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Hydrologic characteristics of lake- and stream-side riparian wetted margins in the McMurdo Dry Valleys, Antarctica

Melissa L. Northcott,[1] Michael N. Gooseff,[2]* John E. Barrett,[3] Lydia H. Zeglin,[4] Cristina D. Takacs-Vesbach[4] and John Humphrey[5]

[1] *Department of Geology & Geological Engineering, Colorado School of Mines, Golden, CO 80401 USA*
[2] *Department of Civil & Environmental Engineering, Pennsylvania State University, University Park, PA 16802 USA*
[3] *Department of Biological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061*
[4] *Department of Biology, University of New Mexico, Albuquerque, NM 87131 USA*
[5] *Department of Geology & Geological Engineering, Colorado School of Mines, Golden, CO 80401 USA*

Abstract:

Water is a limiting factor for life in the McMurdo Dry Valleys (MDV), Antarctica. The active layer (seasonally thawed soil overlying permafrost) accommodates dynamic hydrological and biological processes for 10–16 weeks per year. Wetted margins (visually wetted areas with high moisture content) adjacent to lakes and streams are potential locations of great importance in the MDV because of the regular presence of liquid water, compared with the rest of the landscape where liquid water is rare. At 11 plots (four adjacent to lakes, seven adjacent to streams), soil particle size distribution, soil electrical conductivity, soil water content and isotopic signature, width of the wetted margin, and active layer thaw depth were characterised to determine how these gradients influence physicochemical properties that determine microbial habitat and biogeochemical cycling. Sediments were generally coarse-grained in wetted margins adjacent to both lakes and streams. Wetted margins ranged from 1·04 to 11·01 m in average length and were found to be longer at lakeside sites than streamside. Average thaw depths ranged from 0·12 to 0·85 m, and were found to be deepest under lake margins. Lake margins also had much higher soil electrical conductivity, steeper topographic gradients, but more gradual soil moisture gradients than stream margins. Patterns of soil water $\delta^{18}O$ and δD distribution indicate capillary action and evaporation from wetted margins; margin pore waters generally demonstrated isotopic enrichment with distance from the shore, indicating evaporation of soil water. Lake margin pore waters were significantly more negative in D_{XS} ($D_{XS} = \delta D - 8\delta^{18}O$) than streamside pore waters, indicating a longer history of evaporation there. Differences between lake and stream margins can be explained by the more consistent availability of water to lake margins than stream margins. Differences in margin characteristics between lakes and streams have important consequences for the microbial habitat of these margins and their functional role in biogeochemical cycling at these terrestrial–aquatic interfaces. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS riparian zone; McMurdo Dry Valleys; soil moisture; water isotopes

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INTRODUCTION

The interfaces between terrestrial and aquatic ecosystems are often found to be biological ‘hot spots’, locations of enhanced biodiversity and linked biogeochemical cycling (Naiman and Decamp, 1997), even in dry environments (Holmes *et al*., 1994). These transition zones typically have enhanced soil moisture because of shallow water tables, and often accommodate mixtures of surface water and groundwater which may be geochemically distinct from each other. For example, several studies have reported enhanced denitrification in riparian zones (Groffman *et al*., 1996; Hill, 1996; Burt *et al*., 1999).

In the polar desert of the McMurdo Dry Valleys (MDV) of Antarctica, no vascular plants are present and little precipitation falls (<10 cm year^{-1}, all as snow). Soil moisture is therefore generally low across the landscape, except near streams and lakes, where capillary action wicks water up the shoreline sediments from the water body (Gooseff *et al*., 2007). These wetted margins are visually obvious across the landscape, representing gradients of soil moisture from saturated, adjacent to the water body, to very dry conditions several metres away from the shoreline (Figure 1). Gooseff *et al*. (2007) recently documented the variability in the wetted margin dimensions around Lake Fryxell and the east lobe of Lake Bonney, in Taylor Valley, noting that the length of the wetted margin (i.e. the apparent extent from shoreline to wet-dry edge, as identified in Figures 1C and 1D) during the height of the austral summer is dependent upon near-shore slope and depth of thaw. These terrestrial-aquatic interfaces are locations of enhanced biodiversity (Treonis *et al*., 1999; Barrett *et al*., 2006; Ayres *et al*., 2007) and activity (Zeglin *et al*., 2009), compared to the rest of the MDV landscape which receives very little, if any, liquid water.

In this study we characterize the physicochemical and hydrological properties of wetted margins adjacent to streams and lakes across the MDV at 11 margin plots. We characterized wetted margin dimensions (thaw depth and longitudinal extent from the shoreline), and, in the

* Correspondence to: Michael N. Gooseff, Department of Civil & Environmental Engineering, Pennsylvania State University, University Park, PA 16802 USA. E-mail: mgooseff@engr.psu.edu

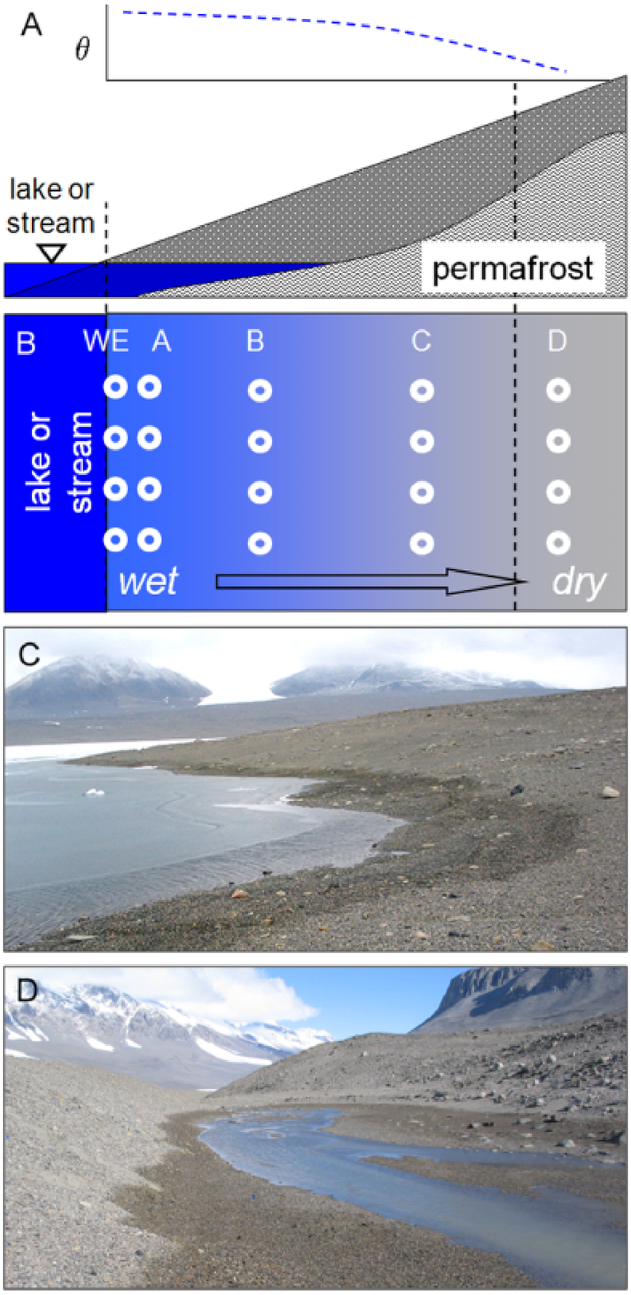

Figure 1. Wetted margins adjacent to streams and lakes in the McMurdo Dry Valleys, Antarctica: (A) longitudinal cross-section with hypothetical pattern of soil water content (θ, unfrozen water) noted (note that all soil shown to lie above the permafrost is soil that is seasonally thawed; soils in contact with the water body are likely to be at or near saturation and decrease in water content away from the shoreline); (B) study plot layout (plan view); (C) margin adjacent to Lake Fryxell; (D) margin adjacent to Priscu Stream, looking downstream

top 10 cm of sediments, soil particle size distribution, soil moisture, soil specific conductivity, and the stable isotopic composition of pore waters and adjacent surface waters. These Antarctic wetted margin plots represent somewhat simplified systems in a global context as they are generally free of vegetation, disturbance from animals, and hydrologic factors such as infiltration and groundwater mixing. We expect patterns of soil moisture, pore water salt content, and pore water isotopic signatures across these margins, and the dimensions of margins to differ between stream and lake locations because streams are intermittent and stage is highly variable, whereas lake levels are, by comparison, relatively consistent on seasonal time scales.

SITE DESCRIPTION

The MDV (76·5°–78·5 °S, 160–164 °E) are a hyper-arid polar desert, receiving less than 10 cm of precipitation annually (Keys, 1980; Conovitz *et al*., 2006), and characterized by low temperatures (annual mean −20 °C) (Clow *et al*., 1988). Coincident low humidity, and high winds lead to high potential rates of evaporation and sublimation despite the cold temperatures (Chinn, 1993). The MDV represent 15% of the ice-free areas of Antarctica. The MDV are characterized by arid soils, perennially ice-covered lakes, glaciers, and ephemeral streams that flow for 10–12 weeks during the austral summer. The elevation of the valley floors range from sea level to 800 m, and the mountains surrounding the valleys reach nearly 2000 m above sea level. The tills and gravelly valley sediments are a result of glaciation and subsequent lacustrine processes attributable to glacial Lake Washburn and Lake Wright, which formerly covered larger portions of the valleys (Doran *et al*., 1994; Hall *et al*., 2001), although there remains debate about the age and extent of ancient lakes in these valleys. In Taylor and Pearse Valleys, Lakes Joyce, Bonney, Hoare, and Fryxell are remnants of Lake Washburn, which existed from 40–6 kya (thousands of years ago) (Lyons *et al*., 2000), whereas Lake Vanda, in Wright Valley, is probably a remnant of Glacial Lake Wright (Hall *et al*., 2001; Bockheim *et al*., 2008a). The MDV are underlain by continuous permafrost (Stuiver *et al*., 1981; Bockheim, 2002), although the surface soils and sediments that regularly thaw make up a variable active layer (surface soils that thaw ∼ annually, generally less than 1 m deep in the MDV) across the landscape (Bockheim *et al*., 2008b). Adjacent to streams and lakes, we expect that the depth of thaw decreases with distance away from the shoreline because there is likely to be less heat advected (via water) to distal soils, similar to the findings of Gooseff *et al*. (2007).

The valleys included in the study consist of the Taylor Valley, Pearse Valley (which is connected to the west side of Taylor Valley, but separated by the Taylor Glacier), and the Wright Valley to the north (Figure 2). Sampling plots were established at 11 sites: four sites are adjacent to lakes and seven border streams. We chose these particular sites to attempt to gain representative information from a variety of lakes and streams across the broad area that is covered by Wright and Taylor Valleys. Located within Wright Valley are two plots adjacent to the Onyx River, the largest stream system in Antarctica, which flows from Lake Brownworth inland to Lake Vanda, Upper Onyx (UO) and Lower Onyx (LO) (Figure 2). In Pearse Valley, we established a study plot on the north shore of Lake Joyce (LJ). In upper Taylor Valley, we established study plots on the south shore of Lake Bonney (LB), and adjacent to Priscu Stream (PS), which flows into

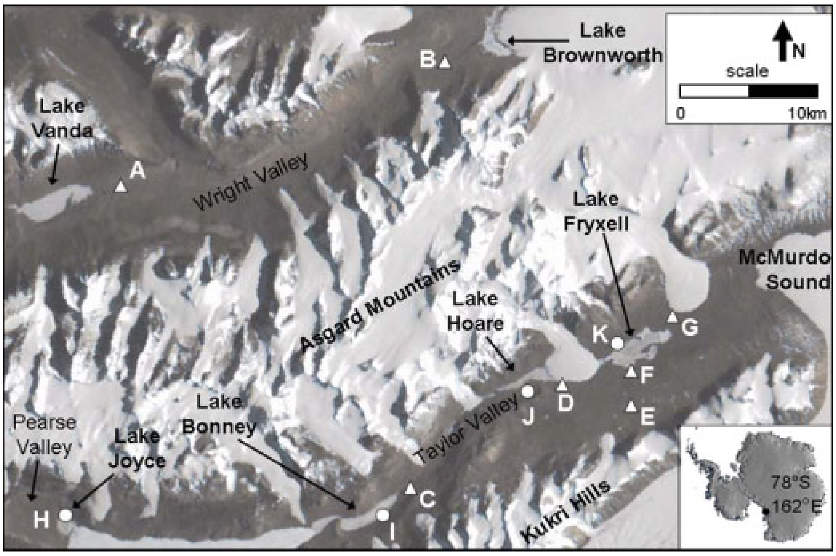

Figure 2. Map of study sites in Wright (north) and Taylor (south) Valleys, Antarctica, where stream margin plots are indicated by triangles: A, Lower Onyx River [LO]; B, Upper Onyx River [UO]; C, Priscu Stream [PS]; D, Green Creek [GC]; E, Upper Delta Stream [UD]; F, Lower Delta Stream [LD]; G, Lost Seal Stream [LS]; and lake margin plots are indicated by circles; H, Lake Joyce (north shore) [LJ]; I, Lake Bonney (south shore) [LB]; J, Lake Hoare (south shore) [LH]; and K, Lake Fryxell (north shore) [LF]. Map scale is approximate. Image from Landsat, available at http://lima.usgs.gov

the eastern end of Lake Bonney. Also in Taylor Valley, we established several plots in the Lake Fryxell basin: Lost Seal Stream (LS), Lower and Upper Delta Stream (LD, UD), and Green Creek (GC) stream-side sites, as well as the Lake Fryxell (LF) site (Figure 2). We also established a study plot on the south side of Lake Hoare (LH), between Lake Bonney and Lake Fryxell.

METHODS

Study-plots were established at the 11 margin sites along sampling transects defined by the length of the visually conspicuous wetted front extending from the shoreline to dry soils. Four parallel transects were established at each plot from water body to dry soil, spaced a few metres apart from each other. Five sampling locations were established within each transect: the location WE was always at the water edge, location A was 20 cm up-shore, location B was approximately equidistant from positions A and C (i.e. in the middle of the margin), and the C and D locations were arranged so that the wetted edge bisected them (D was always in the dry zone) with each being less than 1 m from the wetted edge (Figure 1B). The sampling plots were established in the 2004/2005 austral summer field season during which each site was visited at least once and sampled in January 2005. Each sampling location was surveyed with either a roving Trimble 5700 GPS Real Time Kinematic unit (Fryxell and Bonney basins only, Sunnyvale, California, USA), or an autolevel and surveying rod. The following season, the same sites were revisited and sampled in two campaigns, one in December 2005 and one in January 2006.

At each sampling location within each plot (20 sampling locations per plot), soils were collected from 0–10 cm depth for chemical and physical analyses. Depth of thaw was estimated by manually probing each sample location with a metal T-bar, which has been shown to be a reasonable estimation of depth to frozen ground (Gooseff *et al*., 2007), although the use of a manual probe can be misleading if a stone or other impediment is reached. Further, the use of a mechanical probe may provide only instantaneous information about thaw depth. Gravimetric soil moisture was also estimated from the collected samples that were oven-dried at 105 °C for 24 h at the Crary Laboratory at McMurdo Station, Antarctica. Soil salinity was estimated by measuring the electrical conductivity of a 1 : 5 solution of the fine earth fraction (<2 mm) in DI water using a Corning 311 conductivity meter (Corning, New York, USA) calibrated using a 0·01 mol L^{-1} KCl solution. Subsamples of bulk soils were sieved to determine particle size distribution by mechanical shaker (2005/2006) at the Crary Laboratory at McMurdo Station. The US standard sieve sizes 4·75 mm, 2 mm, 417 µm, and 75 µm were used. Soils were characterized using the Unified Soil Classification (USC) (ASTM D2487-93, 1993) and the United States Department of Agriculture (USDA) textural classification.

The distribution of soil water isotopic signatures of D and ^{18}O were determined as an indication of evaporation of water across wetted margins. Soil samples were taken from each sample location at each plot for isotopic analysis of pore water. The bulk samples were collected from the top 10 cm of soil, stored in manually evacuated whirl packs, frozen immediately, and kept frozen while being shipped to the Colorado School of Mines (CSM). Samples were then thawed, and pore water was extracted by filtering and centrifuging. Soils were thawed in their whirl packs prior to centrifugation and were processed quickly (within minutes) to reduce the possibility of fractionation. For the high soil moisture samples, copious water was available for sampling. For the low soil moisture samples, it is possible that the samples were slightly fractionated during processing because of such low water volumes. Additionally, we used syringes and capsule filters to keep particles out of water samples that were run for stable isotopes, again to reduce potential evaporative fractionation. We take the collected volume to be representative of bulk water within the soil. To compare pore water isotopic signatures with the source waters, water samples were taken near each sampling plot from the adjacent lake or stream by syringe and placed in 2 mL glass vials with sealed caps. Water samples were shipped back to CSM refrigerated (unfrozen). Samples were then analysed in the CSM Stable Isotope Laboratory using an IsoPrime mass spectrometer (GV Instruments Ltd, Lisle, Illinois, USA) for deuterium (D) and oxygen-18 (^{18}O) isotopes. Deuterium was analysed by chromium reduction in continuous-flow mode. Oxygen was analysed by CO_2 equilibration using standard dual-inlet techniques. External precision, measured by repeated analysis of laboratory working standards and replication of sample subsets was better than 0·4‰ and 0·05‰ for δD and $\delta^{18}O$, respectively. Data are reported as a per mil difference from the VSMOW international reference. We expected to see enrichment of δD and $\delta^{18}O$ in samples further from the shoreline, compared with water at or near the shoreline. For brevity, we show only the ^{18}O data. We also calculated deuterium excess ($D_{XS} = \delta D - 8\delta^{18}O$) to characterize the potential evaporative enrichment of the sampled water (Gooseff *et al.*, 2003). Several of the stable isotope samples from source waters were lost during transport when they were inadvertently frozen and the glass vials burst. Thus, stream water isotopic characterizations from Lower Delta Stream, Lower Onyx River, and Lost Seal Stream reported here are from water samples collected in 2004/2005 instead of 2005/2006.

Statistical analyses

We used analysis of variance (ANOVA) to partition variance in the spatial dimensions of wetted margins and physicochemical properties of soil/sediments in and adjacent to these margins among seasonal (December versus January sample collection) and landscape (transect position and lake versus stream) controls. The influences of landscape and seasonality on the width of wetted margin and stable isotope compositions (D and ^{18}O) were tested using a two-way ANOVA. The influences of landscape type, proximity to water (position along transect) and seasonality on moisture content, electrical conductivity and depth of thaw were evaluated using three-way ANOVA. Data were $\log(X + 1)$ transformed to satisfy assumptions of normality when necessary. Partial r^2 values were calculated for each significant main effect and interactions to partition variance. A P-value $<0·05$ was considered the threshold of statistical significance. All analyses were executed in JMP software, version 7 (Cary, North Carolina, USA).

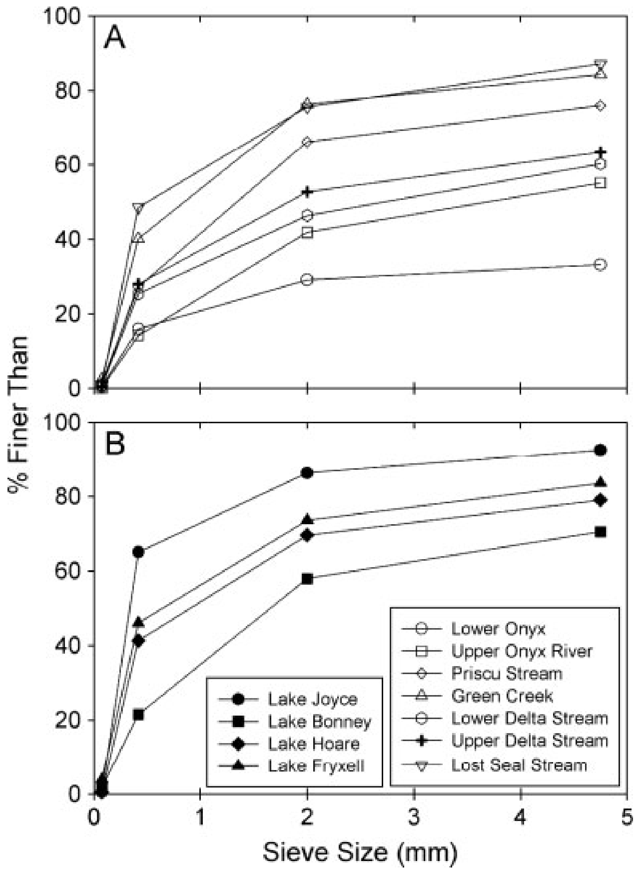

Figure 3. Particle size distributions for (A) stream-side plots; and (B) lake-side study plots. Note that each curve is an average of all 20 samples obtained at each plot. See Figure 2 for location of study plots and site identification nomenclature

RESULTS AND DISCUSSION

Soil texture

The sediments across the Dry Valleys are generally coarse in texture, although there is considerable variation among sites associated with lacustrine history. Particle size distribution curves for streamside plots are shown in Figure 3A and for lakeside plots, in Figure 3B. The particle size distributions were used to classify the soil types using the Unified Soil Classification (USC) scheme. Soils from LH, PS, LO, UO, UD, LS, and GC were categorized as well-graded sand or gravelly sand with little or no fines (SW), whereas those from LF and LD were categorized as poorly graded sands or gravelly sands with little or no fines (SW-SP). The LF site has the highest proportion of clay-sized particles, an average 4%, compared with any of the other 11 sites. Soils from LJ, which has the most poorly graded sediment and the least gravel-sized sediment, are classified as SP. Because the soil textures are fairly similar, we also characterized them under the USDA textural classification. The LF, LH, LS, and GC sites are characterized as sandy loams, whereas PS, LB, UD and LD sites are classified as loamy sands. Loamy sands have a greater amount of sand and less silt than sandy loams. Lake Joyce soil is classified as silty loam. The sediments of LO and UO stream-side sites in the Wright Valley are the most coarse-grained with the

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fewest fines, compared with other MDV plots, and are classified as intermediate between loamy sand and sand.

The particle size distributions at sampling locations WE-D (i.e. from the water's edge to the dry soil) within each plot were evaluated to determine if there was substantial variation in sediment sizes and sorting along the length of the wetted margins, as established by inundation cycles by the lakes and streams (data not shown). When comparing the average percentage of fines at locations nearest the stream or lake (sites WE to B), with those from locations far from the stream or lake (sites C and D) the expected trend was a general increase in fine textured sediments up-shore, away from the stream or lake. A paired t-test indicated that the two samples are indistinguishable (Pearson coefficient $= 0{\cdot}90$, $P = 0{\cdot}41$, two-tailed t-test). The UO site was not included in this analysis because there was insufficient data.

Wetted margin extent

The spatial extents of the wetted zones varied considerably among stream and lake margin plots throughout the Dry Valleys (Table I summary, Figures 4–6). The controls on the variation in this dimension have been investigated in detail around two lakes, LB and LF (Gooseff *et al.*, 2007). Here we compare lengths of stream and lake margins across the Dry Valleys. ANOVA indicates that the lake wetted margin distances are longer (average of 9·73 m in December 2005, and 5·23 m in January 2006) than stream wetted margin distances (average of 3·79 m in December 2005 and 4·26 in January 2006) ($P = 0{\cdot}0004$, $F = 13{\cdot}69$). The most extensive wetted margin was observed at LF, with an average wetted margin length over 11 m; LO stream site has the smallest wetted margin length at just over 1 m (Table I). Separating lake and stream samples, and then determining the variance explained by sampling time during the season shows that lakes have greater wetted margin widths early in the season ($P = 0{\cdot}01$, $F = 7{\cdot}63$), while streams are more likely to have greater wetted margin widths late in the season ($P = 0{\cdot}143$, $F = 2{\cdot}21$). Because stream flow is low and sometimes non-existent early in the season when temperatures are cool, it is reasonable that wetted margins would be small around streams. The lakes, however, are large enough that water is potentially available to the sediments underneath the ice cover in the early fall season and potentially early in the summer season, prior to the initiation of stream flow. Lake levels also may rise faster than the wetted margin is able to respond by increasing in width.

Depth of thaw

Depth of thaw varied according to position within a transect (proximity to water source), landscape type (stream versus lake plot), and time of season (i.e. temperature) across the MDV. In January 2006, when it was expected that maximum thaw for the season had occurred, LB had the deepest mean thaw depth of 85 cm, and UO, PS, and LS all had the smallest average thaw depths of 34 cm (Table I), and all three are stream margin sites. Lake Bonney sediments also had the highest concentration of salt, compared with any other MDV study site. This could be a factor in the large depth to permafrost, as salt lowers the freezing point of water. A more significant factor may be the very steep banks of

Table I. Summary of sampling campaigns from 2005/2006 field season

Site	Sampling dates	Shore slope (m/m)	Wetted margin length (m)	Mean thaw depth (m)	Moisture gradient (% m^{-1})
Stream margins					
Lower Onyx R. (LO)	13 Dec. 2005	0·24	1·04	0·26	−7·30
	10 Jan. 2006		1·38	0·43	−13·77
Upper Onyx R. (UO)	13 Dec. 2005	0·07	3·07	0·20	−2·12
	10 Jan. 2006		3·79	0·34	−4·52
Priscu Stream (PS)	11 Dec. 2005	0·07	4·97	0·18	−1·94
	05 Jan. 2006		6·41	0·34	−2·30
Green Creek (GC)	07 Dec. 2005	0·14	2·03	0·22	−5·30
	06 Jan. 2006		3·07	0·43	−7·09
Lower Delta Stream (LD)	08 Dec. 2005	0·05	6·30	0·31	−1·37
	13 Jan. 2006		7·00	0·54	−2·17
Upper Delta Stream (UD)	08 Dec. 2005	0·11	3·76	0·16	−2·22
	13 Jan. 2006		4·61	0·56	−3·96
Lost Seal Stream (LS)	12 Dec. 2005	0·09	5·39	0·12	−2·20
	12 Jan. 2006		3·59	0·34	−2·10
Lake margins					
Lake Joyce (LJ)	15 Dec. 2005	0·13	3·13	0·30	−5·11
	04 Jan. 2006		2·73	0·44	−6·33
Lake Bonney (LB)	10 Dec. 2005	0·30	6·06	0·56	−1·66
	03 Jan. 2006		4·66	0·85	−3·19
Lake Hoare (LH)	09 Dec. 2005	0·19	—	0·15	—
	11 Jan. 2006		2·59	0·45	−5·18
Lake Fryxell (LF)	07 Dec.2005	0·07	11·01	0·16	−0·88
	12 Jan. 2006		11·01	0·40	−1·25

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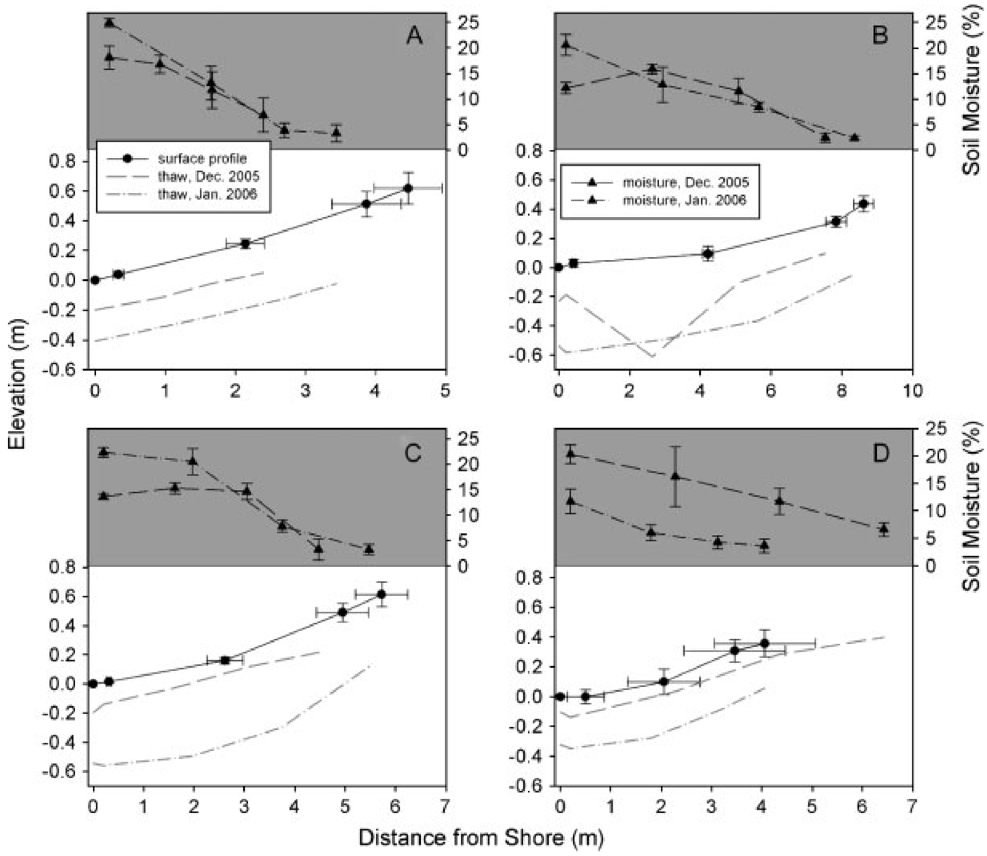

Figure 4. Profile topography, thaw depth, and soil moisture, plotted as averages and standard deviations of replicate measures along each of four transects at each sampling plot at (A) Lower Onyx River, (B) Upper Onyx River, (C) Priscu Stream, and (D) Green Creek

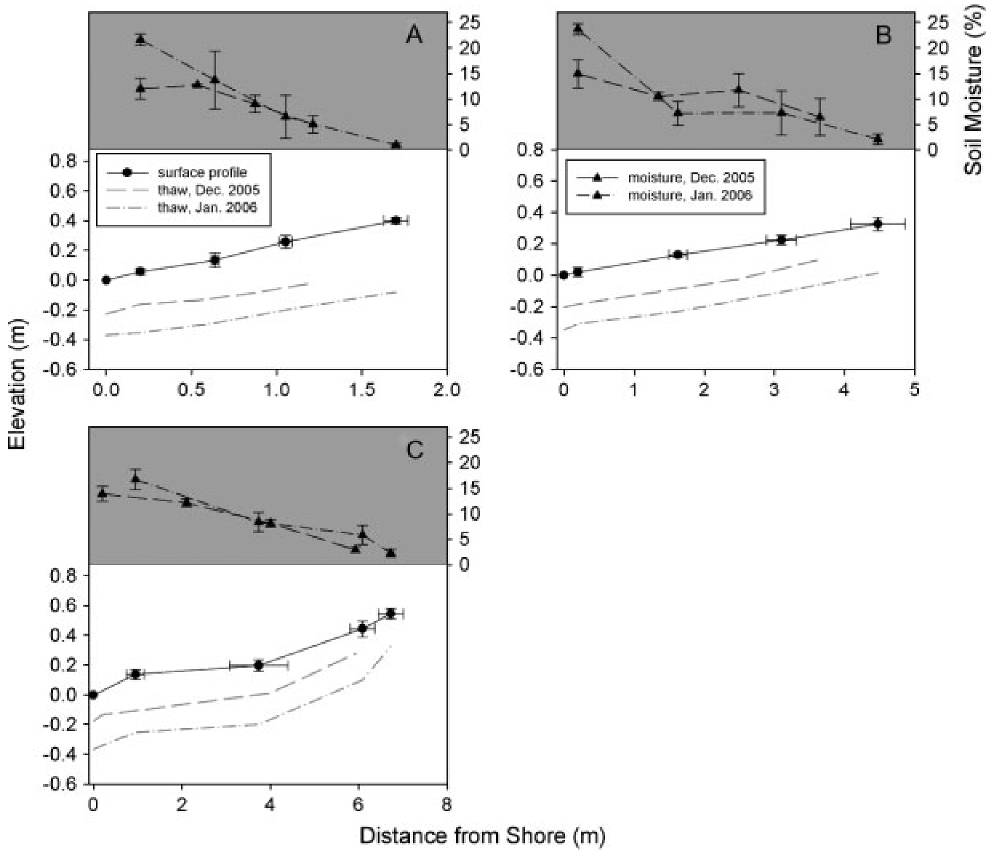

Figure 5. Profile topography, thaw depth, and soil moisture, plotted as averages and standard deviations of replicate measures along each of four transects at each sampling plot at (A) Lower Delta Stream, (B) Upper Delta Stream, and (C) Lost Seal Stream

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Lake Bonney shores. The water table does not follow the steep gradient of the banks, resulting in a further distance to the frozen water below.

Seasonal effects on thaw depth progression (δ+0·23 m) were the most significant (F = 259·73, $P < 0·0001$) source of variation in the model (Table II), followed by differences between lake and stream location (F = 66·85, $P < 0·0001$); lakeside environments had greater depths of thaw on average relative to stream (0·43 and 0·31 m, respectively). At every site, the early sampling season had a shallower depth to permafrost (compare an overall mean of 22 cm early in the season with 51 cm late in the season, Figures 4–6). This reflects the influence of cooler temperatures early in the season as well as the time required for the upper layer of soil to thaw. When temperatures rise, stream and lake water move through

Table II. F statistics and partial r^2 values from three-way analysis of variance of transect position (variable distance from open water), landscape (stream versus lake) and seasonal (December 2005 versus January 2006) effects on soil/sediment physicochemical properties in hydrological margins of the McMurdo Dry Valleys

Source of variation	Depth of thaw		Moisture content†		Electrical conductivity†	
	F	r^2	F	r^2	F	r^2
Transect position	8·43***	0·04	22·03***	0·61	13·52***	0·07
Landscape type	66·85***	0·08	17·83***	0·02	163·97***	0·30
Seasonality	259·73***	0·31	2·97	0·00	1·15	0·01
Transect position × landscape	4·86**	0·03	4·55*	0·02	3·56*	0·01
Transect position × seasonality	4·87**	0·03	3·75*	0·01	0·68	0·00
Landscape × seasonality	0·13	0·00	13·37**	0·02	0·029	0·00
Transect position × landscape × seasonality	3·01	0·01	4·92*	0·02	1·05	0·00

* $P < 0·01$
** $P < 0·001$
*** $P < 0·0001$
† $\log(X + 1)$ transformed

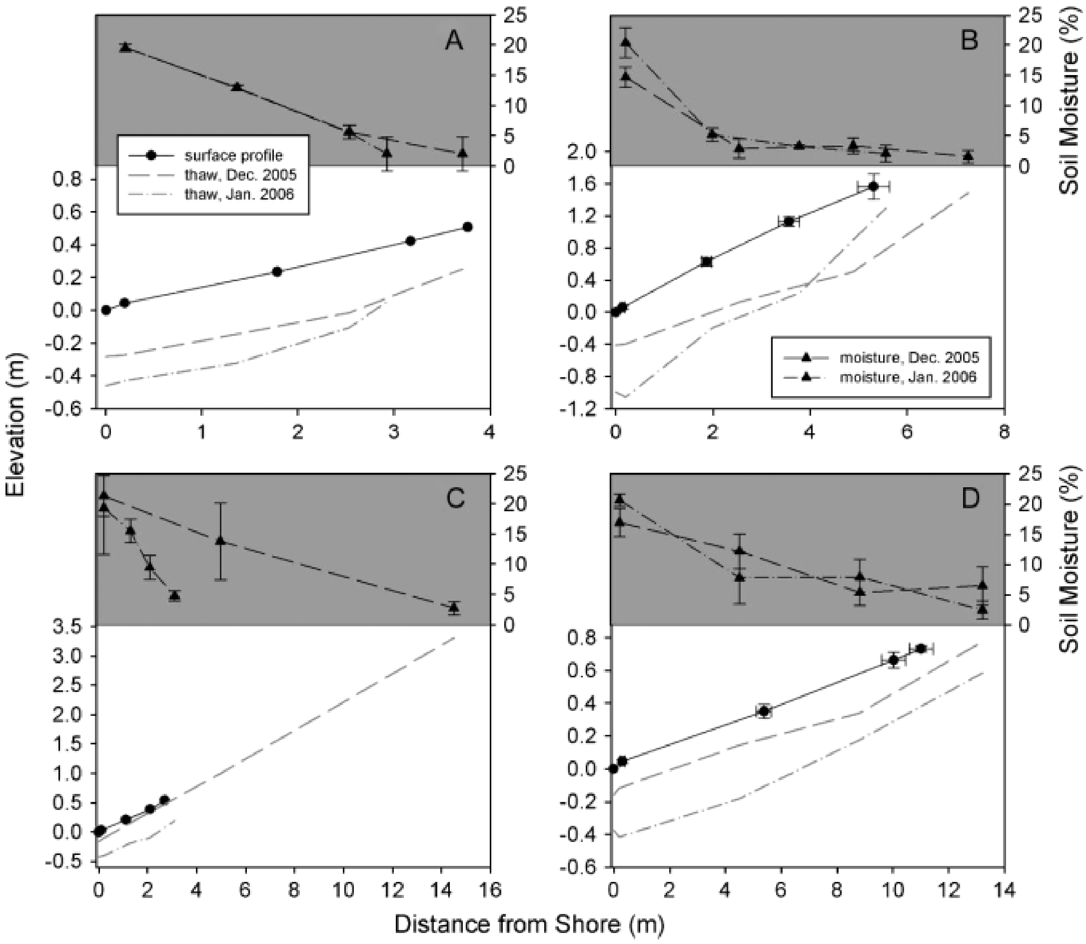

Figure 6. Profile topography, thaw depth, and soil moisture, plotted as averages and standard deviations of replicate measures along each of four transects at each sampling plot at (A) Lake Joyce, (B) Lake Bonney, (C) Lake Hoare, and (D) Lake Fryxell

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Table III. F-statistics from two-way analysis of variance of landscape (stream versus lake) and seasonal (December 2005 versus January 2006) effects on absolute δ^{18}O, δ D, and D_{XS} (‰VSMOW) of soil pore water, and differences between δ^{18}O, δ D, and D_{XS} (‰VSMOW) of soil pore and sources waters

Source of variation	Absolute			Difference		
	δ^{18}O	δ D	D_{XS}	δ^{18}O	δ D	D_{XS}
	‰VSMOW					
Landscape type	19·84***	46·35***	3·31	12·91**	8·28*	11·41**
Seasonality	5·88	6·05	1·73	0·19	0·99	0·13
Landscape × seasonality	1·36	6·68	3·85	6·42	3·99	5·85

* <0·01
** <0·001
*** <0·0001

the subsurface, advecting heat, and accelerating sediment thaw, thereby extending the depth of thaw (Ikard *et al.*, 2009).

There was no interaction between seasonality and landscape type (lake versus stream) on active layer depth, indicating that the deepening of thaw is a consistent phenomenon across MDV wetted margins (Table II). Transect position (distance to open water) was also a significant term in the model ($F = 8{\cdot}43$, $P < 0{\cdot}0001$), although the effect of this variable was not consistent across transects; depth of thaw was greatest in C sampling positions (0·42 m deep, on average), intermediate in positions WE, A, and B, and closest to the surface at the D position (0·29 m deep). Significant interactions between season and transect position ($F = 4{\cdot}87$, $P = 0{\cdot}0008$), and between landscape type and transect position ($F = 4{\cdot}86$, $P = 0{\cdot}0008$) indicate a modulating effect of transect position on depth of thaw, largely due to variation in stream environment where changes in stream flow may have significant influences on active layer hydrology. Note that while significant, these interactions account for a small proportion of variance in active layer thickness ($r^2 = 0{\cdot}06$).

Soil moisture

Spatial influences (distance from open water, landscape gradients) are the dominant control over surface soil water content in the McMurdo Dry Valleys (Table II). We found that transect position (lateral distance from open water) is a first-order control over soil moisture, explaining 61% of the variance in the observations of soil moisture in near stream and lake environments of the Dry Valleys ($F = 222{\cdot}03$, $P < 0{\cdot}0001$), with the highest levels of soil water found in near-shore environments (sampling location A), and the lowest concentrations of soil water found in the sampling locations most distant from open water (sampling location D). In all plots, the general pattern across the wetted margins was a slight decrease in soil moisture from WE-B, and then a more substantial decline from B to D (Figures 4, 5 and 6). Moisture gradients across the margins generally decrease (become more negative) from December 2005 to January 2006, except at the LS plot (Table I). In the December 2005 data set, moisture gradients ranged from −0·88% soil moisture m^{-1} at LF to −7·30% soil moisture m^{-1} at LO. In January 2006, the moisture gradients ranged from −1·25% soil moisture m^{-1} at LF to −13·77% soil moisture m^{-1} at LO.

These data also show that landscape type (lake versus stream) has a significant ($F = 17{\cdot}83$, $P < 0{\cdot}0001$) effect on soil water content, especially in light of the interacting effect of seasonality and landscape type on the movement of soil water ($F = 13{\cdot}37$, $P < 0{\cdot}0003$), which is coincident with the temporal variation of glacial melt stream in the MDV; i.e. stream channel sediment moisture content is dependent on mid-summer glacial melt. This effect is modulated by other physical parameters, mainly those defined by physical gradients perpendicular to stream channels and lake margins (Gooseff *et al.*, 2007). For example, the hydrological gradients existing in stream channels relative to lake margins as illustrated by the significant transect position × landscape interaction ($F = 4{\cdot}5$, $P = 0{\cdot}0039$), is consistent with literature that has demonstrated distinct spatial influences of lake margins versus riparian areas of streams on soil biology and biogeochemical cycling (Treonis *et al.*, 1999; Barrett *et al.*, 2002; Ayres *et al.*, 2007).

Soil salinity

Soil electrical conductivity (a proxy for salinity) differed greatly between lake and stream margins (Table II). These results show that near-shore lake sediments and soils are typically more saline than stream riparian substrates ($F = 163{\cdot}97$, $P < 0{\cdot}0001$). Proximity to open water modulates this effect in that transect position is a highly significant influence over electrical conductivity of soil extracts ($F = 13{\cdot}52$, $P < 0{\cdot}0001$), with the distal boundary of the wetted margin consistently exhibiting the highest levels of conductivity (Figures 7 and 8). The strength of this gradient differs between streams and lakes ($F = 3{\cdot}6$, $P < 0{\cdot}015$), probably based on their physical hydrology (Gooseff *et al.*, 2007).

The soil conductivity values of soils adjacent to streams generally increased monotonically across the wetted margins (Figure 7), with the highest values observed at the PS plot, with LD and GC also exhibiting relatively high specific conductivity, compared with

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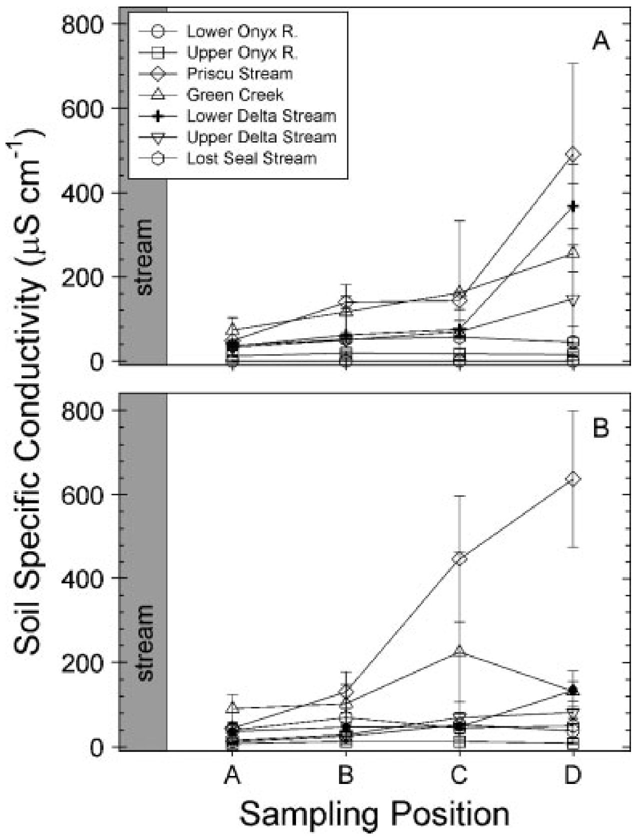

Figure 7. Soil specific conductivity profiles along stream-side sampling plots. Data are presented as averages and standard deviations (bars) of four replicate measurements (from each similar location along four transects), for (A) sampling dates in December 2005, and (B) sampling dates in January 2006

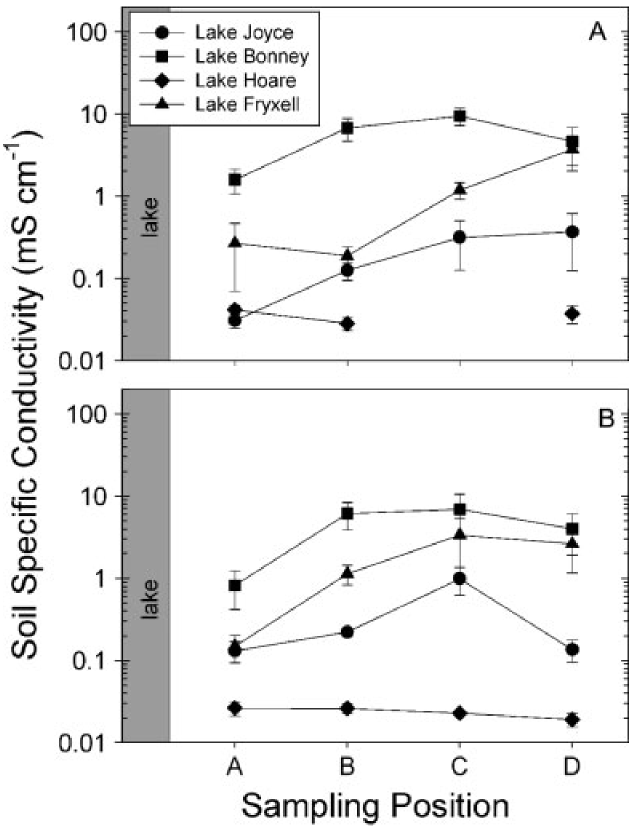

Figure 8. Soil specific conductivity profiles along lake-side sampling plots of hydrologic margins. Data are presented as averages and standard deviations (bars) of four replicate measurements (from each similar location along four transects), from (A) sampling dates in December 2005, and (B) sampling dates in January 2006. Data from the Lake Hoare plot, position D, December 2005 are not available. Note that the y-axis is a log-scale

the rest of the stream margins, which generally had values <100 μS cm^{-1}. Soil conductivity values were several orders of magnitude higher than stream margin values, with highest conductivity levels typically present in intermediate transect positions (Figure 8—note that these units are mS cm^{-1}). The highest lake margin soil specific conductivity values were found at LB, the lowest at LH. Previous work has showed that soil physicochemical variables like salinity vary most over spatial scales associated with till composition and age (Barrett *et al.*, 2004, 2007). These factors were not included in the model, but would probably have improved overall fit. For example, Lake Bonney and Lake Joyce occur on the oldest tills (Bockheim *et al.*, 2008b) and have the greatest soil conductivities.

Stable isotopes of water from streams, lakes, and pore waters

Spatial and temporal patterns in pore water isotopic signatures indicate significant rates of evaporation in lake and stream riparian zones. As water evaporates from soil, the lighter isotopes preferentially evaporate, concentrating the heavier isotopes in the soil. This is demonstrated by enrichment of deuterium D and ^{18}O in pore waters. For efficiency, we show only ^{18}O here, though similar spatial patterns are observed for variation in D. Deuterium excess ($D_{xs} = \delta D - 8\delta^{18}O$) shows the separation between the values of isotopes ^{18}O and D as evaporation takes place and the isotopes fractionate at different rates; D_{XS} decreases as evaporation occurs.

Heavy isotopes, i.e., $\delta^{18}O$ and δD, increased across wetted margins, from sampling location WE to sampling location D (Figures 9A and 10A). D_{xs} was found to decrease across these margins as well (Figures 9B and 10B). Data presented are from samples that were collected in the second sampling period of 2005/2006. These data were selected because they represent the most complete data set; data from other sampling times exhibit similar patterns.

Two ANOVAs were performed using the stable isotope data: (1) based on the absolute values; and (2) based on the differences of the plot data from the water body isotopic signature (i.e. pore water isotopic signature less the source water isotopic signature). The analysis of differences, of course, relies upon the assumption that the isotopic signature of the source water body varies little, and therefore must be assessed with some caution. None of these ANOVAs were highly significant for comparison of sampling position within a plot, though there were consistent differences between lake and stream systems; $\delta^{18}O\delta D$, and D_{XS} isotope values were more depleted in lake sediment pore waters relative to stream pore waters.

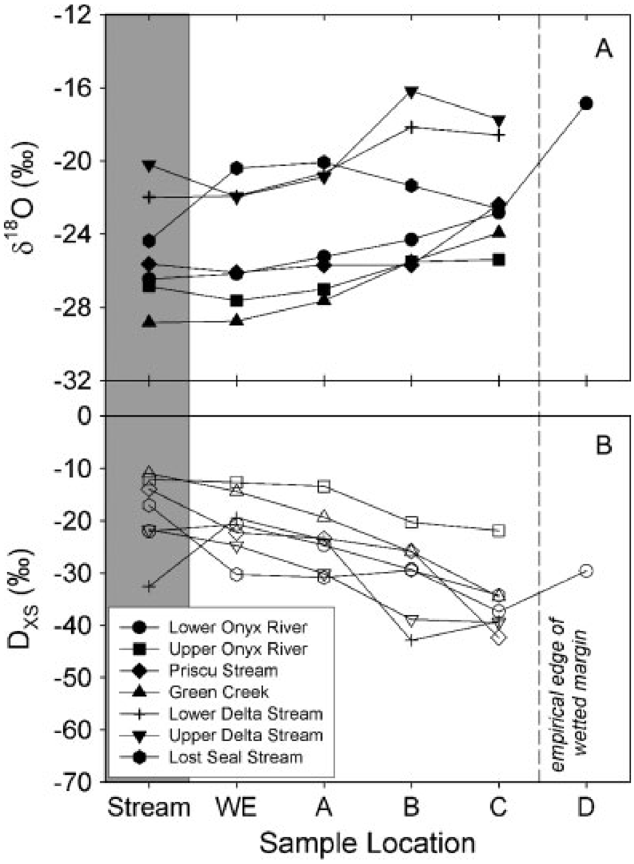

Figure 9. Trends in average (A) $\delta^{18}O$ and (B) D_{XS} of open water and pore water samples across wetted margins of stream-side plots. Average values are from samples at common sample locations along four transects at each sampling plot collected once at all sites except Green Creek, Upper Onyx River and Lower Onyx River, which were sampled twice during the 2005/2006 field season

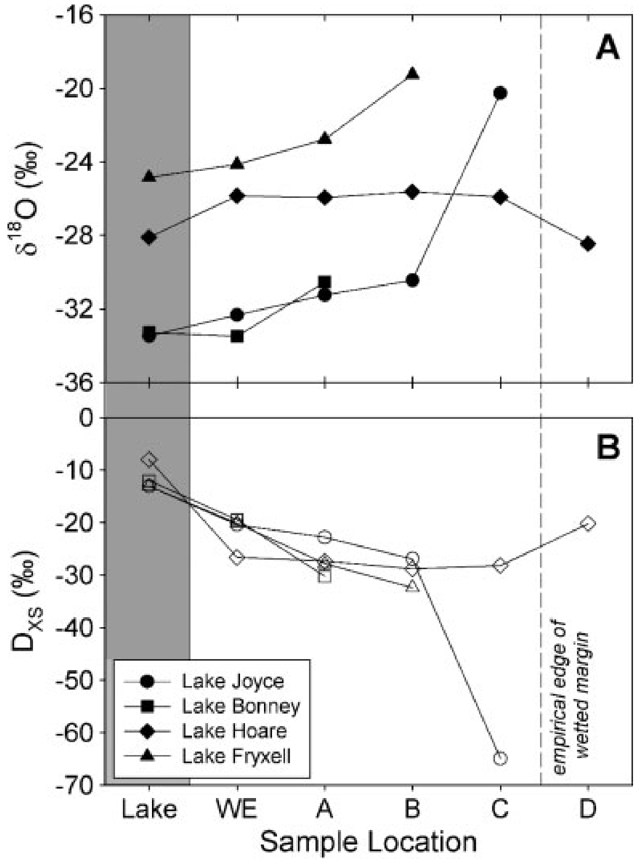

Figure 10. Trends in average (A) $\delta^{18}O$ and (B) D_{XS} of open water and pore water samples across wetted margins of lake-side plots. Average values are from samples at common sample locations among four transects at each sampling plot collected at Lakes Joyce, Bonney, and Fryxell twice in the 2005/2006 field season; pore water was extracted from only one set of samples from the Lake Hoare site (collected January 2006)

Lake margins exhibited greater differences in isotope values from source waters relative to riparian zones. Adding time as a main effect increased the strength of the models, though it did not contribute a statistically significant influence over pore water O and D isotope ratios at the $P < 0{\cdot}01$ level.

Lake-side samples are found to have significantly lighter values of $\delta^{18}O$, δD, and D_{xs} than stream samples (compare means of $-27{\cdot}2$‰, $-243{\cdot}5$‰, and $-28{\cdot}8$‰ to $-23{\cdot}8$‰, $-216{\cdot}8$‰, and $-25{\cdot}6$‰, respectively) indicating greater rates of evaporation in these environments. Lake wetted margins are more likely to demonstrate evaporative fractionation than streams because they are wider; thus, water is retained longer with greater opportunity for evaporation than across stream margins. In addition to the difference between stream and lake margin fractionation gradients, lake and stream water were found to have different isotopic compositions. Lake waters display more negative values of $\delta^{18}O$ and δD than streams, which may indicate that the water originated from a more depleted source (see below).

Lost Seal and LH pore water samples displayed more variable trends than the other nine plots. Lost Seal has the most inconsistent flow paths and stream margins of any MDV study site, as the wetted margins change so frequently that gradients in isotopic composition of pore water may not be consistently maintained. Snow sometimes drifts on the LH site and remains through part of the summer, possibly influencing soil pore water isotopic signatures.

In a study of regional variation in isotopic composition of source waters across the MDVs Gooseff *et al.* (2006) found that the isotopic composition of the water is more depleted inland in Taylor Valley. These spatial patterns correspond with the expected isotopic composition of precipitation, which typically becomes increasingly depleted inland as the heavier water is released first. The relative composition of the pore water at each site is associated with the isotopic composition of the lake and stream water across the Dry Valleys. Lake Fryxell basin water and pore water samples have the most enriched signatures of δD and $\delta^{18}O$; PS and LH follow, and LB and LJ have the most depleted signatures.

D_{XS} values are particularly useful in characterizing potential evaporation because they incorporate changes in both δD and $\delta^{18}O$, relative to each other (and the global meteoric water line). However, D_{XS} values are potentially more variable across margins because they do not depend on δD or $\delta^{18}O$ singularly, incorporating

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variability of both. Because we assessed samples from locations WE-D from each site, spatial patterns of D_{XS} are more indicative of the evaporation that occurs at a particular site, while average $\delta^{18}O$ signatures are more representative of the composition of the water source. Interpreting spatial patterns of D_{XS} as evidence of relative evaporation occurring at a site, we observed the greatest indications of evaporation in the LJ margin (Figure 10) followed by PS (Figure 9). The least changes in D_{XS} observed across wetted margins occurred for UO and LH.

Implications for hydrology and biogeochemical cycling in the McMurdo Dry Valleys

These results indicate that the spatial dimensions and physicochemical environments of wetted margins in near-shore lake and stream environments are quite different. Lake margins are more extensive, both by depth of thaw and distance of wetted front from open water. Moreover, stable isotope signatures in lake margins indicate greater degrees of evaporation and hence more saline conditions relative to stream margins. These differences may be due to the differences in liquid water activity in these two environments. Stream flow in the MDV is temporally variable, both within a given austral summer (Conovitz *et al*., 1998), as well as inter-annually (Doran *et al*., 2008). Even in the middle of the austral summer streamflow may be negligible because of limited glacier melt and generation of liquid water, e.g. snowfall events will often inhibit meltwater generation because of increased albedo on the glaciers until the snow ablates. Thus, saturated conditions in stream margins are dependant upon microclimate boundary conditions during the flow season. In contrast, lakeside sediments are more consistently in contact with liquid water during the austral summer. Liquid water in lake shore environments is present from early in the austral summer (November), prior to full melt of the lake moats, through to the end of the austral summer (February), when ice cover begins to form along the lake moats. As long as there is some evaporative demand for pore water to be removed from margin locations and soil temperatures are above freezing, capillary action will transport water from the lake and to adjacent soils and the atmosphere. Thus, lake-side wetted margins are stable environments with consistent moisture supply during the austral summer relative to stream margins.

During a single season, the spatial dimensions and physicochemical conditions of wetted margins are likely to fluctuate as liquid water becomes available in lakes and streams, capillary-transport of water and evaporation moves solutes, and as thaw depths extend. Stream flow can be non-existent early in the season (November-early December) when temperatures are generally warming, and it is reasonable to speculate that wetted margins are fairly small in stream riparian zones because of the limited amount of available water. Lake margins, however, are large enough that water is available to sediments beneath ice cover even early in the summer season, and continues to be available throughout the thaw season. Lake levels also may rise faster than capillary transport can move water through the wetted margin by increasing in width during particularly warm summers (Barrett *et al*., 2008). This effect may be less important at stream sites because of the dramatic stream flow changes in short time periods.

One important difference between lakes and streams is that lake levels rise and fall over annual and decadal timescales (Chinn, 1993; Doran *et al*., 2008; Barrett *et al*., in press) with rising lakes inundating formerly dry soils. Streams, however, are subject to stage variability based on channel hydraulics and meltwater availability, and are very slow to change geomorphically (McKnight *et al*., 1999). Therefore, stream-side margins are likely to exhibit spatial stability over decades, but be subject to more seasonal variability in boundary conditions, whereas lake-side wetted margins may be temporally dynamic over years to decades (i.e. due to lake level changes) but have more consistent seasonal boundary conditions, e.g. through an austral summer.

Thawed sediments in aquatic-terrestrial transition zones are critical to pore water movement, and thaw generally increases from November to January in response to warming air temperatures and increased solar radiation. As Gooseff *et al*. (2007) demonstrate, thaw depths are in part responsible for the spatial extent of wetted margins adjacent to Taylor Valley lakes. The great thaw depths at the Lake Bonney margin are thus probably due, in part, to its steep banks and salty sediments (Figures 6 and 8). Stream margins may respond to a different set of local edaphic controls. Unlike lake margins, thaw depths and dimensions of wetted zones in stream margins are in part influenced by the downstream movement of water even in the stream channel, which has the effect of advecting stream water and heat into lateral sediment locations, as a result of hyporheic exchange (Cozzetto *et al*., 2006). This notion is supported by the difference in margin extents, the lower soil electrical conductivity in stream margins, and the reduced isotopic enrichment of pore water in stream margins, compared with source waters. The downstream dimension of stream water movement, even in the margins, has the potential to flush pore water back into streams.

Thus, it is reasonable that lake margins would be more likely to have higher and more variable salinity because lake margins are much more stable than stream margins, enabling constant evaporation to take place over soils that are infrequently covered by water. This process can result in evapo-concentration and gradients of salts across the wetted margin. Conversely, stream margins frequently change and the soils are re-wetted and periodically covered with stream water, enabling salts to wash away. Lake Bonney has the most saline of any MDV lakes studied here (Spigel and Priscu, 1998); thus the high conductivity in the margin sediments is not surprising. Lakes Joyce and Hoare follow far behind, with means of 209 $\mu S\ cm^{-1}$ and 36 $\mu S\ cm^{-1}$, respectively. The Onyx River sites have the lowest soil specific conductivity. Variation at each site depends largely on water levels and

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flow at each site as local climate differences are common in the Dry Valleys (Doran *et al*., 2002).

Micrometeorological conditions greatly influence potential evaporation from wetted margin sediments. Lake Joyce and PS are both located toward the western edge of the sites considered in this study, an area known to be fairly windy compared with the other locations studied in this project (Doran *et al*., 2002). This suggests that these locations are subject to climatic conditions that favour evaporation. Corroboration of D_{XS} data from the LB margin is partly evident in Figure 10B, but we were not able to extract water for isotopic analysis from samples beyond sample location A.

The goal of this research was to characterize the hydrologic conditions of these margins to inform relationships and dependencies of patterns of biogeochemistry and microbial ecology in these same margins. These results indicate that both patterns may be strongly influenced by deeper thaw, greater wetness, and more evapoconcentrated solutes in wetted margins around lakes compared with streams. Consequently, we might expect that biogeochemical processes in lake margins will occur in potentially more chemically saturated conditions than in stream margins. Further, we predict that microbial communities present in lake margins are more tolerant of saline conditions than those found in stream margins.

CONCLUSIONS

Observations of obvious wetted margins adjacent to lakes and streams in the McMurdo Dry Valleys indicate several key differences between lake and stream margins. Soil moisture in all margin environments was observed to decrease across the wetted zone from source-water body to dry upland soils. In general, lakes were observed to generate longer wetted margins and deeper thaw depths than streams. Lake margins were observed to have much higher soil salinity than stream margins. Spatial patterns in the isotopic signatures of pore water indicated that significant evaporation occurs as water travels along a wetted margin, from source water toward dry upland soils, resulting in isotopic enrichment up-gradient. D_{XS} values decreased across these zones; this trend was particularly evident in lake margins where availability of liquid water was more stable than in stream locations. We conclude that these characteristics of wetted margins will be important controls over biogeochemical cycling and microbial community patterns in these wetted zones.

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