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What effect does permafrost have on dissolved organic carbon transport to streams during snowmelt?

P.F. Schuster, M.M. Reddy, G.R. Aiken & J.B. Shanley
U.S. Geological Survey, Water Resources Discipline, Denver, Colorado, USA

ABSTRACT: Up to 13% of the Earth's land surface is underlain by permafrost. There are strong indications that permafrost in the northern latitudes is melting in response to climate change. Landscapes underlain by permafrost contain a potential large pool of sequestered organic carbon. Dissolved organic carbon (DOC) export during spring snowmelt from a watershed underlain by permafrost was compared to DOC export during spring snowmelt from a watershed without frozen soil. DOC concentrations exporting the permafrost watershed were about seven times greater than concentrations exporting the non-permafrost watershed. However, DOC fluxes normalized to basin size, are similar. A simple conceptual model demonstrates the potential for increased DOC export from a watershed underlain by permafrost if the permafrost melts. Permafrost degradation, due to climate change, may have major implications for the cycling of carbon, nutrients, and metals in arctic and subarctic ecosystems.

1 INTRODUCTION

There is increasing concern about the effects of climate change on the melting of permafrost at high latitudes and the movement of carbon, nutrients, and metals within and from watersheds underlain by permafrost. Climate has been warming at northern latitudes. For example, there has been a substantial increase in Alaskan tundra plant biomass in the last 20 years (Jia & Epstein 2003), and observed arctic annual mean temperatures have increased about 0.5°C per decade since 1961 (Chapman & Walsh 1993). Steady mean temperature increases will have a substantial effect on permafrost conditions.

Perennially frozen soils (permafrost), are rich in organic matter (Cryosols) and cover about 13% of the earth's surface (Bockheim 1994). Permafrost acts as a confining layer or a barrier to infiltration because of its very low permeability. Often, organic matter concentrates at the top of the permafrost table (Bockheim & Tarnocai 1998). The annual water discharge from watersheds in northern latitudes peaks during snowmelt in the spring. Concurrently, a large percentage of solutes, including DOC, also exits the watershed.

Climate-change driven modification of the hydrologic regime has major implications for the C cycle. Moreover, evidence from northern Europe and North America show that aqueous trace metal mobility (i.e. Hg species) is linked to organic C transport (Driscoll et al. 1995, Bishop et al. 1995, Shanley et al. 2002a). Therefore, it is critical to understand the processes related to the transport of DOC to streams and rivers in northern regions and how long-term climatic changes may alter these processes, thus affecting the cycling of C and metals in an ecosystem.

One of the first steps toward understanding the dynamics of DOC transport in regions dominated by permafrost is to compare these regions to areas where soils are unfrozen throughout the year. We have used consistent field techniques and laboratory methods to compare DOC export in stream water from two watersheds, differing in permafrost conditions, during spring snowmelt. Based on this comparison, a simple conceptual model was developed to show DOC export from a watershed dominated by permafrost, as well as possible changes in DOC export in response to melting permafrost.

2 SITE DESCRIPTIONS

The Sleepers River watershed is located at ~44.5° N in Northeast Vermont (Fig. 1) and has been the focus of more than 40 years of watershed-process research. Recent findings include a strong positive correlation between dissolved and particulate mercury, and dissolved and particulate organic C (Shanley & Chalmers 1999, Shanley et al. 2002a, b).

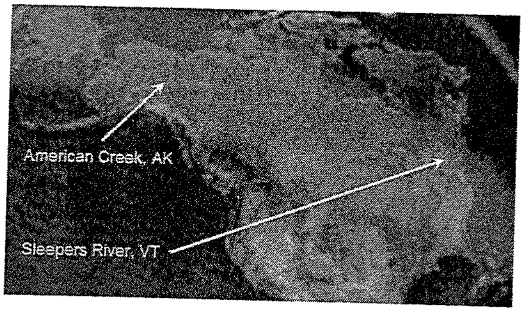

Figure 1. General location of the Sleepers River watershed in Vermont and American Creek in Alaska.

Table 1. General physical characteristics of the Sleepers River and American Creek watersheds.

Watershed	Sleepers River	American Crk
Size (km^2)	111	160
Annual ppt (mm)	1300	260–520
Ppt as snow (%)	30	33
Annual temp °C	4.6	−5
Climate type	Humid continental	Subarctic
Ecosystem type	N. hardwood forest	Int. highlands
Permafrost	None	Discontinuous
Soil type	Spodisols/Inceptisols	Cryosols
Mean elevation (m)	~450	~650

The American Creek watershed is located at ~64° in a remote region of the extreme eastern interior of Alaska. It is a sub-watershed of the Yukon River Basin. The main purpose of research at this watershed is to facilitate USGS research of the Yukon River Basin National Stream Quality Accounting Network study by scaling up results from the American Creek sub-watershed (Brabets et al. 2001).

The Sleepers River and American Creek watersheds are similar in elevation and size but differ greatly in climate and physical soil conditions, owing to the large difference in latitude (Fig. 1). Most notably, the American Creek watershed is underlain by permafrost. Regional permafrost maps (Brown et al. 1997) classified the American Creek basin as discontinuous permafrost. Local observation (House, pers. comm.), however, indicates the permafrost is continuous, generally 2 to 3 meters thick, occurring just below the surface humus layer. In contrast, the Sleepers River watershed contains no permafrost; there is seasonal frost occasionally to a depth of 30 cm (Shanley & Chalmers 1999). Both watersheds are in a cold climate where organic matter mineralization is slow enough to allow considerable accumulation of organic matter in soils. These watershed characteristics, including those listed in Table 1, affect the net flux of DOC from each basin.

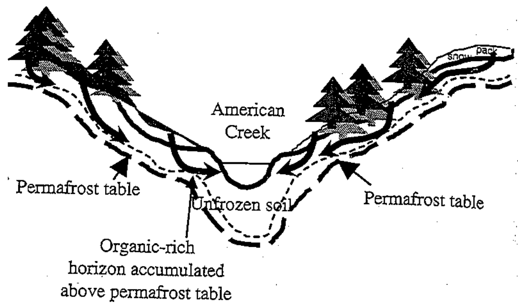

Figure 2. Simple conceptual model of American Creek watershed. Light dashed line, boundary between unfrozen soil and organic-rich horizon above permafrost; thick dashed line, permafrost table; thick arrows, shallow soil water flow paths above the permafrost table.

3 METHODS

Samples were collected from each watershed during peak snowmelt discharge. Samples were collected using established USGS sampling protocols (USGS 1997–99). In brief, grab samples were collected for DOC analysis in 1 L baked, amber glass bottles and filtered (0.45 µm) within 4 hours of collection into 60-mL, baked, amber glass bottles. Samples were kept in the dark and refrigerated until analysis, typically within days of collection.

DOC measurements were made by using the method described in Aiken (1992). Instrument calibration was done with solutions of potassium hydrogen phthalate in distilled water. A 5-point standard curve was repeated for every 8 water samples analyzed in duplicate. Reported values are the averages of duplicate analyses. Standard deviation for the DOC measurement was ±0.2 mg C/L.

4 SIMPLE CONCEPTUAL MODEL

Permafrost underlying the American Creek watershed likely confines the hydrologic flowpaths to shallow surficial materials. Snowmelt infiltrates the unfrozen, organic-rich surface horizon of the Cryosol soil, then flows laterally and down-gradient along the permafrost table in contact with the organic-rich material directly above the permafrost. We suggest that snowmelt following these shallow flow paths (thick black arrows in Fig. 2) would have increased contact time with organic-rich material, resulting in enhanced transport of DOC to the stream and increased export of DOC from the watershed, relative to a watershed without permafrost.

Snowmelt flow paths in the Sleepers River watershed are not impeded by frozen soil (Fig. 3) but are, however, restricted by the bedrock/till interface.

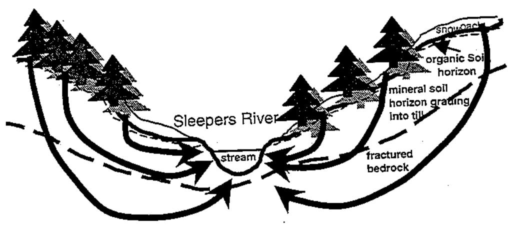

Figure 3. Simple conceptual model of Sleepers River watershed. Light dashed line, boundary between organic soil horizon and mineral soil horizon; heavy dashed line, boundary between till and fractured bedrock; thick arrows, soil water flow paths.

During peak snowmelt, the primary zone of flow and most of the contact time is through the mineral spodisol soil horizon/till interface with a deeper vertical component through the fractured bedrock to the stream. It is likely that DOC will be affected by sorption and degradation in the mineral horizon; a fraction of the DOC may complex with aluminum and iron hydroxides, causing the mineral horizon to act like a filter and inhibit transport of DOC to the stream. As the melt water traverses across the saturated zone to the stream, it usually acquires DOC only at the end of the flow path in the riparian zones.

5 RESULTS AND DISCUSSION

DOC and discharge were measured at the outflow of the Sleepers River and American Creek watersheds during peak snowmelt (Fig. 4). DOC concentrations from both watersheds are correlated to discharge, as expected. The DOC concentration at American Creek during peak snowmelt discharge was about seven times greater than DOC during peak discharge at Sleepers River. The peak discharge at Sleepers River was more than four times the peak at American Creek.

To provide a direct comparison between watersheds, the DOC concentrations were converted to mass loads and normalized to basin size; this is known as a specific daily yield. Discharge was also normalized to basin size for direct comparison. It must be made clear that there are many factors that contribute to DOC export from a watershed (i.e. soil type, vegetation, microbial processes, DOC character such as solubility and reactivity). This normalization is not an attempt to account for all factors. A much more comprehensive study must be conducted to address all the components of the watershed.

Normalized to basin size, at peak flow the DOC mass export from the Sleepers River watershed is about the same as export from the American Creek

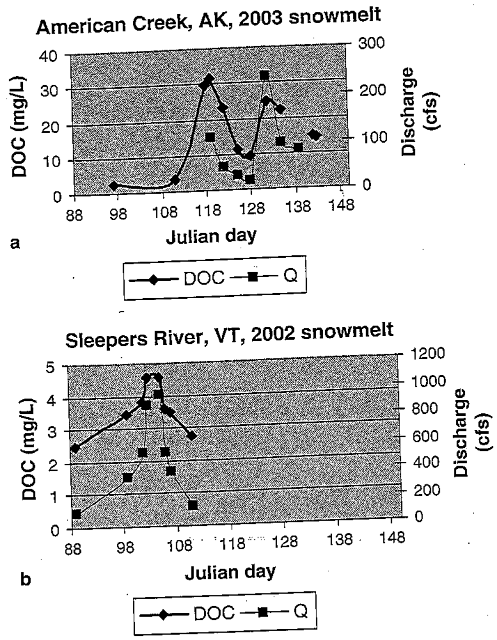

Figure 4. DOC and discharge (Q) for American Creek (a) and Sleepers River (b) watersheds during peak snowmelt.

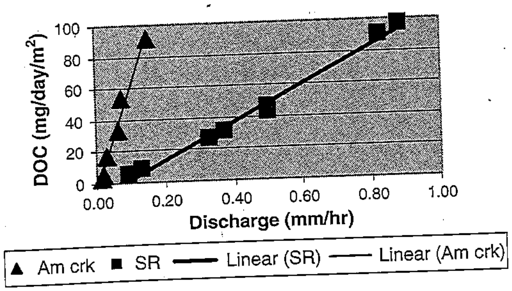

Figure 5. Log-transformed discharge (Q) and DOC data (normalized to basin area) for American Creek watershed during the spring

watershed (Fig. 5). However, a plot of normalized discharge versus normalized DOC (Fig. 6) shows that the amount of DOC relative to discharge is much greater during peak snowmelt at American Creek. This supports the conceptual model that snowmelt flow paths in the American Creek watershed are confined by the permafrost table, directing snowmelt as shallow flow over and through unfrozen organic-rich surface material. These restricted flow paths effectively increase the contact time between soil water and organic matter, resulting in higher concentrations of DOC in American Creek relative to

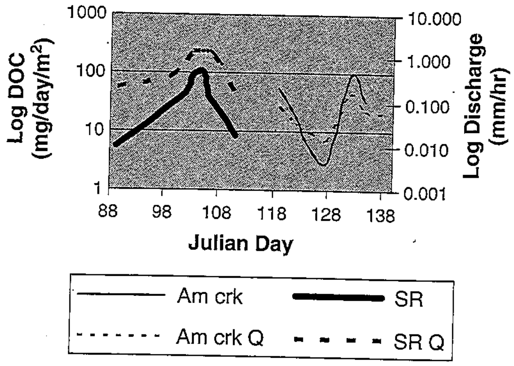

Figure 6. Normalized discharge plotted against normalized DOC of American Creek and Sleepers River watersheds.

DOC concentrations in Sleepers River where there is no permafrost and flow paths are not restricted.

At the Sleepers River watershed, the concentrations of DOC in the streams remain relatively constant with increasing sub-watershed size and increasing discharge (Shanley et al. 2002b). For the DOC concentration to remain constant as discharge increases, the flux of DOC to the stream must increase. Shanley et al. (2002b) suggest "new water" (snowmelt) must follow shallow flow paths (i.e. overland flow). These shallow flow paths would effectively scavenge organic C and, therefore, increase the flux of DOC to Sleepers River down gradient.

How would DOC export change if the permafrost melts and melt-water flow paths are modified by the degradation of the permafrost table? Will changes in flow paths affect transport of DOC to the stream and export from a watershed? This watershed comparison provides insight into the effects of permafrost on DOC export from a watershed but further studies are needed to answer these questions.

Organic matter in permafrost is often considered unavailable C with respect to the C cycle. A permafrost sample taken near Fairbanks, AK, had a DOC concentration of 2950 mg/L (Kraemer, written comm.), suggesting that permafrost soil is a substantial pool of locked C. Analysis of the organic matter in permafrost in the American Creek watershed must be made to assess the importance of this C pool. It is hypothesized that with progressive melting of the permafrost, DOC export from the American Creek watershed will initially increase as new C from the melted permafrost becomes available. Over the long term, however, DOC transport may decrease in response to two processes: (1) the new C pool will eventually be depleted due to increased microbial degradation, and (2) flow paths, moving through the soil mineral horizons to the stream, will be deeper with the absence of the permafrost table. DOC in groundwater along these deeper flow paths will likely react with the mineral horizon, effectively filtering out the DOC before it enters the stream. Because up to 13% of the Earth's land surface is underlain by permafrost, these processes may have global effects on the cycling of C, metals and nutrients.

6 CONCLUSIONS

A warming climate is expected to degrade permafrost in northern latitudes. Perennially frozen soils in the northern latitudes (Cryosols) are rich in organic matter and cover about 13% of the Earth's surface. Comparing permafrost and non-permafrost watersheds supports a simple conceptual model of DOC transport through a watershed underlain by permafrost. Many factors contribute to the export of DOC from a watershed, but the results presented here suggest that the presence of permafrost enhances the export of DOC relative to a watershed without permafrost. Melting of permafrost in the northern latitudes and subsequent release of sequestered C has major implications for global cycling of C, nutrients, and metals in the hydrologic regime.

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