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Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen

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[1] Arctic and subarctic watersheds are undergoing climate warming, permafrost thawing, and thermokarst formation resulting in quantitative shifts in surface water–groundwater interaction at the basin scale. Groundwater currently comprises almost one fourth of Yukon River water discharged to the Bering Sea and contributes 5–10% of the dissolved organic carbon (DOC) and nitrogen (DON) and 35–45% of the dissolved inorganic carbon (DIC) and nitrogen (DIN) loads. Long-term streamflow records (>30 yrs) of the Yukon River basin indicate a general upward trend in groundwater contribution to streamflow of 0.7–0.9%/yr and no pervasive change in annual flow. We propose that the increases in groundwater contributions were caused predominately by climate warming and permafrost thawing that enhances infiltration and supports deeper flowpaths. The increased groundwater fraction may result in decreased DOC and DON and increased DIC and DIN export when annual flow remains unchanged.

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1. Introduction

[2] The hydrology of arctic and subarctic northern watersheds is changing in response to recent climate warming [*Hinzman et al.*, 2005; *Serreze et al.*, 2000]. Several hydrological effects of climate warming are clearly observable, such as permafrost warming and thermokarst development [*Lachenbruch and Marshall*, 1986; *Jorgeson et al.*, 2006], reduction in area and number of closed-basin ponds [*Riordan et al.*, 2006], glacier recession [*Kaser et al.*, 2006], and reduction in snow cover duration [*Brown and Braaten*, 1998]. Other hydrological consequences of climate change, including the effects on groundwater flow rates, pathways, and discharge to surface water, are not so readily apparent. Groundwater behavior in permafrost-dominated regimes is an understudied topic that will become increasingly important as permafrost, which is an effective barrier to recharge, continues to degrade. Furthermore, altering the proportion of groundwater to total discharge will potentially shift the composition of biogeochemical exports, including Dissolved Inorganic Carbon (DIC), Dissolved Organic Carbon (DOC), Dissolved Inorganic Nitrogen (DIN), and Dissolved Organic Nitrogen (DON).

[3] Recent studies describe systematic variations in streamflow in arctic and subarctic rivers linked to climate change; however, the magnitude and direction of these trends vary from region to region [*McClelland et al.*, 2006]. Trends encompass increasing annual flow to the Arctic Ocean from combined Eurasian rivers [*Peterson et al.*, 2002], decreasing annual flow to the Arctic Ocean via Hudson, James, and Ungava Bays [*Déry et al.*, 2005], and relatively unchanging annual flow to the Arctic Ocean from North American rivers [*Déry and Wood*, 2005]. Climate-model results [*Milly et al.*, 2005; *Aerts et al.*, 2006] demonstrate the potential for large changes in annual water discharge resulting from global warming in some basins.

[4] Many major arctic and subarctic rivers in Eurasia have had operational hydroelectric dams in place since the 1950s and 1960s [*McClelland et al.*, 2004], rendering it difficult to evaluate natural baseflow dynamics, except possibly for smaller rivers. Unlike the other major arctic rivers, streamflow dynamics of the Yukon River (YR) are not significantly affected by hydropower. The Yukon River basin (YRB) is covered by sizeable areas of continuous and discontinuous permafrost and the basin drains east to west, making the entire length of the YR vulnerable to permafrost degradation. Other major arctic rivers generally flow south to north; many have headwaters south of permafrost and downstream areas not yet impacted by permafrost thaw. Consequently, the YRB serves as an ideal environment to study groundwater input to a large, natural river system and to investigate hydrologic response to climate warming. Observations in the YRB may provide valuable insight for future responses in other major arctic river systems. Data from an extensive stream sampling campaign of the YRB conducted by the U.S. Geological Survey (USGS) from 2001–2006 and from historical USGS (http://waterdata.usgs.gov/nwis/) and Environment Canada (http://www.wsc.ec.gc.ca/hydat/H2O/) streamflow records were used to evaluate (1) current water and chemical input from groundwater to YRB streams, (2) water and chemical discharge to the Bering Sea, and (3) changes in groundwater discharge to rivers in the YRB over the past half century.

2. Study Area

[5] The Yukon River flows >3,300 km through various physiographic and climatic regions of northwestern Canada and central Alaska (AK), draining 853,300 km^2 (Figure 1). Permafrost coverage and thickness varies greatly throughout the 13 major drainage basins in the YRB [*Brabets et al.*, 2000]. The greatest area of continuous permafrost is in the

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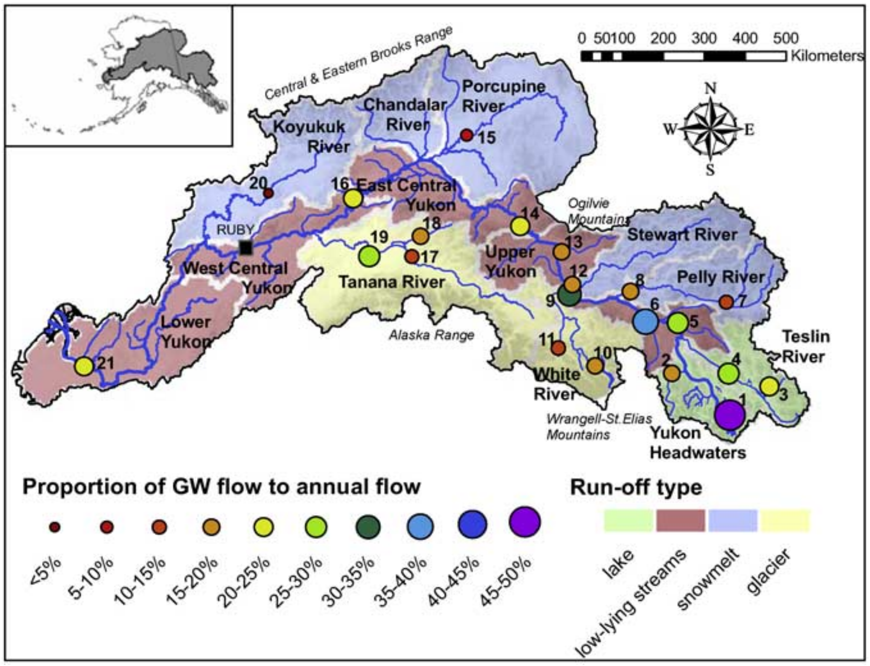

Figure 1. Map depicting proportion of groundwater input to total annual flow in the YRB at numbered stations listed in Table 1. Predominant run-off type is shown for each major drainage basin as characterized by *Brabets et al.* [2000].

north central region of the YRB, occupying most of the Porcupine and Chandalar River watersheds and much of the Koyukuk River watershed. Sporadic masses of permafrost underlie the Yukon Headwaters, Teslin River, and eastern Upper Yukon watersheds. Discontinuous permafrost or moderately thick to thin permafrost generally underlies most of the western and south central YRB, and part of the eastern YRB.

[6] *Hinzman et al.* [2005] provide a thorough review of climate change studies in northern AK and other arctic regions, and concede that although increases in air temperatures and permafrost warming are well documented in northern AK, change in precipitation (ppt) is tenuous. Some arctic stations exhibit slight upward trends in ppt, mostly during winter months. Long-term ppt records from northern AK are sparse, and evidence for trends is even less compelling than for other arctic regions. Recent work by *Clein et al.* [2007] provides evidence that western Arctic (includes the YRB) annual ppt has decreased from 1980 to 2000. One metric that exhibits convincing and pervasive trends is surface water balance expressed as precipitation minus potential evaporation (PPT-PET). This parameter shows significant downward trends from 1960–2001 in interior AK [*Hinzman et al.*, 2005] and from 1980–2000 in the western Arctic [*Clein et al.*, 2007].

[7] Water chemistry data in the YRB are limited. *Striegl et al.* [2005] compared 2001–2003 and 1978–1980 data and submitted that discharge-normalized DOC export via the Yukon River during summer through autumn has decreased in response to permafrost thawing and hypothesized that continued warming could lead to increased DIC:DOC ratio of total C export and reduced DOC export to the Bering Sea, if total annual flow is unchanged. Similar patterns could be expected for DIN and DON exports [*Dornblaser and Striegl*, 2007]. While the Arctic Ocean contains ~1% of the world's ocean volume, current estimates indicate that it receives ~11% of the annual river discharge [*Shiklomanov and Shiklomanov*, 2003] and ~13% of the terrigenous dissolved organic material delivered to the world's oceans [*Stein and Macdonald*, 2003], highlighting the importance of recognizing and predicting changes in organic material exports.

3. Data and Methods

[8] Twenty-one streamflow gaging stations in the YRB were selected for analysis (Table 1). All had year-round records spanning at least 20 years with no >2 yr gaps. All were free from influences of flow regulation with the possible exception of mainstem YR stations closest to the headwaters that may be influenced by the hydroelectric dam at Whitehorse, YT. Surface runoff during winter is negligible due to freezing conditions. Residual autumn flows persist through December at some stations. Assuming that all flow measured under ice from January 1 to March 31 derives from subsurface flow, calculated average flow rate over this period was used to estimate groundwater flow rate. Here, we define groundwater flow to encompass all subsurface flow. Although under-ice flow measurements are subject to low bias and greater uncertainty than flow measurements made in open water [*Moore et al.*, 2002], field methods used by the USGS and Environment Canada described by *Buchanan and Somers* [1969] have not changed over the period of record considered and are the best available. Using winter (Jan 1–Mar 31) flow as a proxy for groundwater errs on the low side because shallow subsurface flow likely increases during warmer months. Long-term trends in annual flow and winter groundwater input were assessed using the non-parametric Mann-Kendall test [*Helsel and Hirsch*, 1992; *Déry et al.*, 2005] and

Table 1. Streamflow Stations, Mean Flow Rates, and Trend Analysis Results[a]

Streamflow Station	Map ID	Period of Record	Groundwater Flow Mean, m^3/s	Groundwater Flow Total Change Over Period of Record, %	Groundwater Flow Average Change/yr, %	Annual Flow Mean, m^3/s	Annual Flow Total Change Over Period of Record, %	Annual Flow Average Change/yr, %
Atlin River near Atlin, BC	1	1950–1999	45.5	**25%**	**0.5%**	95.8	**29%**	**0.5%**
Takhini River near Whitehorse, YT	2	1949–2005	12.0	3%	0.2%	61.9	2%	0.0%
Swift River near Swift River, BC	3	1959–2005	10.9	17%	0.3%	46.6	−11%	−0.3%
Teslin River near Teslin, YT	4	1949–1994	87.8	**50%**	**0.8%**	305.0	2%	0.1%
Big Salmon River near Carmacks, YT	5	1964–1995	18.9	**20%**	**0.6%**	68.2	1%	0.0%
Yukon River at Carmacks, YT	6	1952–1995	284.1	**58%**	**1.0%**	756.3	13%	0.3%
Ross River at Ross River, YT	7	1965–2005	7.5	**41%**	**0.8%**	65.4	2%	0.0%
Pelly River at Pelly Crossing, YT	8	1953–2005	58.9	**36%**	**0.6%**	*388.5*	*3%*	*0.1%*
Yukon River above White River, YT	9	1957–2005	365.7	**21%**	**0.4%**	1183.4	−1%	0.0%
Kluane River at outlet of Kluane Lake, YT	10	1953–1995	12.9	**71%**	**1.4%**	75.9	**25 %**	**0.6%**
White River at AK Hwy near Koidern, YT	11	1975–2005	14.9	***19%***	***0.6%***	115.7	8%	0.3%
Stewart River at mouth near Dawson, YT	12	1964–2005	72.8	**19%**	**0.4%**	470.9	14%	0.3%
Klondike River near Dawson, YT	13	1966–2005	10.6	**53%**	**1.0%**	64.9	16%	0.4%
Yukon River at Eagle, AK	14	1954–2005	554.3	**23%**	**0.4%**	2411.0	3%	0.1%
Porcupine River near Fort Yukon, AK	15	1968–2004	26.7	**56%**	**1.2%**	380.6	−18%	−0.5%
Yukon River near Stevens Village, AK	16	1977–2005	735.3	**−12%**	**−0.5%**	3369	−3%	−0.1%
Salcha River near Salchaket, AK	17	1949–2005	6.4	**62%**	**0.8%**	46	−11%	−0.2%
Chena River near Two Rivers, AK	18	1968–2005	3.2	**59%**	**1.2%**	20	15%	0.4%
Tanana River at Nenana, AK	19	1963–2005	187.4	**20%**	**0.4%**	*689*	*7%*	*0.2%*
Koyukuk River at Hughes, AK	20	1961–1982	19.2	**83%**	**2.6%**	*412*	*−24%*	*−1.4%*
Yukon River at Pilot Station, AK[b]	21	1957–1996	1434.1	**27%**	**0.6%**	6443	2%	0.0%

[a] Reported changes derived from the Sen slope. Bold and underlined values indicate statistical significance of $P < 0.1$ and $P < 0.05$, respectively. Italicized values indicate a positive test for serial correlation in trend, suggesting statistical significance may be inflated.

[b] Record composited using data from YR at Pilot Station 1976–1996 and YR. at Ruby, AK 1957–1978 corrected using mean ratio during 1976–1978 overlap. % GW flow = proportion of groundwater contribution to total annual flow.

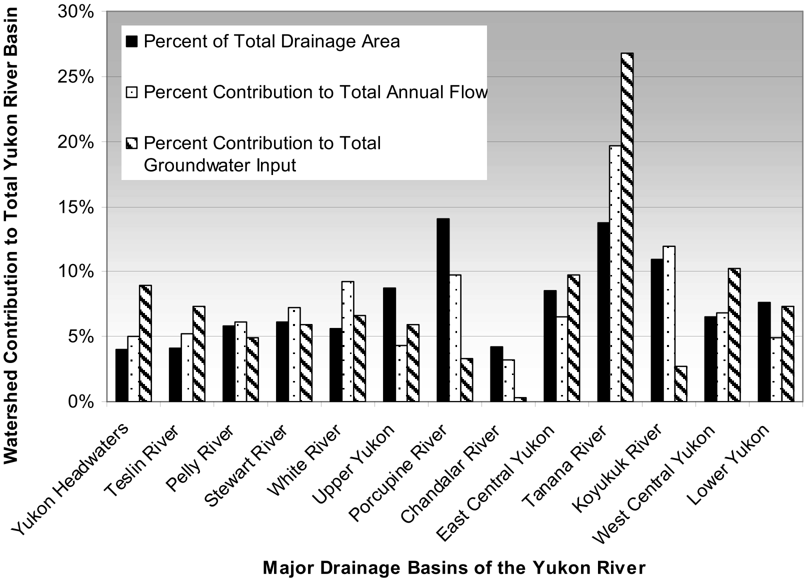

Figure 2. Contribution from the 13 major drainage basins outlined in Figure 1 to: total drainage area of the YRB; total annual flow of the Yukon River (at mouth); and total groundwater input to the Yukon River (at mouth).

tested for serial correlation using the Durbin-Watson statistic. Significant trends were approximated with the Sen slope.

4. Results

[9] Estimates of groundwater contribution to total annual flow at the 21 stations averaged over the individual periods of record range from 4.7–47.4% (Figure 1) and depend largely on the geology and permafrost coverage. The Porcupine and Koyukuk Rivers derive the smallest percentage (<10%) of their annual flows from groundwater. They drain extensive low-lying area underlain by continuous permafrost. Upland glacial meltwater/alpine watersheds in the Yukon headwaters and the south central region generally contribute the largest, although quite variable, proportions of groundwater. In Yukon Territory, groundwater averages 31–38% of annual YR flow. Groundwater contribution to the YR decreases downstream, exhibiting a narrow range of 21–23% in AK, as flow accrues from tributaries having relatively small groundwater components. Based on records from the furthest downstream stations, the YR exports $\sim$50 km^3 of groundwater annually to the Bering Sea. Figure 2 illustrates the contribution from each major watershed to total drainage area, annual flow, and groundwater input within the YRB. The Porcupine River and the Tanana River watersheds are the two largest watersheds, each occupying $\sim$14% of the YRB. The mountainous glacier-dominated Tanana River watershed supplies proportionally greater annual and groundwater flow relative to its size, 20% and 27% respectively. In contrast, the Porcupine River watershed, underlain mostly by continuous permafrost, contributes only 10% of the annual flow in the YRB and 4% of the groundwater discharged to the Bering Sea. As thawing of permafrost proceeds, these proportions are likely to change.

[10] Most streamflow records revealed significant increases in groundwater flow and minimal change in annual flow (Figure 3). Of the 19 long (>30 yr) records, results yielded 15 highly significant ($P < 0.05$) and two moderately significant ($0.05 < P < 0.1$) upward trends in groundwater input. The two short (<30 years) records yielded one moderately significant upward groundwater input trend. Of all 21 records, only one location (Station 16) exhibited a downward trend in groundwater flow; the trend was only moderately significant and derived from a short record. In general, groundwater flow increases were not accompanied by trends in annual flow. No significant decreases in annual flow were calculated. The only statistically significant upward trends in annual flow were at Atlin River and Kluane River (Stations 1 and 10) that drain Atlin and Kluane lakes. Both lakes receive meltwater from glaciers and perennial snowfields.

[11] The magnitude of statistically significant increases in estimated groundwater input varied from 19–83% over the period of individual record, calculated by the Sen slope and reported as total % change from the beginning of the record (Table 1). The lengths of records vary. The average change in increasing groundwater input (normalized to the mean) was estimated to be 0.4–2.6%/yr, with an average 0.9%/yr. Largest increases were observed in the Yukon Headwaters and in the Porcupine and Koyukuk watersheds.

5. Discussion

[12] Increased winter flow throughout the YRB in the absence of evidence for ppt increases, suggests that observed trends are due mainly to enhanced groundwater input to streams. Due to the insufficient spatial coverage of ppt stations in the YRB, the possibility of ppt change cannot be entirely ruled out. However, compelling arguments against ppt as a primary factor responsible for observed winter flow increases can be made. Changes in annual ppt should affect not only winter flow but also flow during other months. No pervasive trends in spring, summer, fall, and annual flow were found. Increases in

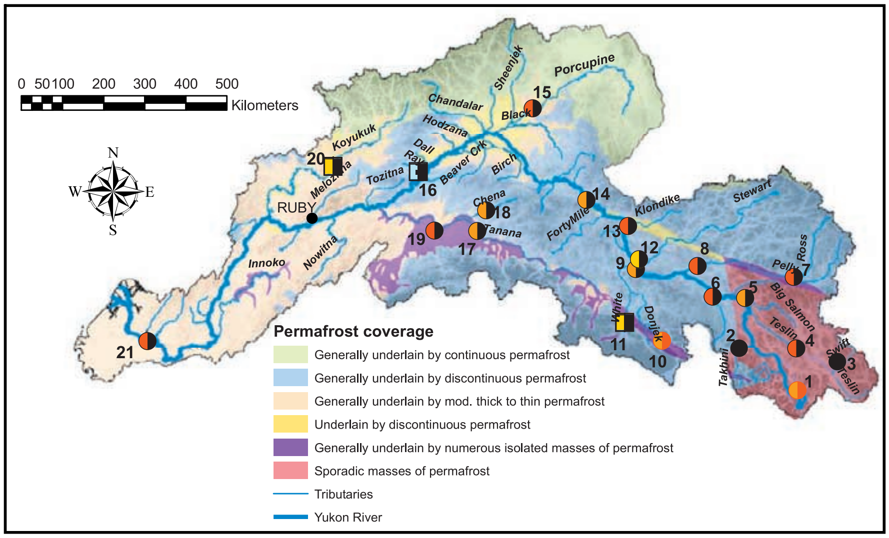

Figure 3. Observed trends in groundwater input (denoted by left side of marker) and annual flow (denoted by right side of marker) at YRB streamflow stations. Circle and square markers indicate flow records >30 years and <30 years, respectively. Marker color scheme indicates statistical significance of Mann-Kendall trend analysis: red, very highly significant ($P < 0.01$) upward trend; orange, highly significant ($0.01 < P < 0.05$) upward trend; yellow, moderately significant ($0.05 < P < 0.1$) upward trend; light blue, moderately significant ($0.05 < P < 0.1$) downward trend; and black, no significant ($0.1 < P$) trend.

(predominately) winter ppt, as documented elsewhere in the arctic, would not directly result in increased winter flow, since most all of the ground surface is frozen. Increased winter ppt may provide a thicker snow layer to better insulate the ground below, perhaps delaying annual freezing of the active layer and/or enhancing thawing of permafrost ice. This possible scenario would have a secondary, at best, effect on winter discharge and relies on the connection to thawing permafrost. Lastly, downward trends in PPT-PET in interior AK suggest that hypothetical increases in ppt are superseded by increases in temperature with respect to surface water availability. Based on the above findings, we submit that changes in ppt are not primarily responsible for observed upward trends in winter flow.

[13] Western Arctic summer temperatures from 1980–2000 have increased at a faster rate than annual temperatures [*Clein et al.*, 2007], resulting in permafrost warming. Permafrost thawing deepens the active layer and allows for increased infiltration, which would cause increased groundwater contribution to annual flow. Such a hydrological shift is expected to be accompanied by a modification of carbon (C) and nitrogen (N) chemistry and export. Water draining from high latitude soil surfaces and wetlands commonly has high DOC and DON and low DIC and DIN concentrations compared to deeper soil water [*Kawahigashi et al.*, 2006]. Surface runoff generates high DOC and DON concentrations in the YR during the ice-free period, especially during spring [*Striegl et al.*, 2007; *Dornblaser and Striegl*, 2007]. Winter flow is derived from groundwater and is much lower in DOC and DON concentration and higher in DIC and DIN concentration.

[14] Assuming that winter flow chemistry represents the chemistry of groundwater, we can project how changes in the ratio of groundwater contribution to annual flow may affect C and N exports from the YRB. We assume that current groundwater input to YR above Yukon Delta is 24% (Station 21) and that it has increased and will continue to increase by 0.7–0.9%/yr. This range is in accordance with the average change observed during the winter at all stations and of all statistically significant increases. We further assume no change in annual flow in agreement with historical records and supported by model projections [*Aerts et al.*, 2006] that predict only a small increase. Using the preceding estimates and 2001–2005 C and N data from YR to define seasonal concentration patterns (http://waterdata.usgs.gov/nwis/), DOC and DON exports decrease by 9–11% and 8–9%, respectively, from 1960 to 2050. Conversely, DIC and DIN exports increase by 16–19% and 17–21%, respectively. Assuming the same conditions, DOC + DIC export is projected to increase by an estimated 10–12% from 1960 to 2050. These projected changes are likely conservative because groundwater flow during the warmer months, which is assumed to exhibit trends similar to those observed during the winter, may yield even larger increases. A large difference in DIC concentration between runoff and groundwater outweighs the much smaller difference in DOC concentrations. In contrast, DON + DIN export is predicted to remain constant, because decreases in DON are essentially balanced by increases in DIN.

[15] Changing the fraction of groundwater input to rivers has implications for C and N export from the YRB, and likely from other major basins draining to the Arctic Ocean. There is a need for improved quantitative understanding of the hydrological and biogeochemical processes underlying observations to assess whether changes are likely to intensify, diminish, or plateau given current climatic projections. Process-based models that accurately integrate changing physical, chemical, and biological conditions are needed to constrain possible scenarios brought on by climate warming and permafrost degradation.

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References

Aerts, J. C. J. H., H. Renssen, P. J. Ward, H. de Moel, E. Odada, L. M. Bouwer, and H. Goosse (2006), Sensitivity of global river discharges under Holocene and future climate conditions, *Geophys. Res. Lett.*, *33*, L19401, doi:10.1029/2006GL027493.

Brabets, T. B., et al. (2000) Environmental and hydrologic overview of the Yukon River basin, Alaska, and Canada, *Rep. WRIR 99-4204*, 106 pp., USGS, Anchorage, Alaska.

Brown, R. D., and R. O. Braaten (1998), Spatial and temporal variability of Canadian monthly snow depth, 1946–1995, *Atmos. Ocean*, *36*, 37–54.

Buchanan, T. J., and W. P. Somers (1969), Discharge measurements at gaging stations, *U.S. Geol. Surv. Tech. Water Resour. Invest., Book 3, Chap. A8*, 42–44.

Clein, J. S., et al. (2007), The effects of different climate input data sets on simulated carbon dynamics in the Western Arctic, *Earth Interactions*, in press.

Déry, S. J., and E. F. Wood (2005), Decreasing river discharge in northern Canada, *Geophys. Res. Lett.*, *32*, L10401, doi:10.1029/2005GL022845.

Déry, S. J., et al. (2005), Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964–2000, *J. Clim.*, *18*, 2540–2557.

Dornblaser, M., and R. G. Striegl (2007), Nutrient (N, P) loads and yields at multiple scales and sub-basin types in the Yukon River basin, Alaska, *J. Geophys. Res.*, doi:10.1029/2006JG000366, in press.

Helsel, D. R., and R. M. Hirsch (1992), *Statistical Methods in Water Resources*, 529 pp., Elsevier, New York.

Hinzman, L., et al. (2005), Evidence and implications of recent climate change in northern Alaska and other Arctic regions, *Clim. Change*, *72*, 251–298.

Jorgeson, M. T., Y. L. Shur, and E. R. Pullman (2006), Abrupt increase in permafrost degradation in Arctic Alaska, *Geophys. Res. Lett.*, *33*, L02503, doi:10.1029/2005GL024960.

Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura (2006), Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004, *Geophys. Res. Lett.*, *33*, L19501, doi:10.1029/2006GL027511.

Kawahigashi, M., et al. (2006), Sorption of dissolved organic matter by mineral soils of the Siberian forest tundra, *Global Change Biol.*, *12*, 1868–1877.

Lachenbruch, A. H., and B. V. Marshall (1986), Changing climate: Geothermal evidence from permafrost in the Alaskan Arctic, *Science*, *234*, 689–696.

McClelland, J. W., R. M. Holmes, B. J. Peterson, and M. Stieglitz (2004), Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change, *J. Geophys. Res.*, *109*, D18102, doi:10.1029/2004JD004583.

McClelland, J. W., S. J. Déry, B. J. Peterson, R. M. Holmes, and E. F. Wood (2006), A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century, *Geophys. Res. Lett.*, *33*, L06715, doi:10.1029/2006GL025753.

Milly, P. C. D., et al. (2005), Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, *438*, 347–350, doi:10.1038/nature04312.

Moore, R. D., et al. (2002), Winter streamflow variability, Yukon Territory, Canada, *Hydrol. Processes*, *16*, 763–778, doi:10.1002/hyp.372.

Peterson, B. J., et al. (2002), Increasing river discharge to the Arctic Ocean, *Science*, *298*, 2171–2173.

Riordan, B., D. Verbyla, and A. D. McGuire (2006), Shrinking ponds in subarctic Alaska base on 1950–2002 remotely sensed images, *J. Geophys. Res.*, *111*, G04002, doi:10.1029/2005JG000150.

Serreze, M. C., et al. (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207.

Shiklomanov, I. A., and A. I. Shiklomanov (2003), Climatic change and the dynamics of river runoff into the Arctic Ocean, *Water Resour.*, *30*, 593–601.

Stein, R., and R. W. Macdonald (Eds.) (2003), *The Organic Carbon Cycle in the Arctic Ocean*, 363 pp., Springer, Berlin.

Striegl, R. G., G. R. Aiken, M. M. Dornblaser, P. A. Raymond, and K. P. Wickland (2005), A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn, *Geophys. Res. Lett.*, *32*, L21413, doi:10.1029/2005GL024413.

Striegl, R. G., M. M. Dornblaser, G. R. Aiken, K. P. Wickland, and P. A. Raymond (2007), Carbon export and cycling by the Yukon, Tanana, and Porcupine rivers, Alaska, 2001–2005, *Water Resour. Res.*, *43*, W02411, doi:10.1029/2006WR005201.

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