

Dynamics and chemistry of dissolved organic carbon in Precambrian Shield catchments and an impounded wetland

T.R. Moore, L. Matos, and N.T. Roulet

Abstract: We examined the sources, sinks, and fluxes of dissolved organic carbon (DOC) and its chemical fractions over a 4-year period in upland and wetland catchments in the Experimental Lakes Area, Ontario. In an upland catchment, the major sources of DOC were precipitation, vegetation, and soil organic matter, resulting in a summer (June to October) export of 2.1 g·m⁻². DOC concentrations in peat pore water ranged from 20 to 60 mg·L⁻¹ and were related to hydrologic pathways. DOC export from catchments containing wetlands ranged from 0.8 to 5.7 g·m⁻² and export from the peatland portion of the catchment was estimated to be 28–30 g·m⁻². Flooding to a depth of 1.2 m in the peatland section of one catchment resulted in an increase in pore-water and pond DOC concentrations, attributed to the decomposition of plant tissues and peat. Because only 14% of the catchment was flooded, impoundment did not result in a significant increase in DOC export. Between 85 and 93% of DOC was contained in the acid fractions, with small amounts in the neutral fractions. Flooding increased the proportion of the hydrophilic neutral fraction in peat pore waters for 2 years after flooding.

Résumé : Nous avons étudié les sources, les pertes et les flux du carbone organique dissous (DOC) et de ses fractions chimiques pendant une période de 4 années dans des bassins versants des terres hautes et des terres humides de la Région des lacs expérimentaux (« Experimental Lakes Area ») en Ontario. Dans un bassin versant des terres hautes, les sources principales de DOC sont les précipitations, la végétation et la matière organique du sol, ce qui entraîne une exportation en été (juin à octobre) de 2,1 g·m⁻². Les concentrations de DOC dans l'eau interstitielle de la tourbe varient de 20 à 60 mg·L⁻¹ et elles sont reliées aux différentes voies hydrologiques. L'exportation de carbone organique dissous de bassins versants comportant des terres humides varie de 0,8 à 5,7 g·m⁻² et celle provenant de la partie tourbeuse du bassin est estimée à 28 à 30 g·m⁻². L'inondation de la section tourbeuse d'un bassin par 1,2 m d'eau a entraîné des augmentations dans les concentrations de DOC dans l'eau interstitielle de la tourbe et dans l'eau d'étang que l'on attribue à la décomposition de tissus végétaux et de tourbe. Puisque seulement 14 % du bassin versant a été inondé, la mise en eau n'a pas entraîné un accroissement significatif de l'exportation de DOC. Entre 85 et 93 % de la DOC se retrouve dans les fractions acides, avec de petites quantités dans la fraction neutre. L'inondation a augmenté la proportion de la fraction hydrophile neutre dans l'eau interstitielle de la tourbe durant les 2 années qui ont suivi la mise en eau.

[Traduit par la Rédaction]

Introduction

Dissolved organic carbon (DOC) is composed of a complex mixture of humic organic compounds: short-chain acids to large molecules known as humic substances may compose up to 90% (Thurman 1985). DOC is produced through the leaching and decomposition of plant material and soil organic matter (Moore and Dalva 2001) and is transported from upland forests and soils through groundwater and stream flow into wetlands and lakes (e.g., Dalva and Moore 1991;

Schiff et al. 1997). Mineral soils can retain DOC, primarily through sorption on the hydroxides of aluminum and iron (e.g., McDowell and Wood 1984; Moore et al. 1992). Fluxes of DOC within catchments are dependent on the sources and sinks of DOC, as well as the hydrologic pathways (e.g., Marin et al. 1990; Dosskey and Bertsch 1994; Fiebig 1995). Pore-water DOC concentrations are high in peatland soils, and DOC export from catchments appears to be strongly related to the proportion of the catchment occupied by peatland (e.g., Moore 1997). DOC is an important energy source for food chains based on microbial activity (Yano et al. 2000) and can affect the transport of metals and nutrients (Thurman 1985). It is also a major source of the export of acidity from catchments (Urban et al. 1989) and may play a role in the methylation of mercury (Heyes et al. 2000).

The complex character of DOC chemistry in natural waters has created problems in identifying its chemical forms and in examining ways in which this chemistry changes as water moves through the landscape and (or) is affected by disturbance. A common distinction is between fulvic and

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humic acids, operationally defined as soluble and insoluble DOC, respectively, when a filtered water sample is acidified to pH 2 (Thurman 1985). Fractionation procedures have been developed, based on the affinity of DOC for resins of different ionic character, thereby isolating compounds based on their aromaticity, solubility, molecular weight, and acid functionality (Leenheer 1981). The hydrophobic acid (HPOA) fraction contains a variety of phenolic and carboxylic acids, such as tannins, flavenoids, humic-bound carbohydrates, and aromatic acids (Qualls and Haines 1991). The hydrophilic acid (HPIA) fraction consists of lower molecular weight acids and inositol and other sugar phosphates. The hydrophobic and hydrophilic neutral fractions (HPON and HPIN, respectively) contain more labile materials such as sugars, polysaccharides, carbohydrates, alcohols, and hydrocarbons. The base fractions (HPOB and HPIB) contain proteins, free amino acids, and aromatic polymer sugars.

Studies of DOC fractionation in forest soils have shown that most (80–90%) of the DOC is contained in the HPOA and HPIA fractions, with little (<20%) in the neutral and base fractions (e.g., Cronan and Aiken 1985; David and Vance 1989). In the pore waters of peatlands, or in small lakes draining peatlands, Bourbonniere (1989) and McKnight et al. (1985) showed that 44–67% and 15–20% of the DOC was in the HPOA and HPIA fractions, respectively, whereas 13–33% was in the neutral fractions.

The Experimental Lakes Area (ELA) of northwestern Ontario contains a mosaic of upland forests and oligotrophic wetlands and lakes developed on Precambrian Shield rocks. A number of studies have focused on the biogeochemistry of these systems, involving elemental export from upland catchments (Allan et al. 1993), and the effect of forest fires on nutrient export (Bayley et al. 1992). Although DOC plays an important role in the chemistry and ecology of the lakes and the general factors affecting DOC in ELA lakes have been established (Schindler et al. 1992), little is known about the sources and chemistry of DOC within this environment.

The creation of hydroelectric reservoirs in the boreal and subarctic regions of Canada has resulted in the flooding of large areas of wetland, increasing the emission of greenhouse gases and the concentration of mercury in water bodies and the food chain (e.g., Duchemin et al. 1995; Rosenberg et al. 1997; St. Louis et al. 2000). The dynamics and chemistry of DOC may also be expected to change upon flooding of upland forests and wetlands, through changes in hydrologic and thermal regimes, the death and decay of vegetation, and changes in peat decomposition. The Experimental Lakes Area Reservoir Project (ELARP) was designed to study the effect of shallow impoundment on the cycling of carbon and mercury in a small boreal wetland. The 632 wetland was used as a control from 1992 to 1995, and the 979 catchment was experimentally impounded by 1.3 m of water in June 1993. Kelly et al. (1997) have shown that this impoundment resulted in a change from a C sink to source as CO₂, increased CH₄ emission rates, and increased rates of mercury methylation.

In this paper, we determine the sources, sinks, and fluxes of DOC in a small upland forest catchment and in two wetland catchments, we establish the spatial and temporal variability of DOC in peat pore water, streams, and ponds, and we define the pathways of DOC transport in the peatland.

We also examine the effect of shallow impoundment on the concentrations and fluxes of DOC in a peatland over 3 years. Finally, we characterise the chemistry of DOC in upland and wetland water samples through a fractionation technique and examine the effect of impoundment on DOC chemistry.

Materials and methods

The catchments

The study was conducted at the Experimental Lakes Area (ELA) near Kenora, northwestern Ontario (49°40'N, 93°43'W). The area is located on granitic and gneissic rocks of Precambrian age, with sandy, shallow soils of the Regosol, Brunisols, and Podzol orders (Canadian Soil Survey Committee 1978). Upland vegetation in the area is dominated by forests with *Pinus banksiana*, *Betula papyrifera*, and *Picea mariana*, though there have been recent fires in some sections (Bayley et al. 1992). The wetlands are commonly made up of ponds surrounded by oligotrophic bogs of Fibrisol peats, dominated by poorly decomposed moss materials, and vegetated by trees (e.g., *P. mariana* and *Larix laricina*), shrubs (e.g., *Chamaedaphne calyculata*), and *Sphagnum* spp. (Bubier et al. 1993). The climate (Table 1) has a mean annual temperature of 1.8°C and a mean annual precipitation of 678 mm, of which 25% falls as snow (K. Beaty and M. Lyng, Freshwater Institute, 501 University Crescent, Winnipeg, MB R3T 2N6, Canada, personal communication).

The study focused on three catchments. The first was a 5.7-ha upland forested catchment (draining into Lake 114) that was logged in 1976, scarified in 1979, and now is covered by *P. banksiana*, *B. papyrifera*, *P. mariana*, and *P. glauca* with approximately 7000 stems·ha⁻¹, most of which are less than 5 cm diameter at breast height. The soils are shallow Orthic Brunisols, and the catchment is drained by an ephemeral stream that passed through a weir, fitted with a water-level recorder. Canopy throughfall was collected in ten 30-cm-diameter funnels placed 40 cm above the forest floor in stands dominated by one of the three major tree species. Stemflow was determined by placing 2.5-cm-diameter tubing around 10 trees (four *P. banksiana*, four *B. papyrifera*, and two *P. mariana*), sealing the tubing to the tree trunk. Bottles to collect throughfall and stemflow were fitted with a plug of glass wool to minimise the effect of particulate matter. Precipitation was sampled by a bulk collector placed in the open. Soil water was collected in zero-tension lysimeters, 900 cm² in area, installed below the litter, and in horizons A and B, following a design similar to that of Jordan (1968). Samples of precipitation, throughfall, stemflow, and soil water were collected at weekly intervals from 15 June to 1 October 1992. Stream samples were collected after rain events and during two major rainfalls. The second catchment was a 40-ha headwater peatland (632) consisting of an upland component dominated by shallow soils underlying coniferous vegetation surrounding a 4-ha peatland in which there was a central pond (0.9 ha). This pond fed a stream that passed through a fen, until it drained the catchment through a weir. Samples of peat pore water were collected from nests of piezometers positioned along a boardwalk (632BW) from the upland contact of the peatland to the edge of the pond. Samples were also collected from the pond and along the stream draining from the pond. Sampling was conducted ev-

Table 1. Monthly precipitation (*P*, mm) and mean temperature (*T*, °C) for May to October 1992 to 1995 and the long-term means (1969 to 1995).

Month	1992		1993		1994		1995		Long-term mean	
	<i>P</i>	<i>T</i>	<i>P</i>	<i>T</i>	<i>P</i>	<i>T</i>	<i>P</i>	<i>T</i>	<i>P</i>	<i>T</i>
May	75	11.9	39	10.6	44	12.0	60	10.5	63	10.0
June	137	13.5	95	14.7	68	17.8	67	20.2	101	14.8
July	137	15.2	152	17.5	181	17.7	81	18.7	91	17.7
August	126	15.6	146	17.4	69	15.6	110	19.3	81	16.7
September	135	10.9	61	8.5	187	13.7	35	11.6	88	10.3
October	14	4.8	26	2.2	53	7.5	56	4.5	52	3.7
Sum or mean	624	12.0	519	11.8	602	14.1	409	14.1	476	12.2
Δ long term	131%	-0.2	109%	-0.4	126%	+1.9	86%	+1.9		

ery 1–2 weeks from June to October 1992 to 1995. The third catchment was a 98-ha riparian peatland (979) with a central pond (2.4 ha) supplied by water draining a lake (Lake 240), as well as streams within the catchment. The peat covers 14 ha. Samples of peat pore water were collected from piezometers along a boardwalk (979BW) located from upland contact with the peatland to the pond, as well as located along a transect in the northeastern arm (979NE) of the catchment at 30, 150, and 250 m from the pond edge. The pond water was sampled, as was the pore water collected from pond sediments located at the east side of the pond. The inflow to the 979 catchment from Lake 240, as well as the 979 outflow, were sampled and discharge was measured. A stream (979EIF) draining upland and wetland sections of the eastern part of the catchment (55 ha) was sampled, and discharge was estimated by prorating with a similar catchment (239NW inflow; Bayley et al. 1992). Samples were collected at 1- to 2-week intervals at the above locations from June to October of 1992 to 1995. Maps of the 632 and 979 catchments can be found in Heyes et al. (1998, 2000).

The impoundment of 979 was accomplished by the creation of a dam at the outlet, which raised the water level in the catchment by 1.2–1.5 m from late June until early October 1993 and late May to early October, 1994 and 1995. The water was drained down to pre-flood levels during the winter, similar to the pattern in hydroelectric reservoirs. This raising of the water level initially flooded the peatland in 979 to a depth of about 1.2 m at the pond edge to a few centimetres at the margin and northernmost extremity in the northeast arm. However, over the course of the 3 years of flooding, peat lifted up, particularly close to the pond edge, so that a floating mat was formed over up to half of the area of flooded peat (Scott et al. 1999; Heyes et al. 2000). The impoundment initially killed all vegetation on the peat surface, but the floating mats became colonised by mosses and sedges, though there has been little regrowth of shrubs, and all trees in the flooded area were killed. Where the peat mat floated, the piezometer nests became displaced and had to be reinstalled; in some cases, they no longer sampled water from the same section of the peat profile as before the impoundment.

Sample analysis

After collection, the water samples were filtered through Gelman A/E glass-fibre filters (1.0 µm; Pall Corp., through VWR International, Mississauga, Ont.) and kept cool, and pH,

electrical conductivity, and DOC concentration were measured, the latter with a high-temperature, catalytic method using a Shimadzu Model 5050 total carbon analyzer.

Water samples (4 L) from the main biogeochemical components of the catchments were collected for DOC fractionation. After filtration through Gelman A/E paper, a 30-mL sample was retained and acidified to pH 2 by the slow addition of HCl. The sample was filtered, with the filtrate representing the fulvic acid fraction (FA) and the difference between initial and acidified samples representing the humic acid fraction (HA). DOC fractions were then separated as follows (adapted from Richmond and Bourbonniere (1987)) to eliminate the hydrophobic base fraction (HPOB). The sample was passed through a chromatographic column containing Amberlite XAD-8 resin (Rohm and Haas), which adsorbed the hydrophobic acids (HPOA) and some hydrophobic neutrals (HPON); the HPOA fraction was removed from the column by a backflush of 0.1 M NaOH. The sample that passed through the XAD-8 resin column contained the hydrophilic fractions and was passed through a strong acid cation exchange resin (Biorad AG MP 50, Bio-Rad Laboratories, Mississauga, Ont.). The hydrophilic bases (HPIB) were retained by the resin and desorbed with a backflush of 1.0 M HCl. The sample that passed through the Biorad column was passed through a third column containing a strong base anion exchange resin (Amberlite IRA 900), which retained the hydrophilic acid fraction (HPIA), subsequently released with a backflush of 1.0 M NaOH. The hydrophilic neutral fraction (HPIN) was defined by its inability to be adsorbed by any of the three resins. DOC concentrations in the fractions were determined with the Shimadzu TOC Analyzer, and estimates of the humic, fulvic, HPOB, HPOA, HPIB, HPIN, and HPIA fractions were made, expressed as a percentage of the total DOC in the sample.

DOC flux calculations

For the upland 114 catchment, input of DOC in precipitation was estimated by combining the DOC concentration data from the wet collector with the precipitation over the season. Throughfall flux of DOC was calculated by combining volumes of water collected and DOC concentrations, and DOC flux in stemflow was estimated using stemflow volumes and concentrations and the number of stems of different tree species in the watershed. Export of DOC from 114 was estimated using the volume of water crossing the weir and the volume-weighted DOC concentration. DOC export

from the 632 and 979 catchments was calculated using continuous discharge data and weekly DOC concentration.

Specific groundwater discharge (qx_z) in peat and sediment profiles was calculated using measurements of piezometric heads from nests of 1.25-cm-diameter polyvinylchloride tubes with a 20-cm slotted base covered with 40- μ m Nitex mesh, and hydraulic conductivity was calculated by the Horslev pumping test:

$$(1) \quad qx_z = K_z \frac{\Delta H}{\Delta l}$$

where K_z is the measured hydraulic conductivity for depth z , and $\Delta H/\Delta l$ is the lateral hydraulic gradient derived from flow nets.

Calculations were made for average summer conditions at sites BWA and BWC in 632 and sites BWA, BWD, NEA, NEB, and NEC in 979, as well as the sediment at the base of the 979 pond (Fig. 1). To calculate flux of DOC (F_{DOC_z}) in the peat profiles, the mean summer water flux was combined with the mean summer pore-water DOC concentration:

$$(2) \quad F_{\text{DOC}_z} = qx_z[\text{DOC}]$$

The total flux of DOC was obtained by summing the F_{DOC_z} for the seepage along the entire profile.

An estimate of the DOC export from peatland sections of catchments 632 and 979 was made by subtracting the estimated upland contribution (and the Lake 240 contribution in 979) from the observed export and converting it to an areal basis.

Results

Upland forest catchment

The volume-weighted mean DOC concentrations in the 114 upland catchment increased from bulk precipitation, through throughfall and stemflow to the soil organic horizons, then decreased in the mineral soil horizons and the stream (Table 2). Concentrations of DOC in the stream were weakly correlated with discharge, with DOC concentrations in the range of 15–25 $\text{mg}\cdot\text{L}^{-1}$ over a three orders-of-magnitude increase in discharge (Table 3). Over the sampling period from 18 June to 1 October 1992, the DOC input to the 114 catchment was 1.6 $\text{g}\cdot\text{m}^{-2}$ from precipitation and 3.8 and 0.5 $\text{g}\cdot\text{m}^{-2}$ from throughfall and stemflow, respectively, and there was an export of 2.1 $\text{g}\cdot\text{m}^{-2}$ in the stream (Table 2). The summer of 1992 was the wettest summer on record (31% greater precipitation than average), with 610 mm of precipitation falling from May to September (Table 1), so that the export of DOC in this year is likely to be close to the maximum for this system.

Wetland catchments

Mean pore-water concentrations of DOC, collected from May to October 1992, generally decreased with depth in the peat profiles along the transects in the 632 and 979 catchments, ranging from 20 to 60 $\text{mg}\cdot\text{L}^{-1}$ (Fig. 1). This pattern was most strongly established in profiles collected from the mineral margin of the peatland and weakest in profiles from the pond edge. Mean DOC concentrations were larger (30–90 $\text{mg}\cdot\text{L}^{-1}$) in 979NE and were generally greatest in the mid-

dle part (50–150 cm) of the peat profile. DOC concentrations in peat pore water generally increased over the season, especially in the lower sections of the profile, and were largest in late June and September–October, associated with heavy rainfall events. During the dry summer months, increasing DOC concentrations were observed in the surface water, especially in 979NE. The 3 m of sediment in the centre of the 979 pond contained interstitial waters with DOC concentrations between 25 and 35 $\text{mg}\cdot\text{L}^{-1}$ with little variation with depth (Table 4).

Computed lateral flux of DOC for seven peatland cross sections ranged from 0.02 to 4.5 $\text{g}\cdot\text{day}^{-1}$ (Fig. 2) and was primarily controlled by the large decrease in hydraulic conductivity below about 50 cm in the peat profile. Some profiles displayed a pattern of water and DOC movement that is typical of bogs, mainly lateral within the top 50 cm of the profile (profiles at 632BWC, 979BWD, 979NEB, and 979NEC). There was a more complex movement of water and DOC, with an increased flux at the base of the profile, controlled either by local hydraulic patterns or by an increase in hydraulic conductivity, such as gyttja sediments, at sites close to the pond margin (632BWA, 979BWA, and 979NEA). Zones of convergence of flow paths coincided with large concentrations of DOC, such as 1–1.5 m beneath the peat surface at distances of 0–50 and 150–200 m along the 979NE transect (Fig. 1*b*; the latter caused by an underlying topographic ridge) and in the lower sections of 979BW (Fig. 1*c*).

Pond DOC concentrations in the 632 and 979 catchments in June to October 1992 averaged 13.8 and 10.0 $\text{mg}\cdot\text{L}^{-1}$, respectively, the latter being diluted by water draining from Lake 240, with DOC concentration averaging 8.1 $\text{mg}\cdot\text{L}^{-1}$ (Table 4). The streams draining catchments 632, 979EIF, and 979OF contained DOC concentrations ranging from 10 to 210 $\text{mg}\cdot\text{L}^{-1}$ (Table 4). We estimated input and output of DOC to the 632 and 979 catchments from June to September 1992, using precipitation and upland and stream DOC fluxes as input to the wetland section (Table 5). The difference in DOC export from the catchment and the estimated input can be taken as an indication of the export of DOC from the peatland and pond sections, with 28–30 $\text{g}\cdot\text{m}^{-2}$ being calculated as the net export of DOC.

Effect of impoundment

The considerable variation in monthly precipitation and mean temperature from 1992 to 1995 (Table 1) confounds the interpretation of the changes in DOC concentration and export associated with the impoundment of the peatland section of catchment 979. Profiles of DOC concentrations in the pore waters of the 632 peatland showed little interannual variability from 1992 to 1995 (Fig. 1). DOC concentrations in the pond and outflow of 632 varied from 1992 to 1995, being largest in 1994 and smallest in 1995, wet and dry years, respectively (Table 6).

Pore-water DOC concentrations near the peat surface at 979BW increased threefold after impoundment, whereas concentrations in 979NEA increased to ~100 $\text{mg}\cdot\text{L}^{-1}$ (Fig. 1). At a depth of 6 m at 979BW, DOC concentrations increased from ~40 in 1992 to ~120 $\text{mg}\cdot\text{L}^{-1}$ in 1994, related to a steepening of the hydraulic gradients and an increase in the groundwater flux originating in 979NE. In 1995, drier condi-

Fig. 1. Mean concentration of dissolved organic carbon (DOC) sampled from June to October 1992 to 1995 in peat profiles along transects from the upland margin to the pond (a) at 632BW, (b) along 979NE, and (c) at 979BW.

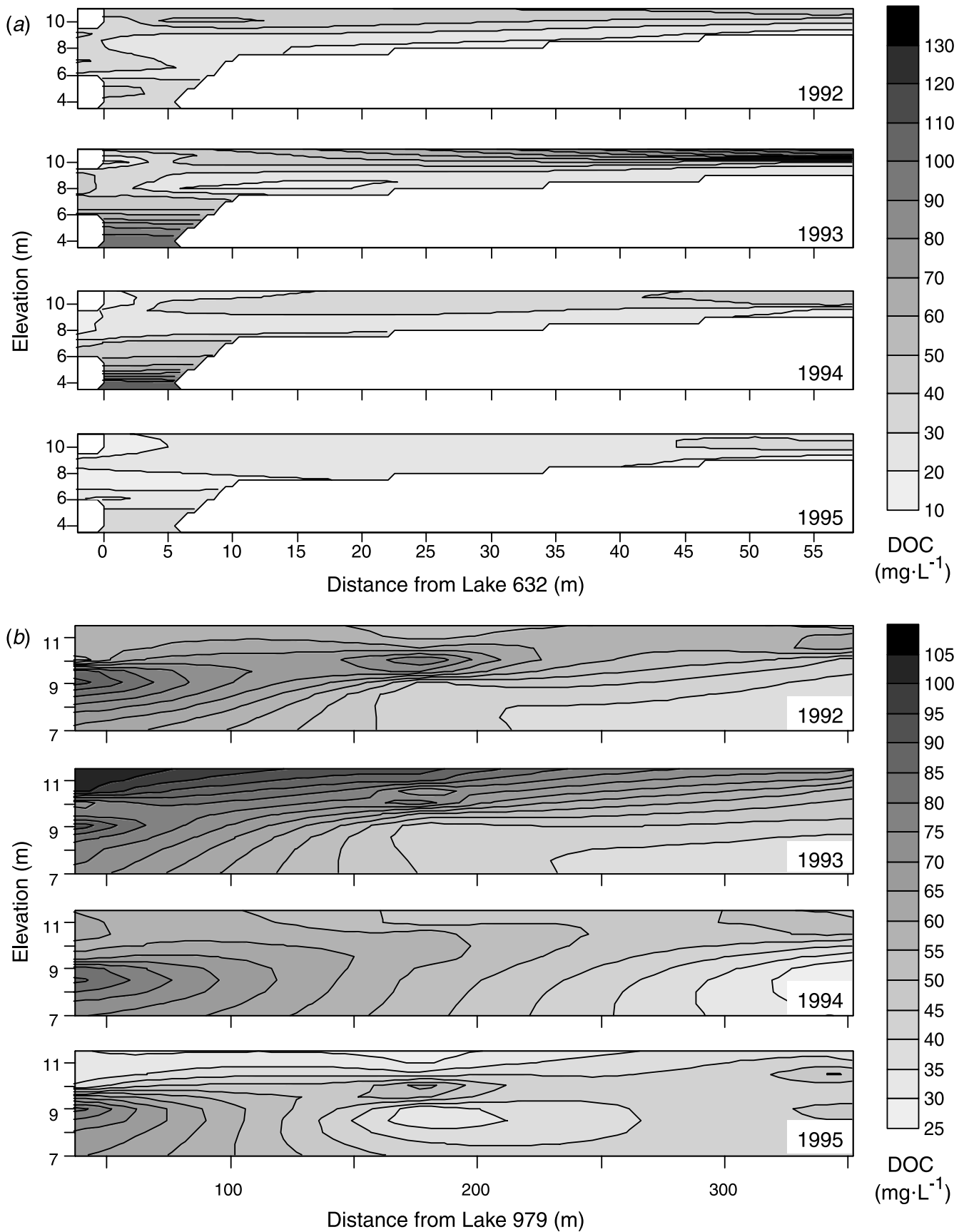
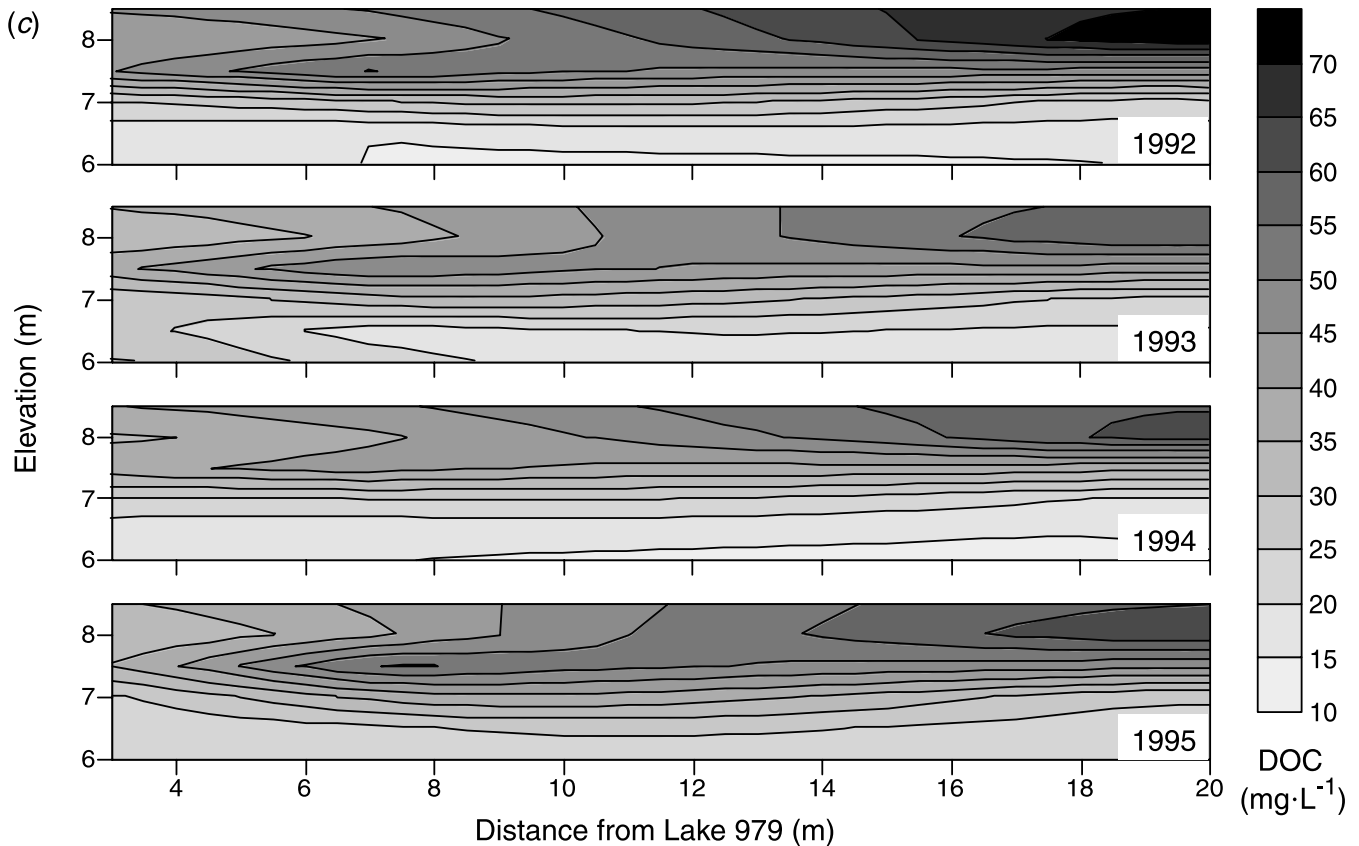


Fig. 1 (concluded).



tions reduced the hydraulic flow at this 6-m groundwater convergence point, producing a decrease in DOC concentrations to $\sim 40 \text{ mg}\cdot\text{L}^{-1}$. In contrast, the less precipitation and the reduction in flow in the northern portion of 979NE resulted in stagnant conditions, producing higher pore-water DOC concentrations at depths of 2 and 3 m (Fig. 1).

Flooding of the 979 peatland also caused physical disturbance to the peat through methane production and the creation of floating peat (Scott et al. 1999). Separation of peat layers initiated around the pond margin, increasing mixing of peat pore water with pond water and generating static hydraulic equilibrium conditions, resulting in smaller DOC concentrations. In 1995, the DOC concentrations at 979BW were relatively small ($20\text{--}40 \text{ mg}\cdot\text{L}^{-1}$) and showed little variation to a depth of 4 m, and a similar pattern was observed at 979NEA in 1994 and 1995 (Fig. 1).

From 1992 to 1993 (impounded), DOC concentrations in the lake and outflow stream rose from 10.0 to $13.3 \text{ mg}\cdot\text{L}^{-1}$ in the 979 pond and from 11.5 to $14.7 \text{ mg}\cdot\text{L}^{-1}$ in the 979 outflow, respectively (Table 6). The pattern was repeated in subsequent years, resulting in seasonal mean concentrations of $129\text{--}179\%$ (pond) and $109\text{--}151\%$ (outflow) of the pre-impoundment values. DOC concentrations in the 632 pond and outflow decreased significantly in the dry year 1995, as base flow predominated, but increased in 979 pond and outflow. DOC concentration and discharge were positively correlated in the 979 outflow before impoundment but became inversely correlated after impoundment, primarily because of changes in the hydrology (Fig. 3).

DOC export from the two catchments was controlled primarily by runoff, ranging from 0.8 to $5.7 \text{ g}\cdot\text{m}^{-2}$ in the driest (1995) and wettest (1992) years in the 632 catchment, respectively (Table 6). Despite higher DOC concentrations in the 979 outflow following impoundment, DOC exports in 1993 to 1995 remained smaller than in 1992, with a similar pattern to that observed in the 632 catchment. The small response of DOC export to impoundment in 979 may be related to the change in the DOC concentration and discharge relationship in the 979 outflow and that the impounded portion of the 979 catchment was small compared with the whole catchment, with the import of water and DOC from Lake 240 and the 979 eastern inflow playing a large role in controlling exports.

DOC chemistry

Fulvic acid ranged from 58 to 97% of the total DOC in the samples with no discernible pattern between DOC from different sources (Fig. 4). In water draining the upland portions of the 114 and 632 catchments, between 85 and 93% of the DOC consisted of the acidic fractions HA, HPOA, and HPIA, primarily the HPOA fraction. In the DOC collected from peat pore waters in the 632 and 979 catchments, the acid fraction ranged from 64 to 87%, but without a consistent pattern of variations of the various fractions among sites. The highly condensed and relatively insoluble HA fraction increased with depth in the peat.

The HPIN fraction of DOC was consistently small, averaging less than 5%, except at one site in the 632 catchment,

Table 2. Volume-weighted mean dissolved organic carbon (DOC) concentrations and DOC flux in bulk precipitation, tree throughfall and stemflow, soil horizons, and stream in the 114 upland catchment sampled from 15 June to 1 October 1992.

		Concentration (mg·L ⁻¹)	Flux (g·m ⁻²)
Bulk precipitation		3.4 (0.4, 23)	1.6
Throughfall	Pine	22.2 (2.1, 21)	
	Spruce	16.2 (5.5, 7)	
	Birch	14.3 (2.6, 20)	
	Overall	18.1	3.8
Stemflow	Pine	29.5 (2.5, 12)	
	Spruce	152.6 (48.3, 5)	
	Birch	21.9 (3.1, 8)	
	Overall	51.9	0.58
Soil	LFH ^a	61.8 (7.0, 24)	
	Ae ^a	27.1 (2.9, 10)	
	Bm ^a	11.0 (4.2, 2)	
Stream		18.6 (2.8)	2.1

Note: Values in parentheses indicate the standard error of concentration and sample size, respectively.
^aSoil horizon nomenclature per the Canadian Soil Survey Committee (1978).

Table 3. Relationships between dissolved organic carbon (DOC) concentration (mg·L⁻¹) and discharge (Q , L·s⁻¹) in streams draining upland, wetland, and combined catchments in the summer of 1992.

Stream	n	Regression equation	r^2	p
Upland 114	38	DOC = 1.20log ₁₀ Q + 22.4	0.16	0.013
Wetland 239NW	20	DOC = 0.22log ₁₀ Q + 21.1	0.01	0.757
Wetland 632	28	DOC = 4.61log ₁₀ Q + 27.8	0.44	<0.001
Wetland 979 east	18	DOC = -1.29log ₁₀ Q + 22.1	0.02	0.501
Lake 240 outflow	22	DOC = 0.10log ₁₀ Q + 8.6	0.17	0.060
Lake 979 outflow	22	DOC = 9.20log ₁₀ Q + 22.1	0.33	0.008

Table 4. Mean dissolved organic carbon (DOC) concentrations in ponds in catchments 632 and 979, pond sediments in catchment 979, and volume-weighted mean DOC concentrations in streams draining catchments 632 and 979, the 979NE inflow, and Lake 240 in the summer of 1992.

System	DOC (mg·L ⁻¹)
Catchment 632 pond	13.8 (3.0)
Catchment 632 outflow	16.8 (3.6)
Catchment 979NE inflow	21.3 (5.2)
Lake 240 outflow	8.1 (2.4)
Catchment 979 pond	10.0 (2.5)
Catchment 979 pond sediments	28.6 (5.3)
Catchment 979 outflow	10.5 (3.5)

Note: Values in parentheses indicate the standard deviation of concentrations.

where it reached 26%. The labile hydrophilic fractions composed an average of 34% of the DOC in the 979 peat pore water, with the HPIA fraction representing the largest of these. In the upper layers of the peat, the HPIN and HPIB fractions were typically below 2% of the DOC and increased to about 5% in the deeper layers. Before impoundment, the HPIN fraction in the upper 50 cm of the 979 peatland was similar to that measured in the 632 peatland bog and Thoreau's Bog (McKnight et al. 1985).

The most pronounced change in DOC chemistry upon impoundment of the 979 peatland was the increase in the HPIN

fraction (Fig. 5). In 1993, the HPIN fraction in the surface layers increased to 18% of the DOC at the 979BW site and to 6% at the 979 NEA site, followed by further increases to 22 and 28%, respectively, in 1994. In 1995, the HPIN fraction decreased to 5%, suggesting that more of the readily soluble compounds had been depleted from the dying vegetation. The pattern of HPIN fraction with depth in the peat profile was quite similar to that observed in the upper layers of the peat. The HPIA fraction had a lower overall percentage in 1994 but increased above its pre-flood values in 1995 as the HPIN fraction was degraded and oxidised to shorter-chain compounds. The percentage of HPIN in the water overlying the peat at 979BW and 979NE and the 979 outflow also showed a decline from 1994 to 1995.

Combining the increase in the proportion of DOC in the HPIN fraction with the overall DOC concentration at the impounded sites (Fig. 1) resulted in a substantial increase in the concentration of HPIN DOC. At the 979BW and 979NE sites in 1992, the HPIN concentration in peat pore water rose from <1 to 3–20 mg·L⁻¹ in 1993–1994, before falling to <3 mg·L⁻¹ in 1995 (Fig. 5).

Discussion

Sources, sinks, and fluxes of DOC

This study has confirmed the important sources and sinks of DOC in upland Canadian Shield catchments. Precipitation is a major source of DOC, with an average DOC concentration of 3.4 mg·L⁻¹ in the 114 catchment, which is within the

Fig. 2. Lateral flux of dissolved organic carbon (DOC) within peat profiles in catchments 632 and 979, before impoundment, based on DOC concentrations and calculations of water movement from hydraulic pressures and conductivities.

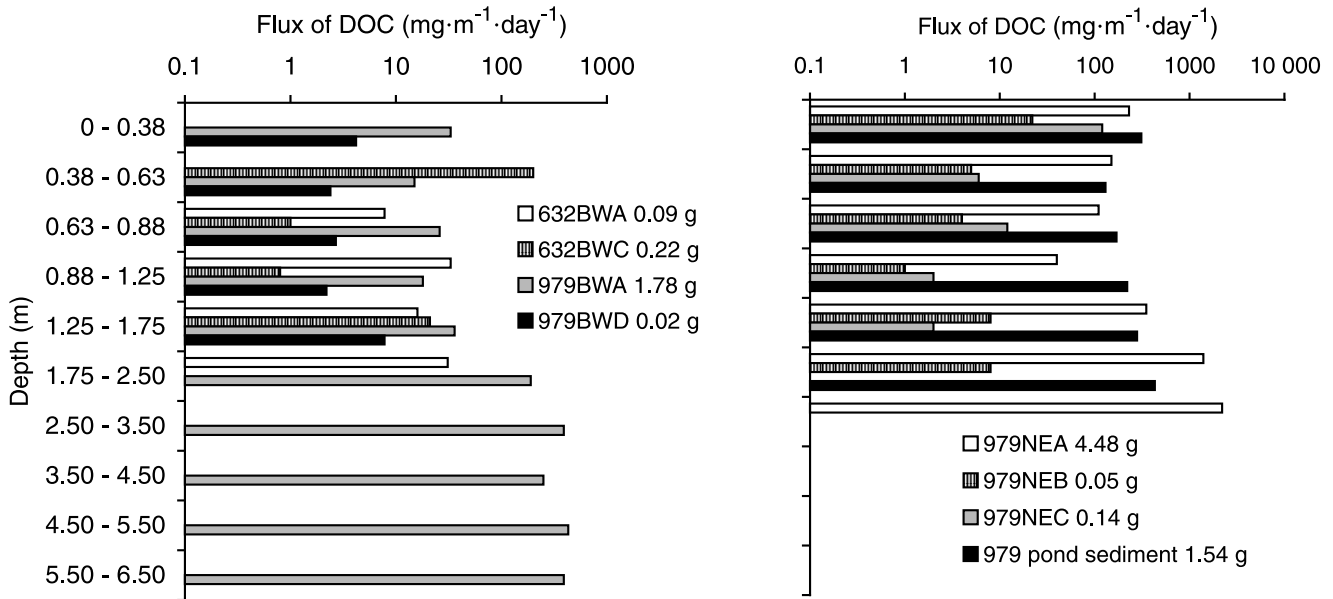


Table 5. Estimated fluxes of dissolved organic carbon within and from the 632 and 979 catchments, 14 June – 30 September 1992.

	Catchment 632		Catchment 979	
	kg	g·m ⁻²	kg	g·m ⁻²
Input				
Precipitation	115	1.6	340	1.6
Upland	745	2.1	542	2.1
Lake 240 outflow ^a			10 203	6.0
Catchment 979NE inflow ^b			2 080	3.8
Export				
Stream	1806	4.5	17 363	17.7
Wetlands	946	27.9	4 198	29.4

^aOutflow from the Lake 240 catchment, which flows into the 979 pond.

^bExport from the catchment draining into the 979NE peatland.

Table 6. Mean dissolved organic carbon concentrations (mg·L⁻¹) in the central pond and outflows and dissolved organic carbon export (g·m⁻²) of the 632 and 979 catchments, May–October 1992 to 1995.

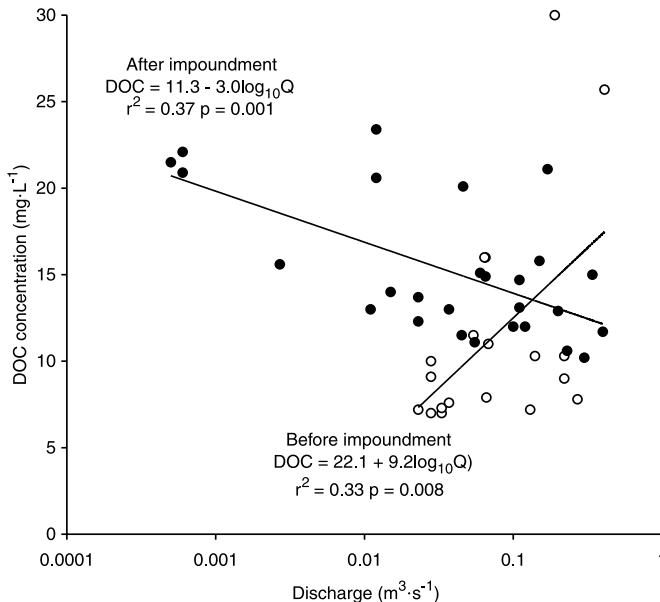
Year	Catchment 632			Catchment 979		
	Pond	Outflow	Export	Pond	Outflow	Export
1992	13.8 (3.0)	16.7 (5.7)	5.7	10.0 (2.5)	11.5 (6.5)	8.7
1993	13.2 (2.9)	17.2 (3.1)	3.8	13.3 (5.5)	14.7 (4.0)	6.1
1994	17.7 (4.4)	18.1 (3.2)	3.9	12.9 (2.4)	12.6 (1.6)	5.1
1995	10.5 (1.3)	11.2 (3.2)	0.8	17.9 (4.4)	17.4 (4.9)	1.8

Note: Values in parentheses indicate the standard deviation of the seasonal sampling.

range reported by Allan et al. (1993) at the ELA and globally by Moore (1997). The import of 1.6 g·m⁻² of DOC in the 1993 summer at upland catchment 114 represents 76% of the export of DOC over that period, though transformations have occurred. Further contributions of DOC arise from throughfall in the forest canopy, with DOC concentrations ranging from 15 to 22 mg·L⁻¹ also similar to that reported at ELA (Allan et al. 1993) and elsewhere (Moore 1997). Although stemflow DOC concentrations are large (22–

153 mg·L⁻¹) and vary by tree species, the small volume of stemflow reduces the importance of this contribution. Further DOC is produced by the decomposition of organic matter in the organic horizons of the soil: less decomposed material produces larger amounts of DOC (Gödde et al. 1996; Moore and Dalva 2001). As the DOC-rich soil solution passes into the mineral horizons, DOC concentrations decreased from 30–60 to <11 mg·L⁻¹, similar to that reported by Allan et al. (1993). This decrease with passage through

Fig. 3. Relationship between dissolved organic carbon (DOC) concentration and discharge in the 979 catchment outflow, before (open circles) and after (solid circles) impoundment.



the profile is a common phenomenon (Moore 1997) and results from microbial utilization of DOC and adsorption on the surfaces of mineral particles, especially where there are iron and aluminum oxides and hydroxides (McDowell and Wood 1984; Moore et al. 1992). In a review of the controls of dissolved organic matter in soils, Kalbitz et al. (2000) suggest that up to 40% of DOC in upland soils may be biodegradable.

In the upland catchments with their shallow soils, there is considerable internal cycling of DOC. In a similar series of Shield catchments in Ontario, Schiff et al. (1997) used ^{14}C analysis of DOC from upland streams to show that most of the DOC exported was incorporated into the catchment in the last 40 years. The catchment mosaic of bare rock surfaces, lichen-covered areas, forests, and pockets of organic matter over thicker soils creates a spatial pattern of variable DOC production, transport, and export, so that DOC export is dependent on the proportional coverage and hydrologic pathways (Allan et al. 1993). Fast rates of internal cycling result in relatively small amounts ($<5 \text{ g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$) of DOC exported from upland catchments to streams, wetlands, and lakes (Moore 1997).

Concentrations of DOC in peat pore waters of 30–100 $\text{mg}\cdot\text{L}^{-1}$ at ELA are similar to those observed in other peatlands (e.g., McKnight et al. 1985; Moore 1997; Fraser et al. 2001). These high concentrations reflect high rates of DOC production, even under anaerobic conditions (Moore and Dalva 2001), the absence of strong adsorption mechanisms, and the long residence time of water, particularly in the lower sections of the peat profile, where the hydraulic conductivities are small. Diffuse or point sources from uplands contribute small amounts of DOC to peatlands, based on the data from catchment 114 and the work of Allan et al. (1993).

The estimated DOC export of 28–30 $\text{g}\cdot\text{m}^{-2}$ from the peatland sections of the 632 and 979 catchments at ELA is similar

to, or higher than, that reported from other peat-dominated catchments in the boreal zone (e.g., Urban et al. 1989; Fraser et al. 2001). Several studies have shown that the DOC concentration in lakes and streams is related to the proportion of wetland or peatland within the catchment (e.g., Schindler et al. 1992; Moore 1997).

The interannual variability in DOC export from the 632 catchment at ELA is related to the hydrologic controls in these systems, which consist of uplands with shallow soils and wetlands. DOC concentrations in peat pore water are stable from year to year (632 catchment), and stream DOC concentration is relatively insensitive to changes in discharge (Schindler et al. 1992), so that changes in precipitation and evapotranspiration play a major role in controlling DOC export. Over 4 years at a 7-ha upland catchment at ELA, Allan et al. (1993) observed a twofold variation in annual runoff (148–318 $\text{mm}\cdot\text{year}^{-1}$), even though the annual precipitation ranged from 488 to 601 $\text{mm}\cdot\text{year}^{-1}$. Schindler et al. (1992, 1996) have shown that changes in DOC concentration and retention within ELA lakes can be related to changes in runoff from the source catchments.

Variations in DOC chemistry

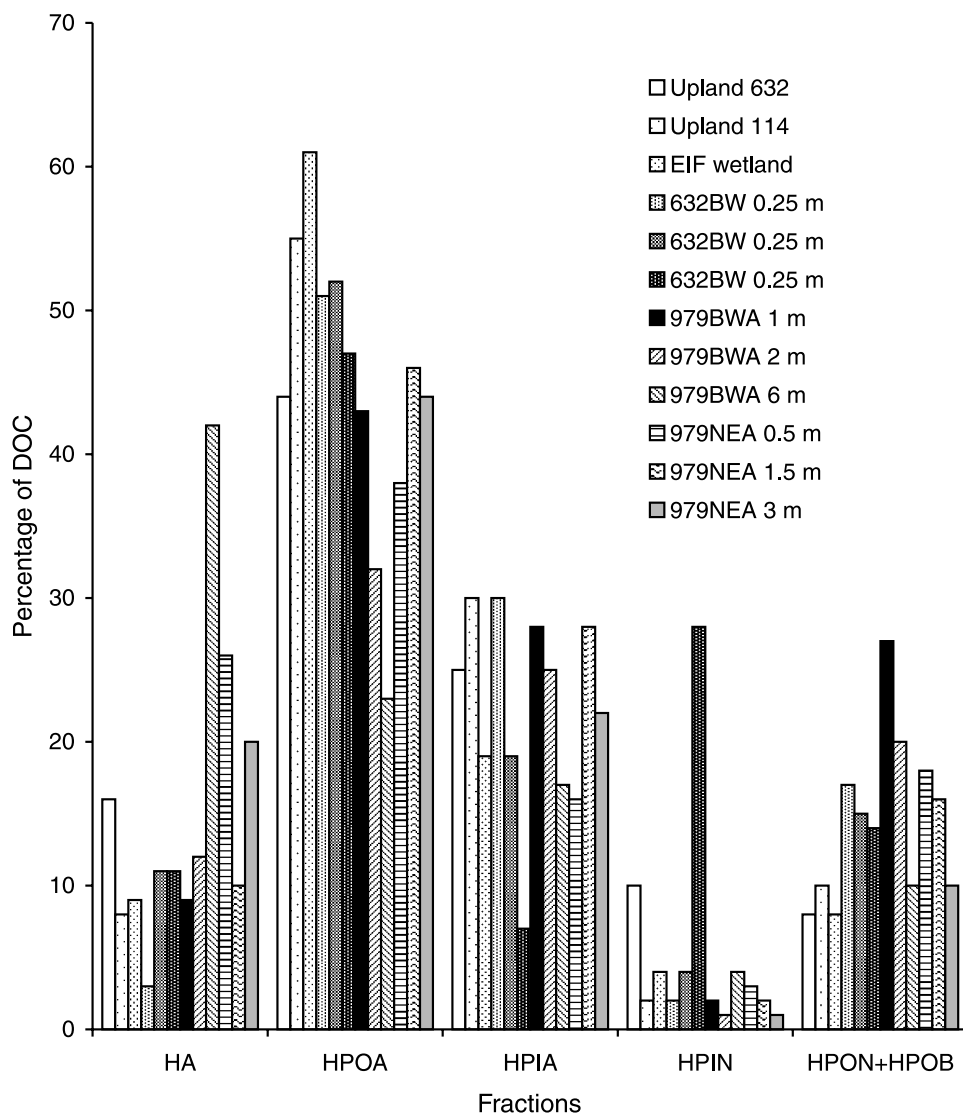
The DOC chemistry in samples derived from the upland catchment (114) was dominated (85–93%) by the acid (HA, HPOA, and HPIA) fractions, with relatively small amounts in the neutral (HPON, HPIN) fractions. This distribution is similar to results reported for other forested and well-drained soils (e.g., Cronan and Aiken 1985; David and Vance 1989; Qualls and Haines 1991). Changes in the fractions may be brought about by adsorption onto mineral material and microbial utilization (Kalbitz et al. 2000).

The fractionation of the peat pore-water DOC also confirms a pattern observed from a more restricted range of peat pore-water samples reported by Bourbonniere (1989) and McKnight et al. (1985). The HA fraction in the peat pore waters averaged 16%, with the highest value of 42% observed at a depth of 5–6 m in the 979 site, which corresponded to contact with mineral soil and a higher specific conductivity. An increasing HA proportion with depth in the peat profiles, on average, is a trend common in some eastern Canadian bogs (Bourbonniere 1989). The combined HPOA and HA fractions average of 60% of DOC is similar to that reported for Thoreau's Bog by McKnight et al. (1985), and the more labile HPIN fraction comprised $<5\%$ of the DOC.

Effect of impoundment on DOC

The impoundment had a profound effect on the concentration of DOC in the peat pore water in the 979 catchment, raising concentrations in the first and second years, but decreasing it in the third year. The increased DOC concentrations can be traced to changes in the peatland thermal regime, the death, decomposition, and leaching of the peatland vegetation, and changes in the hydrology. The warming of the surface 50 cm of the peat surface by 3–5°C (Kelly et al. 1997) would have increased peat decomposition rates. Laboratory studies by Gödde et al. (1996) and Moore and Dalva (2001) have shown that DOC production rates in decomposing plant tissues and soils is temperature dependent with Q_{10} values of 1.5 to 2.0 (Q_{10} being the factorial increase in production rate brought about by a 10°C increase in tempera-

Fig. 4. Percentage of dissolved organic carbon (DOC) in five chemical fractions (HA, humic acid; HPOA, hydrophobic acid; HPIA, hydrophilic acid; HPIN, hydrophilic neutral; HPON + HPOB, hydrophobic neutral + base) from upland waters and peat pore waters before impoundment.



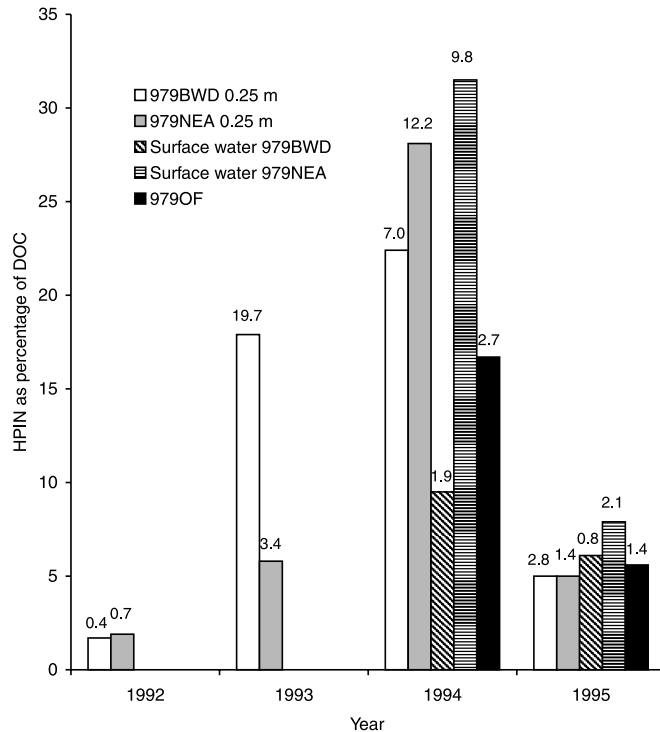
ture). However, most of the increased DOC concentration in the peat pore water after impoundment in the 979 is likely to be derived from the decomposition of the biomass. Before flooding, the aboveground biomass on the 979 peatland averaged $800 \text{ g C}\cdot\text{m}^{-2}$, mainly shrubs (Dyck and Shay 1999). During the two years after impoundment, mass loss of decomposing plant tissues amounted to $230 \text{ C}\cdot\text{m}^{-2}$ (Kelly et al. 1997). The results of Gödde et al. (1996) and Moore and Dalva (2001) showed that in fresh plant tissues undergoing decomposition, the ratio of DOC to CO_2 production is high, though some of the DOC produced is likely converted by microbes into CO_2 . Kelly et al. (1997) estimated that the increased flux of $\text{CO}_2\text{-C}$ and $\text{CH}_4\text{-C}$ to the atmosphere from the impounded peat surface at 979 was $260 \text{ g}\cdot\text{m}^{-2}$ over the two years. Of this, they estimated that $220\text{--}240 \text{ g}\cdot\text{m}^{-2}$ was derived from plant tissue decomposition and $30\text{--}40 \text{ g}\cdot\text{m}^{-2}$ from accelerated decomposition of the peat.

The hydrologic pathways in the wetland changed substantially after flooding. The most significant change was an al-

teration of flow from a relatively restrictive path near the peat surface to a broad zone of mixing throughout the peat profile. This would have increased mixing and formation of previously relatively immobile, DOC-rich water but would also allow the penetration of fresh C sources to a greater depth. These changes in decomposition and hydrology account for the pronounced increased concentration of peat pore-water DOC after impoundment, but the effect is short-lived as the development of floating peat allowed greater mixing of pond and pore waters, increasing the concentration in the former and decreasing it in the latter.

Despite the increased production of DOC in the peatland part of the 979 catchment after impoundment, there was no significant change in DOC export from the catchment when compared with the export from the undisturbed 632 catchment. This may be attributed to the possibility of photolysis and microbial uptake of DOC in the 979 pond before being exported; Kelly et al. (1997) reported increased microbial activity and nutrient concentrations in the 979 pond. Of greater

Fig. 5. Percentage dissolved organic carbon (DOC) in the hydrophilic neutral fraction of peat pore water in the impounded catchment, 1992–1995. Samples were collected from a depth of 0.25 m at 979BWD and 979NEA, from surface water at 979BWD and 979NEA, and from the 979 outflow. Number above each column represents the hydrophilic neutral fraction concentration ($\text{mg}\cdot\text{L}^{-1}$).



importance, though, is the fact that much of the water exported from 979 is derived from Lake 240 and the upland sections of 979, which were unaffected by the impoundment. Only 14 ha of peat were flooded, compared with the total catchment area of 98 ha. Thus, interannual variations in runoff dominate patterns of DOC export from the 979 catchment.

There was a profound effect of impoundment on the DOC chemistry, as revealed by the fractionation. The increase in the HPIN fraction, containing the most biodegradable organics, can be attributed to the decomposition of biomass, especially in the first year after impoundment. The increase in proportion of DOC and absolute concentration in the pore water and pond water suggests an enhancement of microbial activity, which was reported in the pond after impoundment (Kelly et al. 1997). The effect on DOC fractions is short-lived, however, probably because the readily decomposable plant tissues have been consumed in the first two years and because of increased mixing of the pond water and peat pore water, plus dilution from Lake 240 and the 979 upland runoff.

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References

- Allan, C.J., Roulet, N.T., and Hill, A.R. 1993. The biogeochemistry of pristine, headwater Precambrian shield watersheds: an analysis of material transport within a heterogeneous landscape. *Biogeochemistry*, **22**: 37–79.
- Bayley, S.E., Schindler, D.W., Beaty, K.G., Parker, B.R., and Stainton, M.P. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorus. *Can. J. Fish. Aquat. Sci.* **49**: 584–596.
- Bourbonniere, R.A. 1989. Distribution patterns of dissolved organic matter fraction in natural waters from eastern Canada. *Org. Geochem.* **14**: 97–107.
- Bubier, J., Comer, N., Dalva, M., Heyes, A., Moore, T., and Savage, K. 1993. Peat thickness and characteristics in Catchment 979. Experimental Lakes Area Reservoir Project Rep. No. 1. Available from Freshwater Institute, Department of Fisheries and Oceans, Winnipeg, MB R3T 2N6.
- Canadian Soil Survey Committee. 1978. The Canadian system of soil classification. Canadian Department of Agriculture Publication No. 1646, Ottawa.
- Cronan, C.S., and Aiken, G.R. 1985. Chemistry and transport of soluble humic substances in forested watersheds of the Adirondack Park, New York. *Geochim. Cosmochim. Acta*, **49**: 1697–1705.
- Dalva, M., and Moore, T.R. 1991. Sources and sinks of dissolved organic carbon in a forested swamp catchment. *Biogeochemistry*, **15**: 1–19.
- David, M.B., and Vance, G.F. 1989. Chemical character and origin of organic acids in streams and seepage lakes of central Maine. *Biogeochemistry*, **12**: 17–41.
- Dosskey, M.G., and Bertsch, P.M. 1994. Forest sources and pathways of organic matter transport to a blackwater stream: a hydrologic approach. *Biogeochemistry*, **24**: 1–19.
- Duchemin, E., Lucotte, M., Canuel, R., and Chamberland, A. 1995. Production of the greenhouse gases CH_4 and CO_2 by hydroelectric reservoirs of the boreal region. *Global Biogeochem. Cycl.* **9**: 529–540.
- Dyck, B.S., and Shay, J.M. 1999. Biomass and carbon pool of two bogs in the Experimental Lakes Area, northwestern Ontario. *Can. J. Bot.* **77**: 291–304.
- Fiebig, D.M. 1995. Groundwater discharge and its contribution of dissolved organic carbon to an upland stream. *Arch. Hydrobiol.* **134**: 129–155.
- Fraser, C., Roulet, N., and Moore, T. 2001. Hydrology and dissolved organic carbon biogeochemistry in an ombrotrophic bog. *Hydrol. Proc.* **15**: 3151–3166.
- Gödde, M., David, M.B., Christ, M., Kaupenjohann, M., and Vance, G.F. 1996. Carbon mobilization from the forest floor under red spruce in the northeastern U.S.A. *Soil Biol. Biochem.* **28**: 1181–1189.
- Heyes, A., Moore, T.R., and Rudd, J.W.M. 1998. Mercury and methyl mercury in decomposing vegetation of a pristine and impounded wetland. *J. Environ. Qual.* **27**: 591–599.
- Heyes, A., Moore, T., Rudd, J., and Dugoua, J-J. 2000. Methyl mercury in pristine and impounded boreal peatlands, Experimental Lakes Area, Ontario. *Can. J. Fish. Aquat. Sci.* **57**: 2211–2222.
- Jordan, C.F. 1968. A simple, tension-free lysimeter. *Soil Sci.* **105**: 81–86.

- Kalbitz, K., Solinger, S., Park, J.-H., Michalzik, B., and Matzner, E. 2000. Controls on the dynamics of dissolved organic matter in soils: a review. *Soil Sci.* **165**: 277–304.
- Kelly, C.A., Rudd, J.W.M., Bodaly, R.A., Roulet, N.T., St. Louis, V.L., Heyes, A., Moore, T.R., Schiff, S., Aravena, R., Scott, K.J., Dyck, B., Harris, R., Warner, B., and Edwards, G. 1997. Increases in fluxes of greenhouse gases and methyl mercury following flooding of an experimental reservoir. *Environ. Sci. Tech.* **31**: 1334–1344.
- Leenheer, J.A. 1981. Comprehensive approach to preparative isolation and fractionation of dissolved organic carbon from natural waters and wastewaters. *Environ. Sci. Tech.* **15**: 578–587.
- Marin, L.E., Kratz, T.K., and Bowser, C.J. 1990. Spatial and temporal patterns in the hydrogeochemistry of a poor fen in northern Wisconsin. *Biogeochemistry*, **11**: 63–76.
- McDowell, W.H., and Wood, T. 1984. Podzolization: soil processes control dissolved organic carbon concentrations in stream water. *Soil Sci.* **137**: 23–32.
- McKnight, D., Thurman, E.M., and Wershaw, R.L. 1985. Biogeochemistry of aquatic humic substances in Thoreau's Bog, Concord, Massachusetts. *Ecology*, **66**: 1339–1352.
- Moore, T.R. 1997. Dissolved organic carbon: sources, sinks and fluxes and role in the soil carbon cycle. *In* Soil processes and the carbon cycle. *Edited by* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart. CRC Press, Boca Raton, Fla. pp. 281–292.
- Moore, T.R., and Dalva, M. 2001. Some controls on the production of DOC by plant tissues and soils. *Soil Sci.* **166**: 38–47.
- Moore, T.R., De Souza, W., and Koprivnjak, J.-F. 1992. Controls on the sorption of dissolved organic carbon by soils. *Soil Sci.* **154**: 120–129.
- Qualls, R.G., and Haines, B.L. 1991. Geochemistry of dissolved organic nutrients in water percolating through a forest ecosystem. *Soil Sci. Soc. Am. J.* **55**: 1112–1123.
- Richmond, M.A., and Bourbonniere, R.A. 1987. Manual for the fractionation of dissolved organic matter in natural waters. National Water Research Institute Rep. No. 87-145, Burlington, Ont.
- Rosenberg, D.M., Berkes, F., Bodaly, R.A., Hecky, R.E., Kelly, C.A., and Rudd, J.W.M. 1997. Large-scale impacts of hydroelectric development. *Environ. Rev.* **5**: 27–54.
- Schiff, S.L., Aravena, R., Trumbore, S.E., Hinton, M.J., Elgood, R., and Dillon, P.J. 1997. Export of DOC from forested catchments on the Precambrian Shield of central Ontario: clues from ^{13}C and ^{14}C . *Biogeochemistry*, **36**: 43–65.
- Schindler, D.W., Bayley, S.E., Curtis, P.J., Parker, B.R., Stainton, M.P., and Kelly, C.A. 1992. Natural and man-caused factors affecting the abundance and cycling of dissolved organic substances in Precambrian Shield lakes. *Hydrobiologia*, **229**: 1–21.
- Schindler, D.W., Curtis, P.J., Parker, B.R., and Stainton, M.P. 1996. Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes. *Nature (Lond.)*, **379**: 705–708.
- Scott, K.J., Kelly, C.A., and Rudd, J.W.M. 1999. The importance of floating peat to methane fluxes from flooded peatlands. *Biogeochemistry*, **47**: 187–202.
- St. Louis, V.L., Kelly, C.A., Duchemin, E., Rudd, J.W.M., and Rosenberg, D.M. 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. *BioScience*, **50**: 766–775.
- Thurman, E.M. 1985. Organic geochemistry of natural waters. M. Nijhoff/W. Junk Publishers, Boston, Mass.
- Urban, N.R., Bayley, S.E., and Eisenreich, S.J. 1989. Export of dissolved organic carbon and acidity from peatlands. *Water Resour. Res.* **25**: 1619–1628.
- Yano, Y., McDowell, W.H., and Aber, J.D. 2000. Biodegradable dissolved organic carbon in forest soil solution and effects of chronic nitrogen deposition. *Soil Biol. Biochem.* **32**: 1743–1751.