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Higher tritium concentrations measured in permafrost thaw lakes in northern Alberta

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Abstract:

Tritium concentrations were measured in a survey of 24 lakes, 15 wetlands, and 133 groundwaters in the oil sands region of northeastern Alberta and compared with both recent precipitation and precipitation sampled during the 1960s tritium peak caused by atmospheric thermonuclear weapons testing. Water samples from lakes included a group of 14 thaw lakes that had higher runoff attributed to melting of permafrost in peat plateaus within their watersheds. While tritium in all lakes was found to be intermediate between recent and 1960s concentrations, the thaw lakes were found to be significantly enriched in tritium compared with other lakes, as were unfrozen wetlands characterized by a thick sequence of low-hydraulic conductivity peat. The results provide further evidence of different water sources to the thaw lakes and may indicate that melting of modern permafrost in part formed since the 1950s is occurring in these systems. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS tritium; isotopes; lakes; water balance; water yield; permafrost thaw

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INTRODUCTION

Lakes are important features of the landscape in northern Alberta, providing wildlife habitat and water supply to communities, promoting development, and supporting recreational activities such as boating and sport fishing (Mitchell and Prepas, 1990). A recent long-term study of the 50 Regional Aquatic Monitoring Program (RAMP) lakes in northern Alberta (Gibson *et al*., 2015) revealed a population of lakes with inflow that was substantially enhanced by thawing of permafrost (Figure 1). The region is in a zone of active permafrost degradation as described by Vitt *et al*. (1999), and the hydrological characteristics of lakes were derived from a 9-year isotope mass balance analysis based on oxygen-18 and deuterium. Basic characteristics of lakes are summarized in Table I. The most striking property of the thaw lakes is that their watersheds have substantially higher runoff ratios, and on average, they receive more than two times as much runoff (or water yield) from the landscape than other lakes. While runoff ratio and water yield to lakes were found to be controlled by multiple factors including climate, morphometry, and land cover, runoff depth to the thaw lakes was also found to be strongly correlated with percentage of bog and bog-forest-permafrost-collapse scar, a terrain unit classification that indicates the presence of thawing peat plateaus. As permafrost thaws, small rounded to elliptical collapse scars form in association with peat plateaus. Irregular internal lawns may also form in bog landforms with discontinuous permafrost (Beilman *et al*., 2000). Detailed mapping of these features using 1:20 000 black and white photography revealed negative correlations regionally between the percentage of peat plateau that had collapsed and water yield, suggesting that these properties are causally related. Based on these observations (Gibson *et al*., 2015), it appears that peat plateaus may generate less water yield as they progressively thaw. A significant population of lakes (termed other lakes) was found to be unaffected by permafrost thaw. Clues also exist that thawing is a progressive process, including the fact that thaw lakes only occur at the higher elevation ranges in the Birch Mountains, presumably because the lower elevation ranges may already have thawed completely. The distinctiveness of thaw lakes relative to other lakes, in terms of watershed bog cover, degree of bog cover collapse, and water yield, is shown in Figure 2.

Better understanding of the linkage between permafrost thaw and water yield to lakes is important for local and regional water budget assessment as well as

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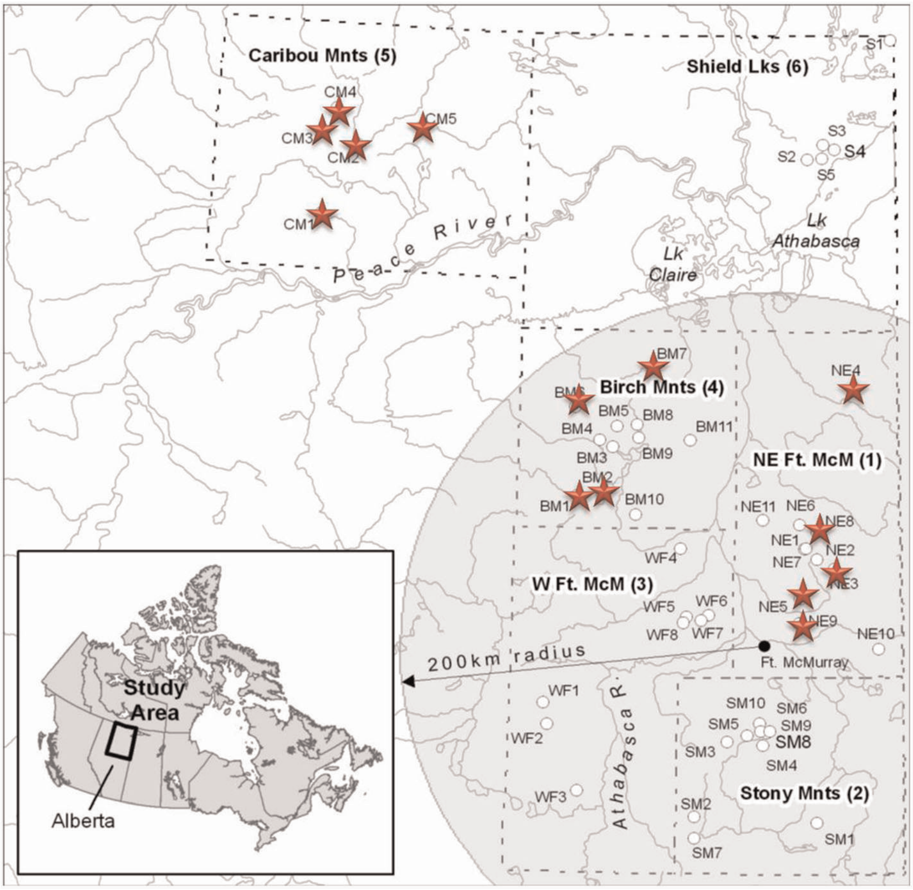

Figure 1. Map of the study region in northeastern Alberta showing lake locations. Stars denote lakes that are fed by substantial quantities of permafrost meltwater, based on isotope mass balance (Gibson *et al*., 2015)

for predicting impacts of climate change, acid deposition, and oil sand development in the region. To further investigate the conditions in the thaw lakes, a survey of tritium was conducted to assess if there might be an indication of the relative age of the permafrost meltwater. Tritium is a naturally occurring radioactive isotope of hydrogen with a half-life of 12.32 years that was introduced in significant concentrations into the atmosphere and precipitation in the post-1950s period as a result of atmospheric thermonuclear weapons testing (Michel, 2005). Tritium concentrations in precipitation peaked in the 1960s and have since returned to lower levels. Relatively old permafrost is expected to have little or no tritium, whereas modern permafrost that formed from post-1950s precipitation sources is expected to have significant tritium. Previous studies have demonstrated that tritium is present in shallow permafrost that has formed since the 1950s owing to intense moisture exchange between the active layer and permafrost (Michel and Fritz, 1978; Michel, 1986; Chizhov and Dereviagin, 1998). Based on measurements of tritium in ground ice, Burn and Michel (1988) concluded that tritium movement in permafrost is due to temperature-induced mass transport rather than molecular diffusion. Using tritium and stable isotope data, Michel (1986) found massive ground ice to be a mixture of recent (post-1960s) precipitation and groundwater seepage. Chizhov and Dereviagin (1998) compare tritium concentrations in permafrost with modern precipitation to infer the modern moisture content in permafrost. However, no studies to our knowledge have looked at tritium content in permafrost thaw lakes.

Our hypothesis was that higher tritium might be found in thaw lakes as compared to other lakes if they are sourced by melting of modern permafrost, lower concentrations might be found in thaw lakes if they are fed by melting of old permafrost, and similar tritium levels might be found if they are fed by similar sources (i.e. precipitation, groundwater, wetlands, and snowmelt). Of course, results might be more ambiguous where a mixture of old and new permafrost meltwater is present.

Table I. Average (minimum to maximum) enriched tritium, stable isotope composition and estimated residence time, water yield, and runoff ratio for lakes in northeastern Alberta by type

	n	Max depth (m)	Lake area (km^2)	Watershed area (km^2)	Residence time (years)	Water yield (mm/year)	Runoff ratio (unitless)	e^{3}H* (T.U.)	δ^{18}O (‰V-SMOW)	δ^2H (‰V-SMOW)
Thaw lakes	14	5.8 (0.9 to 27)	6.2 (0.11 to 48)	24.4 (0.71 to 122)	2.02 (0.13 to 9.03)	390 (139 to 652)	0.78 (0.25 to 1.2)	14.64 (10.71 to 19.60)	−13.58 (−17.8 to −7.8)	−121.4 (−142.8 to −93.9)
Other lakes	36	3.7 (1.2 to 27)	1.5 (0.03 to 5.8)	20.2 (0.52 to 113)	1.1 (0.14 to 5.35)	161 (23 to 428)	0.31 (0.04 to 1.04)	11.47 (10.30 to 14.11)	−11.38 (−16.5 to −6.5)	−110.0 (−137.4 to −81.6)

n, no. of lakes.

*$n = 10$ for other lakes, $n = 14$ for thaw lakes.

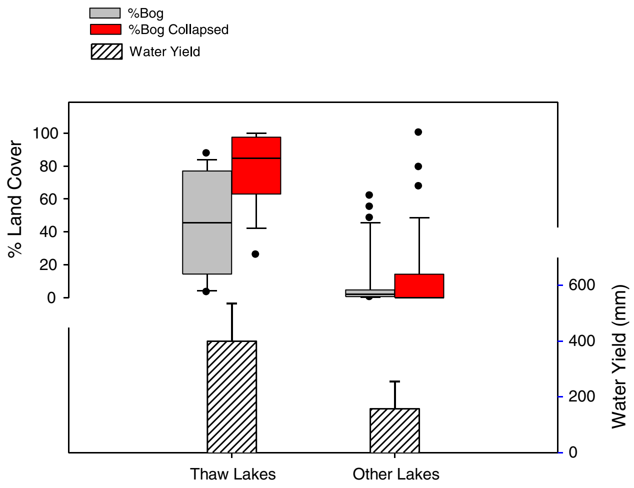

Figure 2. Box plots illustrating differences in percentage of bog cover and percentage of bog cover collapsed (i.e. %bog-forest-permafrost-collapse scar/%bog) for thaw lakes and other lakes sampled in northern Alberta. Bar plots also show differences between water yields for both types of lakes

STUDY AREA AND METHODS

Water samples for enriched tritium analysis were collected in September 2013 and August 2014 from RAMP lakes. Wetland waters (depth of 0–8 m in peat) were collected in October 2014 from the Mariana Lakes bog-fen complex located 60 km south of Ft. McMurray. Groundwater samples were collected from Cretaceous strata (McMurray, Clearwater, and Grand Rapids Formations) and Quaternary aquifers in the Fort McMurray area during 2007–2015. All samples were collected in 1-L high-density polyethylene bottles and shipped to the University of Waterloo Environmental Isotope Laboratory or Isotope Tracer Technologies Inc. where they were electrolytically enriched and then measured using a liquid scintillation counter. Results are reported in tritium units (T.U.) with analytical uncertainty ranging from ±0.4 to 1.6 T.U. Reference values for precipitation were taken from the Canadian Network for Isotopes in Precipitation database (see Birks and Gibson, 2009). These values are corrected for radioactive decay and normalized to 15 September 2014 to represent nominal concentrations that would be measured today in these samples.

RESULTS AND DISCUSSION

Box plots of the enriched tritium concentration in the thaw lakes, other lakes, and a variety of reference samples are shown in Figure 3. Tritium data are provided in Table II. Tritium is found to average 14.64 ± 2.25 T.U. in the thaw lakes as compared with 11.47 ± 1.07 in other lakes, and the difference between these groups is statistically significant based on a *t*-test ($p < 0.001$). Local

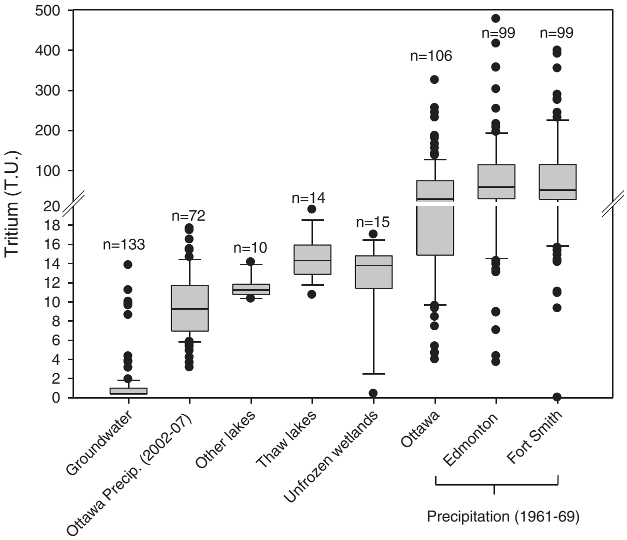

Figure 3. Tritium concentrations in thaw lakes, other lakes, and a variety of reference samples including precipitation, groundwater, and unfrozen wetlands

groundwater and recent precipitation from Ottawa (2002–07) decay corrected to 2014, as shown in Figure 3, are found to be significantly different from either group based on a *t*-test ($p < 0.001$), whereas the difference between thaw lakes and unfrozen wetlands is not statistically significant based on a Mann–Whitney rank sum test ($p = 0.123$). Tritium concentrations representative of the time of peak concentrations in the atmosphere are also shown for Edmonton, Fort Smith, and Ottawa, decay corrected to 2014 (Figure 3). Observations of higher tritium concentrations measured in thaw lakes on a regional scale cannot be explained unless these lakes are fed by sources containing a higher proportion of precipitation from the 1960s to 1970s period as compared with other lakes. This is attributed to thaw of frozen peat plateaus that had incorporated a higher proportion of 1960s precipitation. The presence of 1960s water is also suggested by higher tritium found in unfrozen wetlands (statistically indistinguishable from thaw lakes), which is instead attributed to long residence times in low-hydraulic

Table II. Lake locations, characteristics, tritium, and stable isotope compositions

Type	Lake no.	Latitude	Longitude	Max depth (m)	Lake area (km^2)	Watershed area (km^2)	e^{3}H (T.U.)	1σ (T.U.)	δ^{18}O*	δ^{2}H*
Thaw lakes	NE3	57.96	−110.40	1.2	1.16	22.8	15.78	1.51	−13.06	−117.2
	NE4	57.05	−110.59	2.1	0.58	2.59	17.49	1.59	−14.07	−124.9
	NE5	56.89	−110.90	1.8	1.89	5.43	14.44	1.34	−10.61	−105.5
	NE8	57.23	−110.75	1.2	0.11	0.71	15.74	1.41	−14.59	−125.0
	NE8repeat						13.90	1.28		
	NE9	56.77	−110.91	1.8	3.15	8.06	12.90	1.22	−9.32	−98.3
	BM1	57.41	−112.93	9.1	17.0	41.7	12.78	1.22	−12.31	−113.5
	BM1repeat						13.30	1.25		
	BM2	57.42	−112.69	27	44.0	122	10.71	1.07	−11.96	−111.8
	BM6	57.85	−112.97	0.9	1.29	12.4	14.57	1.36	−15.27	−130.3
	BM7	58.06	−112.27	1.5	0.68	3.98	16.38	1.48	−14.18	−124.2
	CM1	58.77	−115.44	8.5	1.60	22.5	12.83	1.27	−16.79	−138.3
	CM2	59.13	−115.13	6.0	9.55	37.2	14.23	1.29	−13.61	−122.2
	CM3	59.19	−115.46	1.5	2.30	25.7	13.43	1.26	−15.09	−131.3
	CM3repeat						13.50	1.27		
	CM4	59.31	−115.35	16	2.63	35.4	14.03	1.35	−16.32	−137.6
	CM5	59.24	−114.53	1.5	0.55	2.23	19.60	1.55	−12.94	−119.5
	Average[+]	58.02	−112.88	5.8	6.18	24.4	14.64	2.25	−13.58	−121.4
Other lakes	NE7	57.15	−110.86	2.0	0.11	5.80	10.94	0.89	−16.03	−130.9
	NE10	56.64	−110.20	1.5	4.19	12.9	11.63	0.92	−9.34	−98.4
	NE11	57.29	−111.24	3.5	5.75	71.4	10.72	0.86	−11.69	−111.8
	WF4	57.15	−111.98	1.5	0.03	1.76	10.29	0.83	−9.80	−106.4
	BM10	57.31	−112.40	1.5	0.39	4.76	11.42	0.90	−9.33	−100.9
	BM11	57.69	−111.91	5.0	0.06	0.52	11.79	1.04	−11.37	−111.8
	BM11repeat						11.11	0.88		
	SM7	55.68	−111.83	3.0	1.48	5.46	12.02	0.94	−8.88	−95.9
	SM8	56.21	−111.20	2.5	1.91	7.72	11.06	0.88	−10.28	−102.6
	SM9	56.22	−111.25	1.2	1.07	7.21	10.83	0.86	−11.92	−110.1
	SM10	56.26	−111.26	1.2	1.35	16.8	14.10	1.33	−12.03	−111.0
	Average[+]	56.76	−111.41	2.3	1.63	13.4	11.47	1.07	−11.07	−108.0
	All other	57.11	−111.57	3.7	1.50	20.2			−11.38	−110.0

*Average of annual 9-year sampling, ‰V-SMOW (Gibson *et al.*, 2015).

[+] Note that repeat analyses are not included in calculation of the averages.

conductivity peat. In fact, the deepest sample from this 8-m-deep peatland did not contain any tritium, suggesting that it contains water that pre-dates the 1950s. Much of this wetland water is immobile; however, in the case of frozen wetlands, such water may be released if the peatland were to collapse.

Evaporation is expected to have only a minor enrichment effect on tritium content in lakes, estimated to be close to our detection limit for enriched tritium (0.8 T.U.) for the most enriched lakes. Note that the tritium differences measured between thaw lakes and other lakes is also opposite to that of the stable isotope differences and is therefore not in the way expected if evaporation were the causal factor.

While permafrost meltwater was not found to have a distinctive δ^{18}O or δ^{2}H signature (Gibson *et al.*, 2015), melt lakes tend to be less evaporatively enriched than other lakes and with higher water yields (Table I) owing largely to higher rates of flushing attributed to throughput of meltwater.

The combined evidence of permafrost sources to thaw lakes therefore includes a significantly higher percentage of collapse scar terrain, higher water yields, higher runoff ratios, and higher concentrations of tritium. Given the similarity in tritium concentrations in unfrozen wetlands and thaw lakes, it is possible that thaw simply causes release of larger quantities of wetland water, which is enriched in tritium owing to both incorporation of post-1950s water in permafrost and longer residence time due to low-hydraulic conductivity prior to collapse. Unfortunately, tritium was not measured on permafrost itself, although stable isotopes were measured on permafrost pore ice and meltwater (Gibson *et al.*, 2015). In any case, tritium content in permafrost is expected to be quite variable and would require a regional survey to identify any systematic anomalies. This was beyond the scope of the current sampling programme.

CONCLUSIONS AND IMPLICATIONS

The presence of lakes fed by substantial quantities of permafrost meltwater is significant from the perspective of understanding regional water resources. Presumably, melt-fed systems will eventually transition to unfrozen systems followed by a significant decline in water yield. This may contribute to acidification of lakes, reduction in water levels, and changes in aquatic habitat. Herein, tritium data provide further evidence that the high water yield lakes identified in the RAMP survey by Gibson *et al.* (2015) are likely sustained by permafrost melt. Further work to directly monitor and evaluate the effect of permafrost thaw on the hydrological and ecological systems in thaw lakes and implications for local and regional water resources management is warranted. Better understanding of watersheds that have already completely thawed will also give insight into long-term trends expected for thaw lakes and regional runoff. Similar processes are expected to be occurring in thaw lakes situated across the pan-Arctic region. Tritium anomalies may provide information on the age of permafrost melt sources in these lake-rich regions.

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