13 (17 300)	8.50 (33 300)
Mackenzie River at Fort Simpson	10GC001	1938–1992	61°52′07″N 117°29′48″W	1 270 000	4.83 (6770)	7.03 (14 200)	9.62 (23 500)
Mackenzie River near Fort Providence	10FB001	1961–1978	61°15′04″N 117°29′48″W	971 000	151.21 (4280)	152.28 (7160)	152.83 (8830)
Liard River near the mouth	10ED002	1972–1992	61°44′50″N 121°13′25″W	277 000	2.70 (2490)	5.56 (7600)	8.58 (16 100)
Great Bear River at outlet of Great Bear Lake	10JC003	1961–1992	65°08′05″N 123° 31′06″W	145 000	1.89 (534)	2.05 (590)	2.19 (644)[b]
Peel River above Fort MacPherson	10MC002	1969–1992	67°14′10″N 134°54′28″W	70 600	5.01 (694)	7.67 (2540)	12.24 (8800)
Willowlake River above Metahdali Creek	10GB006	1975–1992	62°39′01″N 122°53′51″W	20 200	4.58 (71)	6.12 (335)	9.50 (1910)
Arctic Red River near the mouth	10LA002	1968–1992	67°47′19″N 133°04′46″W	18 600	2.29 (158)	3.57 (532)	7.94 (3000)
Redstone River 63 km above mouth	10HB005	1974–1992	63°55′32″N 125°18′02″W	15 400	2.69 (181)	3.37 (495)	5.30 (3030)[b]
Mountain River below Cambrian Creek	10KC001	1978–1992	65°13′38″N 128°34′00″W	11 100	3.86 (123)	4.70 (403)	5.50 (1400)
Root River near the mouth	10GA001	1974–1992	62°28′34″N 123°25′49″W	9820	2.70 (95)	3.28 (235)	9.763 (5730)
Blackwater River at outlet of Blackwater Lake	10HC006	1986–1992	63°54′06″N 123°19′22″W	7850	1.52 (47)	5.19 (181)	6.63 (573)
Ramparts River near Fort Good Hope	10KD004	1985–1992	66°07′00″N 129°16′16″W	7410	1.88 (43)	2.84 (167)	5.00 (662)[b]
Carcajou River below Imperial Creek	10KB001	1976–1992	65°17′52″N 127°41′05″W	7400	4.17 (74)	5.03 (220)	8.90 (1900)[b]

[a] River stages were extrapolated from Water Survey of Canada discharge-stage graphs and are relative to arbitrary datum points at the location of the gauging stations i.e. a stage of 0 m does not necessarily correspond to a discharge of 0 m^3/s.
b Maximum stage and discharge on the available discharge-stage graph. Higher discharges have been reported for these rivers, estimated by extrapolating the existing curves.

highest mean monthly flow, particularly for rivers draining the Mackenzie Mountains to the west of Mackenzie River. From January to March, discharge is very low because precipitation occurs as snow and base flow is severely limited by the deeply frozen land surface. The onset of snow melt in April causes the discharge cycle to repeat itself.

The subarctic, nival regime is readily apparent on the hydrographs of Liard, Root, Redstone, Carcajou, Mountain, Ramparts, Arctic Red, Peel, and Willowlake rivers, and Mackenzie River at Fort Simpson, Norman Wells and Tsiigehtchic (formerly Arctic Red River) (Fig. 1). These hydrographs depict average mean monthly discharge, but there is considerable variation in mean monthly flow from year to year, particularly between April and November, as illustrated by the plus and minus two standard deviations of mean monthly flows plotted on the selected hydrographs of Figure 2. Daily streamflow during these months, however, may vary considerably, and even significantly depart from mean month flow conditions (Fig. 2) because of fluctuations in short-term weather conditions (e.g. periods of warming and cooling, rainstorms).

The subarctic, nival flow regime is attenuated where large lakes are present within a watershed (e.g. Mackenzie River at Fort Providence, Great Bear River). Large lakes function as natural reservoirs where water is stored and released gradually, thus minimizing extreme discharges and decreasing the variation between maximum and minimum mean monthly flows. The degree of flow regime dampening is a function of the lake basin size, the size of the lake relative to the drainage basin, and proximity of the stage recorder to the lake outlet. The attenuation of runoff is very pronounced for both daily and mean monthly flows for the Great Bear River station at the outlet of Great Bear Lake, as the surface area of the lake represents 21% of the drainage basin (Fig. 2c).

Comparison of the four hydrographs for Mackenzie River (Fig. 1) reveals an obvious change in the flow regime downstream along the Mackenzie valley. At Fort Providence, Mackenzie River has an attenuated discharge regime reflecting the proximity of the station to the outlet of Great Slave Lake. The late spring, summer, and fall mean monthly flows increase significantly downstream between the successive stations because of the addition of runoff from the tributary basins. Overall, the subarctic, nival regime of Mackenzie River becomes more developed downstream. During the winter, the downstream increase in mean monthly flow is relatively insignificant because of the very low winter tributary flows being added to the Great Slave Lake outflow. The most important supplement to Mackenzie River discharge comes from the largest tributary, Liard River. Flow from Liard River produces a marked increase in the summer and fall mean monthly flows of the lower Mackenzie River; the Fort Simpson hydrograph essentially consists of the Liard River and Fort Providence hydrographs superimposed upon one another.

ICE JAMS

Ice jamming along the river channels during the annual spring breakup is an important process in the Mackenzie River system. Major ice jamming in Mackenzie River often occurs as snowmelt runoff from the tributaries is being routed into the trunk stream at the same time as the Mackenzie River ice cover is breaking up. Large ice jams can severely obstruct river flow locally causing a major rise in river stage. A reconstruction of flood events at selected communities along Mackenzie, Liard, and Peel rivers by Kriwoken (1983) found that most large floods were associated with high backwater conditions generated by large ice jams situated downstream. Determining the levels and frequencies of such floods must often rely upon geomorphic evidence along the river banks or historical records rather than flow-based flood frequency relationships, because stage-discharge curves are not applicable under backwater conditions generated from ice jams or water-level data is either unavailable or available for only a short duration.

The critical role of Liard River streamflow in initiating the spring breakup of Mackenzie River is particularly noteworthy. In most years, the winter ice cover of Mackenzie River downstream of the Mackenzie–Liard confluence breaks up before the section of river upstream (MacKay and Mackay, 1973). This breakup pattern is triggered by a rise in stage of Mackenzie River resulting from the influx of the Liard River spring flow (Prowse, 1984). The addition of the Liard spring flow exerts great pressure on the Mackenzie River ice cover resulting in the lifting and fracturing of the ice mass (MacKay and Mackay, 1973). The actual breakup commonly is caused by the physical jamming and push of broken-up Liard ice into the Mackenzie River ice cover. In the section of Mackenzie River upstream, the ice cover is not subject to a significant rise in stage due to the damping effects on discharge caused by Great Slave Lake and thus breakups occur later than below the Mackenzie–Liard confluence.

MACKENZIE RIVER TRIBUTARIES

Many of the Mackenzie tributaries occupy large river basins that appear relatively small when compared to the continental scale of the Mackenzie River system. Rivers draining the Mackenzie Mountains to the west of Mackenzie River have ‘flashy’ discharge regimes, because streamflow can rise and fall rapidly in response to rainstorms and diurnal snowmelt. This characteristic is not apparent from the mean monthly discharge patterns depicted in Figure 1, but can be seen in the 1991 mean daily hydrographs of Redstone and Willowlake rivers (Fig. 2a, 2d.). Rivers draining the lowlands and plains east of Mackenzie River have a less responsive discharge regime because of the presence of lakes and extensive bogs, which attenuate runoff from both snowmelt and rainstorm events. Also, the more subdued plain and lowland topography east of Mackenzie River does not produce widespread intense rainfall, as generated the major orographic uplift of moist air masses over the Mackenzie Mountains to the west.

All of the tributaries, except for those whose flow regime is conditioned by large lakes (e.g. Great Bear River and, to a lesser extent, Blackwater River), experience large periodic increases in discharge, due to severe summer rainstorms (*see* Mackay et al., 1973; Jasper and Kerr, 1992). Because such events only last for a few days and may not reoccur for up to 20–30 years, the magnitude of extreme discharges are not always apparent in historic maximum daily discharge and

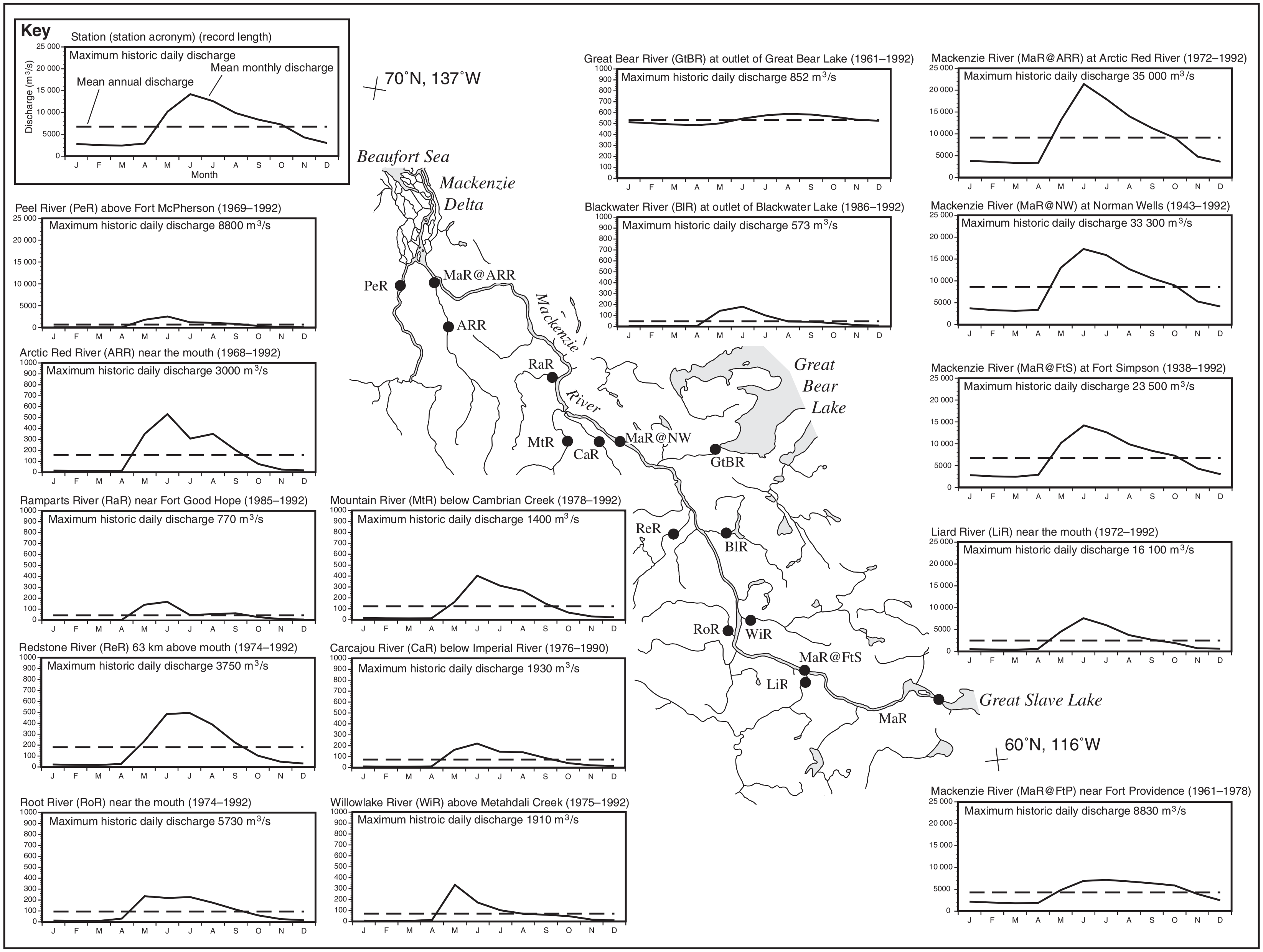

Figure 1. *Hydrographs for the Mackenzie and eleven major tributaries and a map showing the location of the streamflow gauging stations. Each hydrograph shows the mean monthly flow (m^3/s) and the maximum recorded daily flow. Note that hydrographs are plotted at two different scales, 0–1000 m^3/s and 0–25 000 m^3/s.*

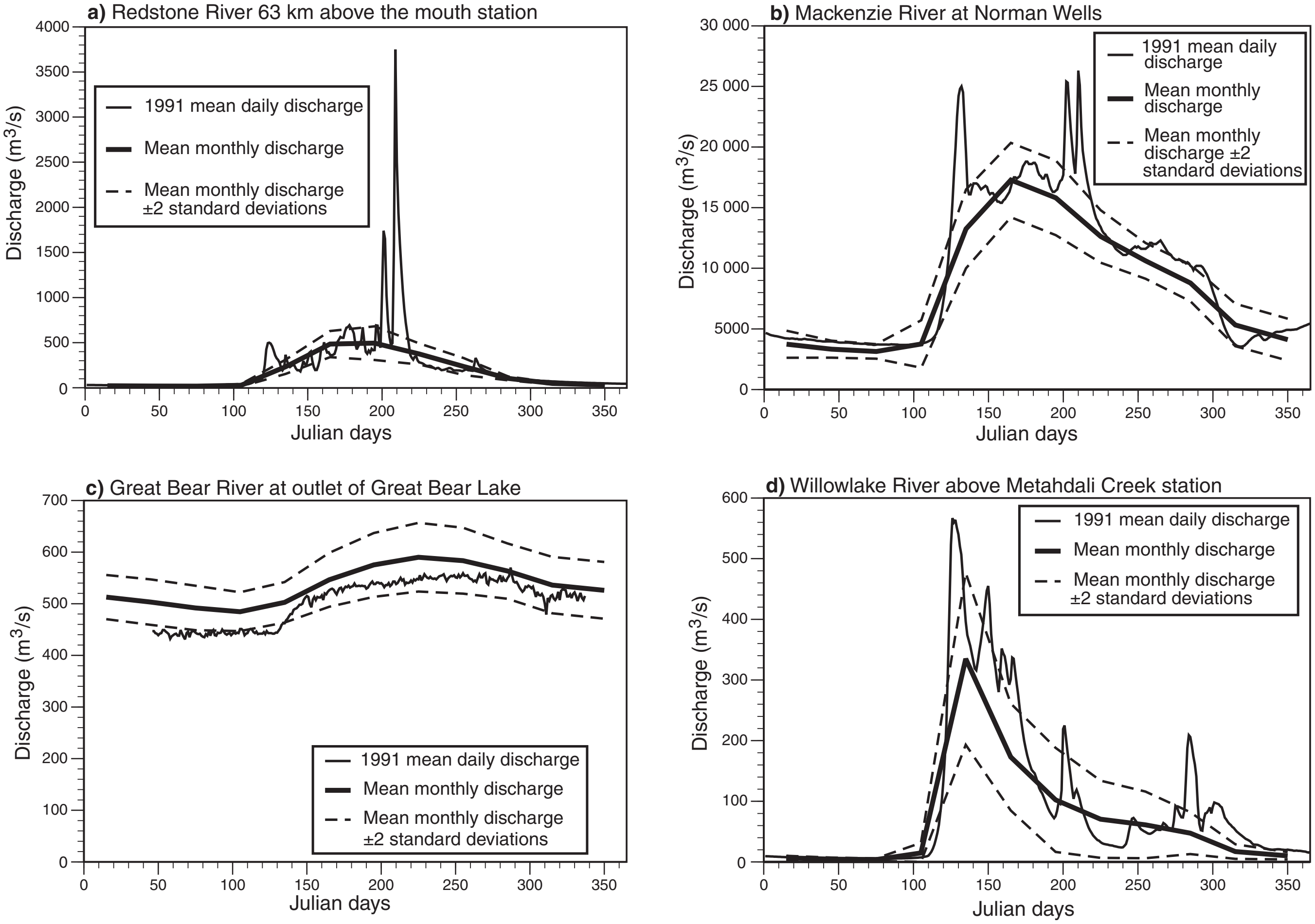

Figure 2. *Selected hydrographs showing the 1991 mean daily discharge and the mean month discharge (shown to two standard deviations) based upon the entire streamflow record, for the four stations.*

mean monthly discharge records for stations of relatively short duration (compare the daily and mean monthly hydrograph of Redstone River in Fig. 2a). For example, an early July 1988 storm generated a mean daily discharge along Root River that was a full order-of-magnitude larger than the highest mean monthly discharge. Maximum daily discharges for the period of record have therefore been added to the hydrographs in Figure 1 to illustrate the upper limit of flows recorded at each station. The short (and in some cases incomplete) discharge record for many stations may therefore be insufficient to have recorded extreme events. Thus, the maximum daily discharge for many stations is unrepresentative of the extreme flows expected over longer time periods.

CLIMATE CHANGE

The effects of global climatic change upon the streamflow of the Mackenzie valley river systems are not known with certainty, and only recently have been the subject of investigation. Hydrological modelling at the global scale suggests that there will be an increase in runoff for rivers at the high latitudes of North America, in response to an increase in precipitation (Miller and Russell, 1992). More locally, preliminary information from Soulis et al. (1994) for a number of Mackenzie basin watersheds also indicates that precipitation will increase, which suggests an increase in runoff. Some of the modelling scenarios of Soulis et al. (1994), however, indicates that this increased precipitation will be offset by greater evapotranspiration making the landscape drier than present. These contradictory results need to be clarified, but perhaps suggest that the net effects upon average streamflow may be minimal. Another possible effect of climate warming upon streamflow will be an earlier onset and longer period of spring melt. Although not related to streamflow, additional factors that could be affected by climate warming include an earlier spring breakup and later fall freeze-up, and reduced winter ice cover which may lead to less severe ice jamming during the spring breakup.

Global climatic change may also have a major impact upon the frequency of flood events, which have been shown to increase in some regions of North America (Knox, 1993). Flood events are very important to the discharge regimes and geomorphology of many Mackenzie valley rivers and can induce considerable change in channel morphology along some river reaches (*see* Brooks, 2000). The effects of an increased flooding frequency may be most pronounced along braided rivers, which can experience major channel change during these events.

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EFFECTS OF DAMS

It should be noted, however, that considerably more immediate and drastic changes to the flow regime of a given watershed than those caused by global change could arise from dam construction for hydroelectric generation. Many of the large Mackenzie valley tributaries were assessed for hydroelectric potential in the early 1970s, but this work has never proceeded beyond the initial evaluation (E.B. Owen, unpub. report, 1973). Beginning in 1967, however, streamflow of Mackenzie River has been partially regulated by operations of Bennett Dam in the upper Peace River basin, northeastern British Columbia. As exemplified by the gauging station at Arctic Red River, the total annual inflow of Mackenzie River is unchanged, but the average flows during the winter months have increased 20–30% while the summer and fall flows have diminished up to 5–10% (Wiens, 1991). The regulatory effect of Bennett Dam upon the flow of Mackenzie River at Tsiigehtchic is relatively insignificant, because the dam is situated well upstream of the natural regulation by Great Slave Lake, and because of the addition of flow from numerous unregulated tributary basins located between Great Slave Lake and Tsiigehtchic.

Particularly significant, however, would be the effects of hydroelectric development in the Liard Basin, although this seems unlikely under present economic conditions. Liard River is the large tributary of Mackenzie River whose flow is not regulated by a large lake. As is well documented, Liard River is an important sediment source and has a critical role in initiating the spring breakup of the Mackenzie River downstream of the Laird–Mackenzie confluence. If Liard River becomes regulated by a dam, significant effects include a reduced Liard freshet, reduced sediment supply affecting areas downstream as far as the delta, an increase in the daily fluctuation of Liard River discharge, and a delay in the spring breakup of Mackenzie River (Hardy Associates (1978) Ltd., 1982).

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