Shallow groundwater systems in a polar desert, McMurdo Dry Valleys, Antarctica

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Abstract The McMurdo Dry Valleys (MDVs), Antarctica, exist in a hyperarid polar desert, underlain by deep permafrost. With an annual mean air temperature of −18°C, the MDVs receive <10cm snow-water equivalent each year, collecting in leeward patches across the landscape. The landscape is dominated by expansive ice-free areas of exposed soils, mountain glaciers, permanently ice-covered lakes, and stream channels. An active layer of seasonally thawed soil and sediment extends to less than 1m from the surface. Despite the cold and low precipitation, liquid water is generated on glaciers and in snow patches during the austral summer, infiltrating the active layer. Across the MDVs, groundwater is generally confined to shallow depths and often in unsaturated conditions. The current understanding and the biogeochemical/ecological significance of four types of shallow groundwater features in the MDVs are reviewed: local soil-moisture patches that result from snowpatch melt, water tracks, wetted margins of streams and lakes, and hyporheic zones of streams. In general, each of these features enhances the movement of solutes across the landscape and generates soil conditions suitable for microbial and invertebrate communities.

Keywords McMurdo Dry Valleys · Antarctica · Arid regions · Groundwater/surface-water interaction · Active layer hydrology

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Introduction

The McMurdo Dry Valleys (MDV) are in a polar desert on the western edge of the Ross Sea and make up a significant portion of the ice-free part of the Antarctic continent (Fig. 1). The climate is cold and dry with mean annual air temperatures of ~−18 °C (Doran et al. 2002) with precipitation ranging from 3 to 50 mm water equivalent, which falls as snow and much of which sublimates (Eveland et al. 2012; Fountain et al. 2010). Snow that falls is generally collected into topographic depressions creating discrete patches during the austral winter (Gooseff et al. 2003a). The landscape is comprised of open areas of bare soils, mountain and piedmont glaciers, stream channels, and lakes. In the austral summer, incoming surface energy is sufficient to melt ice (glaciers and lake ice-covers) and snow, providing liquid water to soils, stream channels, and lakes. Despite the cold, dry environment, liquid water exists both at the surface and shallow subsurface across the MDV landscape during the austral summer.

The MDVs are underlain by extensive permafrost extending to depths of several hundred meters (McGinnis and Jensen 1971), with active layers (seasonally thawed surface soils) extending from 0 to 75 cm depth (Bockheim et al. 2007). Active layer thicknesses within most of the MDV span 20–45 cm (McGinnis and Jensen 1971), with extreme values found only at the coast (thick active layers) and inland at higher elevations (thin or absent active layers). Potential sublimation rates well in excess of precipitation (Clow et al. 1988; Gooseff et al. 2006) result in desiccation of the upper portion of the permafrost soil column to depths of 50–100 cm across broad sections of the MDV (Bockheim 2002). These dry frozen conditions generate unusual soil/ice distributions in the MDV, in which 43 % of MDV soil surfaces are “dry frozen” (lacking ice in the upper 100 cm), 55 % are ice-cemented (but which commonly are ice-free within the upper 10–20 cm), and the remaining 2 % are composed of massive ice bodies (buried snow, buried glacier ice, etc.; Bockheim et al. 2007). Spatial variability between ice table depth (the depth to ice cemented sediment) and active layer thickness provide a seasonally controlled soil volume in which shallow groundwater (groundwater present between the ice table and the ground surface) processes can occur in the MDV.

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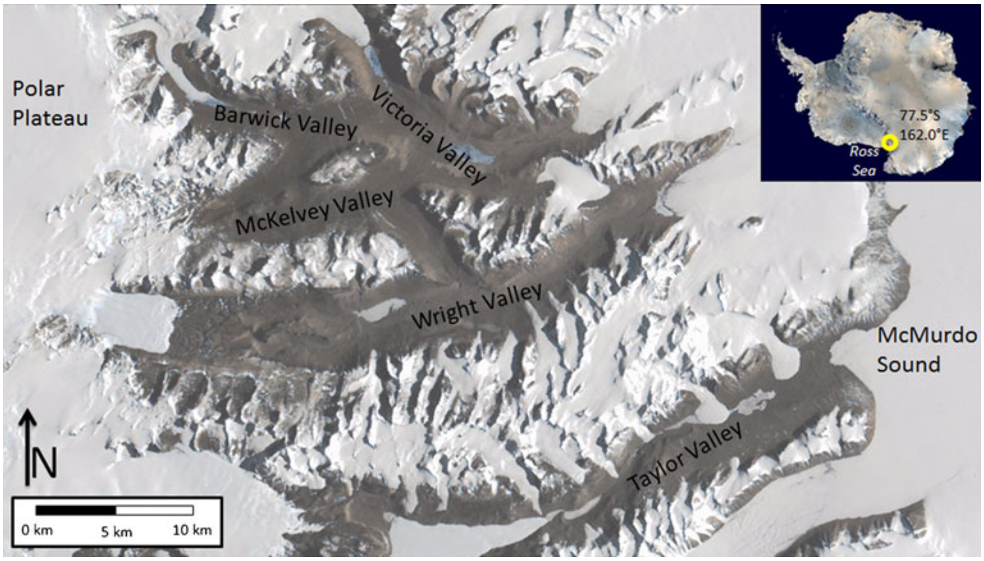

Fig. 1 Location map of the central McMurdo Dry Valleys. In *Taylor Valley*, the major lakes are Lake Bonney, Lake Hoare, and Lake Fryxell (from west to east)

The hydrology of the MDVs is largely driven by glacial melt (Bomblies et al. 2001; Chinn 1993), and therefore hydrological studies have generally focused on surface-water bodies. There has been some study of the hydrogeology of the MDVs, mostly relying upon geochemistry of closed basin lakes to determine the potential for groundwater inflows. Green and Canfield (1984) suggest that the contemporary chemistry in Lake Vanda, Wright Valley, cannot be explained by lone surface input (Onyx River). Nearby in the Wright Valley, Don Juan Pond is underlain by a briny aquifer to a depth of at least 20 m below the surface (Harris and Cartwright 1981), actively exchanging water between surface and subsurface. Shallow groundwater (groundwater present between the base of the ice table and the ground surface) has historically been considered an insignificant component of MDV hydrology, with groundwater fluxes generally considered to be two orders of magnitude smaller than glacial stream discharge (Cartwright and Harris 1981).

This paper describes the current understanding of the influence of several types of shallow groundwater systems of the McMurdo Dry Valleys on hydrology and soil biogeochemistry (Fig. 2): (1) snowmelt contribution to local soils, (2) snowmelt contribution to water tracks that extend a long distance from sources, (3) wetted margins of streams and lakes, and (4) hyporheic zones of streams. Existing data has been reviewed and new biogeochemical results presented that illustrate the role that shallow groundwater processes play in shaping the MDV soil ecosystem. Whereas thaw depths across the majority of the landscape extend to as much as 20–40 cm during the austral summer, all of these systems occur within preferentially deepened active layers, which are on the order of 40–70 cm in depth. Despite the shallow depth, these systems are important vectors of water, heat, and solutes, and have been documented to be locations of enhanced biogeochemical cycling and habitat suitability (Barrett et al. 2009; Takacs-Vesbach et al. 2010).

Snowmelt in relation to moisture in local soils

Spatial variability in snow pack distribution

While snowfall has been dismissed as being of little hydrologic importance because of low accumulation and rapid sublimation rates in the McMurdo Dry Valleys, sufficient water exists in soils unconnected to aquatic habitats (lakes and stream) to support active microbial and invertebrate communities (Barrett et al. 2008; Treonis et al. 2002; Zeglin et al. 2009), heterotrophic soil CO_2 flux (Ball et al. 2009; Parsons et al. 2004) and to facilitate geochemical weathering (Harris et al. 2007). Moreover, widespread distribution of ice-cemented permafrost (Bockheim 2002) may indicate a more active hydrology than previously described, driven primarily by inputs of water through snowfall. For example, despite low levels of precipitation and high ablation rates, snow does accumulate in discontinuous patches in the dry valleys as evidenced by written accounts, aerial photography and satellite images collected since the International Geophysical Year (1957–1958).

Until recently, accounts of snow accumulation were based on point measurements of snowfall and ablation rates with very limited spatial and temporal resolution (Chinn 1993; Fountain et al. 2010). More recently, Eveland et al. (2012) used repeat high-resolution satellite imagery of regions within Taylor Valley and Wright Valley to assess spatial dynamics of snow accumulation and ablation through two austral summer seasons (i.e., whether snow patches accumulate in the same places each winter; whether snow ablation patterns are similar across elevation, aspect, and slope gradients). Several studies (Eveland et al. 2012; Fountain et al. 2010; Gooseff et al. 2003a), support several generalizations about geographic variation in snow patch dynamics. Broad-scale patterns in snow accumulation coincide with climatic gradients (e.g., increasing air temperature with distance up valley) and ablation rates such that more snowfall occurs (and persists

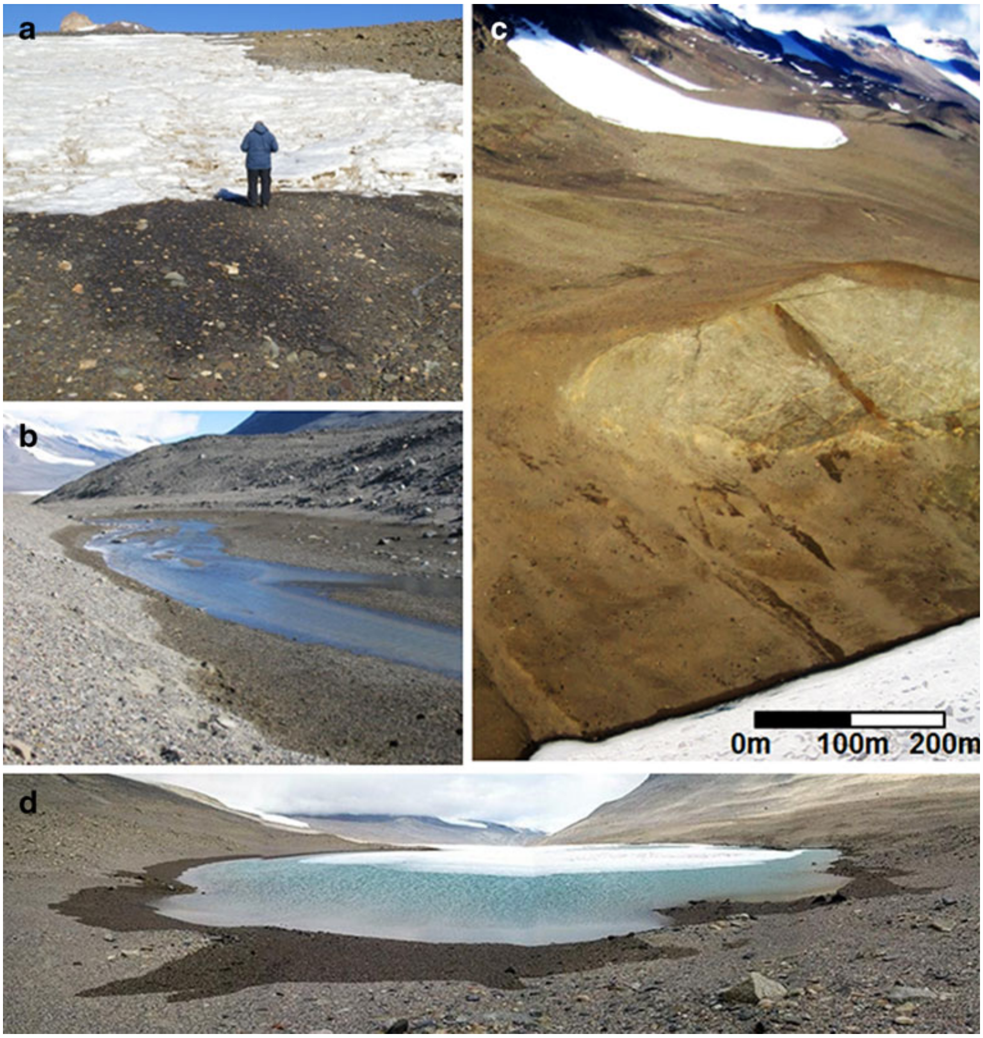

Fig. 2 Common occurrences of shallow groundwater observed across the McMurdo Dry Valleys are associated with surface wetting because of capillary rise or saturation in **a** snow pack melt, providing local soil moisture, **b** wetted margin and hyporheic zone, **c** water tracks above the south shore of Lake Bonney, and **d** wetted margin on the lake shore of the eastern end of Lake Bonney (note the variability in surface wetting along the shoreline)

longest) in coastal regions of Taylor and Wright valleys where relative humidity is typically higher than in inland regions (e.g., Doran et al. 2002), as opposed to areas further up-valley and at higher elevation (Eveland et al. 2012; Fountain et al. 2010). Moreover, inland regions are closer in proximity to the Polar Plateau and therefore subject to drainage winds (Nylen et al. 2004), which may contribute to greater heating and wind-scour, and thus to greater ablation rates relative to coastal regions. Indeed, much (20–64 %) of the observed snow accumulation in the region, especially on the valley floors is due to aeolian deposition of wind-scoured snow, presumably of surface glacial origin (Fountain et al. 2010). The role of wind in snow accumulation is supported by the observation that snow patches preferentially occur in topographic hollows leeward of the prevailing westerly winds (Gooseff et al. 2003a).

The emerging view is that regional controls over accumulation and ablation of snow are driven by broad-scale gradients in climate constrained by the orientation of the valleys and the proximity of coastal vs. Plateau influences (which also co-vary with elevation in the major valley systems), while at finer scales, elevation, slope and local topography and aspect determine where snow packs can develop and persist (Eveland et al. 2012; Fountain et al. 2010; Gooseff et al. 2003a). Such differences in snowpack accumulation and persistence are consistent with broad-scale patterns of habitat suitability, e.g., water and salinity, nutrient availability and solute mobility and presence and absence of invertebrate communities.

Influence of snow packs on soil hydrological and geochemical properties

Subnivian (i.e., under snow) soils and soils within 10–30 m of snow packs have greater soil-water content than exposed soils through the austral summer (Gooseff et al. 2003a,; Fig. 3). Indeed many snow-influenced soils maintained saturated conditions (>12 % gravimetric water content for these sandy soils) through half of the 2009/

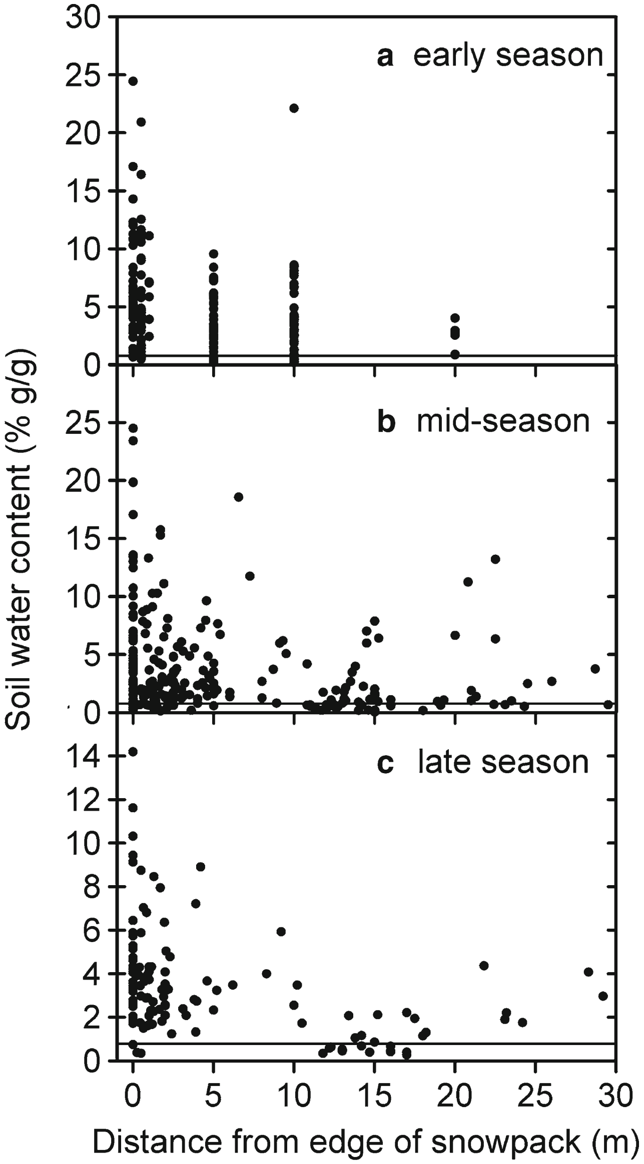

Fig. 3 Seasonal variability in the influence of snow packs on soil-water content in snow-affected soils adjacent to 18 snow packs in Taylor and Wright valleys from the 2009/2010 summer season. *Black horizontal line* shows average soil-water content for exposed soils. Note the different scales reflecting seasonal drying of the active layers

2010 summer season (Fig. 3). Overall, water content in surface soils (top 10 cm of soil profile) collected from within 30 m of snow packs averaged 3.7 % water content by weight, more than three-fold higher than samples from exposed soils where gravimetric water content averages 1 % (see Barrett et al. 2006b), and increased on average over the course of the austral summer (Fig. 3). Since previous work has demonstrated that habitat suitability for soil invertebrates is strongly influenced by soil-water content (Treonis et al. 1999), with thresholds for metabolic activity of ~4 % water content by weight (Treonis et al. 2002), snow packs may enhance soil habitat quality and the potential for biogeochemical cycling. For example, nearly 40 % of soils collected from within 30 m of snowpacks had water content in excess of 4 % by weight.

Snow accumulation influenced the spatial distribution of active layer depths for soils near snow packs (Fig. 4); soils within 1–2 m of snowpacks had average active layer depths of 7–20 cm over the course of the 2009/2010 summer season, compared with depths of 13–30 cm for soils more than 5 m away from snowpacks. These results may illustrate the combined influence of the insulation properties of snow on soil-water and temperature dynamics.

The influence of snow pack melt on soil geochemistry is superimposed on pre-existing variation in major ion

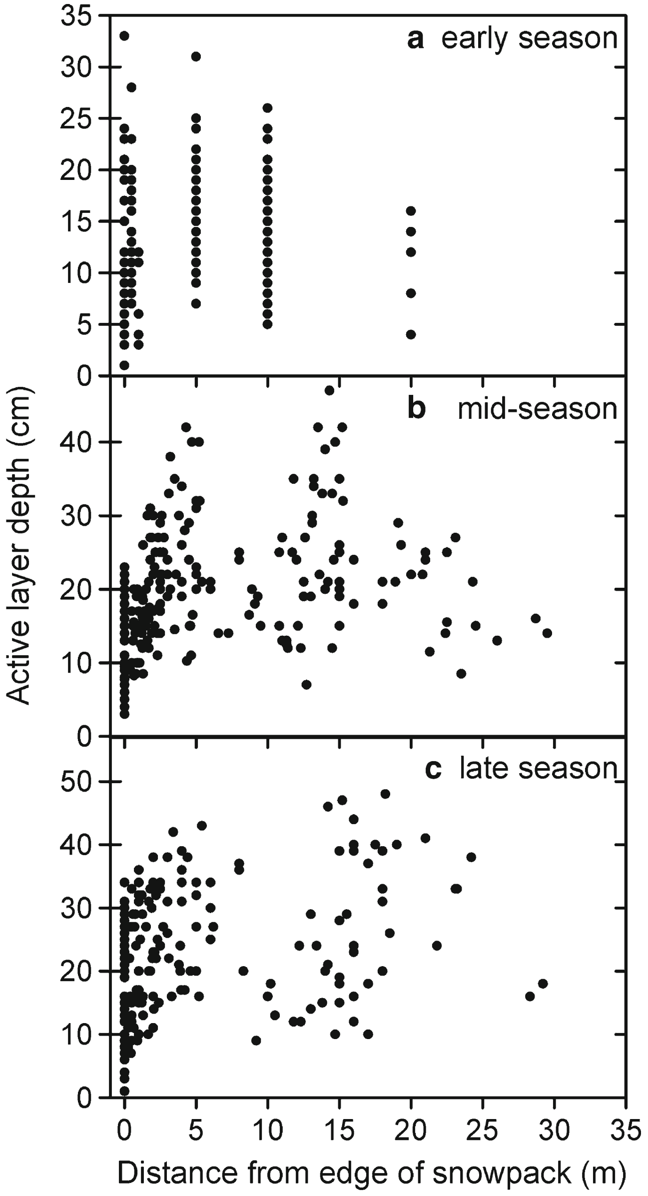

Fig. 4 Seasonal variability in the influence of snow packs on depth to ice cement in snow-affected soils adjacent to 18 snow packs in Taylor and Wright valleys from the 2009/2010 summer season. Note the increasing scale reflecting the deepening thaw of the active layer during the season

content (i.e., soil lithology), which is primarily influenced by landscape history (Barrett et al. 2006a; Burkins et al. 2000; Lyons et al. 2000) and surface exposure age of soils (Bockheim 1997). For example, nitrate (NO_3^-) and chloride (Cl^-) content in soils adjacent to 18 snow packs in Taylor and Wright valleys reflected a combined influence of variation in geographical distance to marine influences from the Ross Sea and surface exposure age (Lyons et al. 2000). Nitrate content, which is influenced primarily by aerial deposition (Michalski et al. 2005), is enriched in soils from upper Taylor and Wright valleys (Fig. 5), which occur at higher elevations and have longer exposure ages (Bockheim 2008). In contrast, chloride concentrations are enriched in lower Taylor and Wright valleys, consistent with closer proximity to marine aerosol inputs from the Ross Sea (Fig. 5). Snow pack influences on soil geochemistry are primarily through the dissolution and mobilization of these and other major ions (i.e., leaching; Fig. 6a and b), which results in significantly lower electrical conductivity of soil solutions in subnivian environments relative to exposed soils (e.g., Gooseff et al. 2003a), presumably due to rehydration and mobility of salt minerals. Since variation in salt content and composition influences distribution of invertebrate species (Poage et al. 2008) and at high concentrations contributes to greater mortality (Nkem et al. 2006), snow packs also contribute to factors that determine habitat suitability for soil organisms through modification of geochemical conditions, in addition to effects on water availability and hydrology. While these local effects on physical and geochemical conditions can thus have significant influences on resident biota, their overall significance on hydrology and geochemistry is less clear. If snow packs are a significant source of melt water to dry valley soils, then their influence on dry valley hydrology should be evident through their contribution to the mobilization and accumulation of salts in flow paths or water tracks down gradient of snow packs.

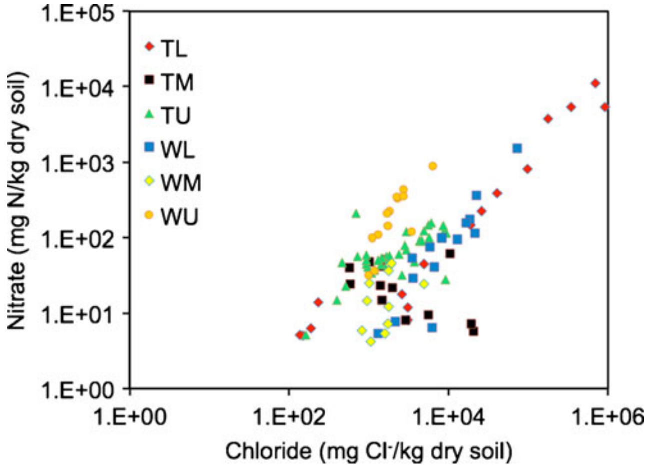

Fig. 5 Nitrate and chloride content in soils adjacent to 18 snow packs in Taylor and Wright valleys. Ion concentrations of (1:5) soil:deionized water extracts determined through ion chromatography. Symbols indicate different sampling regions with Taylor (*T*) and Wright (*W*) valleys, at upper (*U*), middle (*M*), and lower (*L*) valley locations

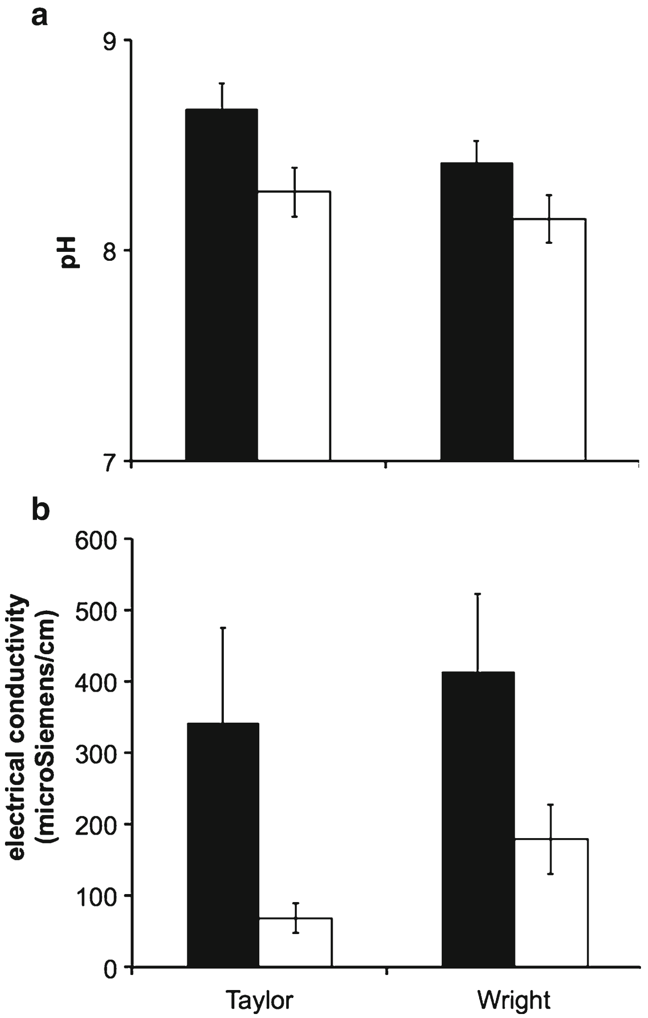

Fig. 6 **a** Soil pH and **b** electrical conductivity of soil solutions adjacent to 18 snow packs in Taylor and Wright valleys in subnivian (*black bars*) and exposed (*white bars*) soils

Water tracks

Water tracks are narrow bands of high soil moisture that route water downslope, in the absence of overland flow, through permafrost dominated soils in polar regions (Hastings et al. 1989; Levy et al. 2011; McNamara et al. 1999) (Figs. 2 and 7). In water tracks, moisture moves as shallow groundwater, flowing through the permafrost active layer along linear depressions in the ice table (the portion of the permafrost that remains frozen and ice-cemented during summer months), resulting in channelized flow (Figs. 7 and 8). In this section, we provide an overview of water track characteristics in Taylor Valley including water track water fluxes of water and solutes, along with a preliminary synthesis of water-track biological effects.

In water tracks, water flows through broad channels in the ice table, typically 1–10 m wide, but with saturated flow (and surface darkening) typically confined to 1–3 m in width (Levy et al. 2011). Water tracks in Taylor Valley range in length from hundreds of meters (Fig. 7) to up to

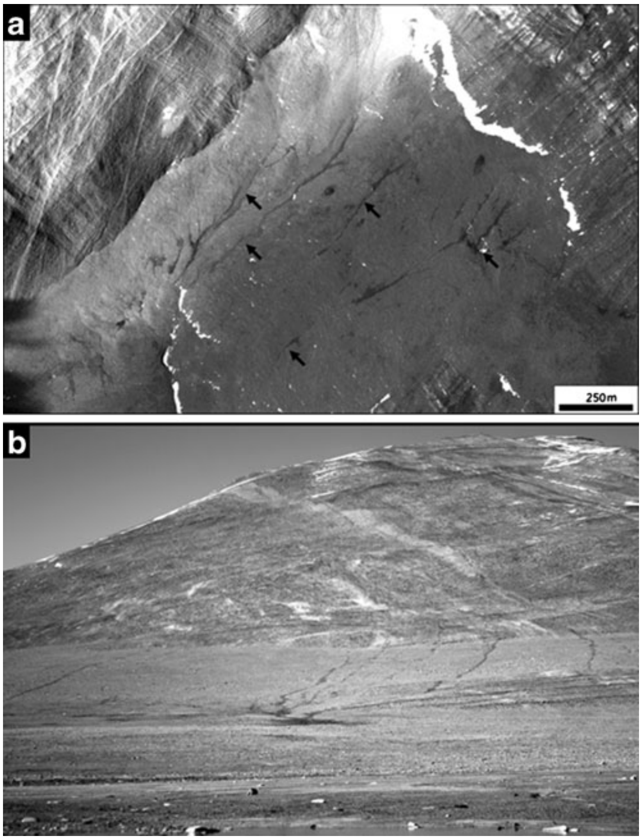

Fig. 7 Water tracks in Taylor Valley, Antarctica. **a** Quickbird satellite image of water tracks (*arrows*) in the Goldman Ponds section of Taylor Valley. Downslope and north to image bottom. **b** Ground view of water tracks below Goldman glacier, Taylor Valley, Antarctica. Quickbird image data provided by the Polar Geospatial Center

2 km. Water tracks in the Lake Hoare basin are significantly different from adjacent, non-water-track soils (see summary in Table 1). Water-track soils are ~10 times wetter than adjacent, off-track soils and are 5–10 times more solute-rich. The active layer (thaw depth) beneath water tracks is more than twice as deep as that of non-water-track locations. Water tracks are solute "superhighways," capable of moving salts downslope nearly six times faster than adjacent, dry soils (Campbell et al. 1997; Levy et al. 2011). Rock weathering products (e.g., Si) and NO_3 (from aerial deposition) are concentrated in water tracks. Si concentrations in water-track fluids are the highest of any dry valleys water body (Lyons et al. 1998)

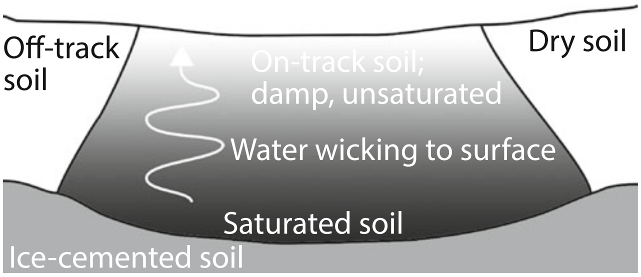

Fig. 8 Schematic cross section of a water track

Table 1 Comparison of geochemical, physical, and biological parameters between water-track soils, adjacent off-track soils, and Taylor Valley streams. *P* values are determined by single-ended ANOVA analysis of water track and off-track data, where *GWC* is gravimetric water content, *EC* is electrical conductivity, *DTR* is depth to refusal, which is a proxy for thaw depth

Means	GWC (%)	EC (μS/cm)	DTR (cm)	Ionic migration rate (m/yr)	Cl (mg/L)	TDS (mg/L)	NO_3 (μg/L)	C (%wt)	PO_4 (μg/L)	pH	Nematodes (#/kg dry soil)		
											Live	Dead	Live + dead
On track	6.1	2700	45	1.7	1046	1836.1	6718.8	1.2	55.5	8.6	17.8	9.3	27.1
Off track	0.8	400	19	0.3	88.6	294.5	860.4	0.4	164.4	9.6	83.8	19.4	103.3
P	<0.001	0.005	<0.001	<0.05	0.002	0.023	0.112	0.03	0.002	<0.001	0.07	0.13	0.077
Streams	NA	0.1[a]	50–60[b]	NA	0.13[a]	0.09[c]	48.8[a]	0.0004[d]	9.4[a]	7.2[c]	NA	NA	NA

[a] From McKnight et al. (2004)

[b] From McKnight et al. (1999)

[c] From Green et al. (1988)

[d] From Downes et al. (1986)

including Taylor Glacier's "Blood Falls" hyperconcentrated subglacial discharge (Nezat et al. 2001), suggesting that similar to stream hyporheic zones, water tracks are loci of chemical weathering (Gooseff et al. 2002; Lyons et al. 1998; Lyons et al. 1997; Nezat et al. 2001). Interestingly, water tracks are also three times more carbon rich than adjacent soils (and in places, are an order of magnitude more carbon-rich) based on measurements of ash-free dry mass (J. Levy. Oregon State University, unpublished data, 2012); which, coupled with phosphorous depletion in the water tracks, suggests that they are locations of significant microbial metabolism and possibly primary production. Electrical conductivity (EC), gravimetric water content (GWC), and total dissolved solids (TDS) all increase with depth in water tracks, suggesting that solute transport is concentrated in the basal, saturated portion of the water track.

Recent observations of shallow groundwater discharge from the active layer as saline seeps during peak summer warming helped initiate reconsideration of long-held assumptions about groundwater processes in Taylor Valley (Harris et al. 2007; Lyons et al. 2005) and revived interest in early reports of saline groundwater activity in nearby Wright Valley (Cartwright and Harris 1981; Wilson 1981). Levy et al. (2011) showed that these seeps are embedded within water tracks and discharge like springs at abrupt breaks in slope. Despite recent new studies on water-track processes, water tracks in Taylor Valley are not "new" features of the landscape, and are evident in aerial photographs collected between 1958 and 1999 and even in ground-based photographs from ca.1911. Accordingly, annual and interannual variations in water-track flow rates provide important controls on ecosystem functioning within water-track affected soils (Nielsen et al. 2012).

Water-track water and solute fluxes

Because water-track flow occurs only between the surface (where snowmelt infiltrates during summer thaw) and the permafrost ice table, water-track hydrology can be understood largely through simple Darcy flow calculations (Levy 2012; Levy et al. 2011). Water tracks in the Lake Hoare basin within Taylor Valley, descend slopes averaging ~5° slope, composed of sandy, colluvium—calcic haplorthels (Campbell 2003)—with a mean hydraulic conductivity of 0.02 cm/s. For typical water tracks (3 m in width and consisting of saturated horizons ~10 cm thick), the estimated flux through them is expected to be ~500 L/day—less early and late in the season when pore ice reduces hydraulic conductivity (Kleinberg and Griffin 2005). This discharge per water track is approximately two orders of magnitude smaller than discharge from adjacent glacial meltwater streams; however, the abundance of water tracks in the Lake Hoare basin, coupled with their high salinity (see the following) suggests that they may be both volumetrically and geochemically significant components of the Taylor Valley water budget.

Water tracks in Taylor Valley are strongly enriched in soluble salts, and transport a higher concentration of dissolved solids than any other surface or near-surface hydrological pathway (Fig. 9) (Levy et al. 2011; Lyons et al. 1998). Water-track fluids have low Na^+/Cl^- molar ratios on average (0.66, compared to 0.86 in seawater), suggesting the possibility of cryogenic concentration of salts during seasonal freezing (Starinsky and Katz 2003). However, the high Ca^{2+}/Na^+ ratio (0.72 on average) more strongly suggests humidity-driven salt separation at the permafrost surface as a primary driver of solute enrichment (Wilson 1979). Under this mechanism, brines produced by the deliquescence of highly hygroscopic salts ($CaCl_2$, $MgCl_2$) mix with water snowmelt and ground ice melt in water tracks to produce solutions enriched in Ca^{2+}, Mg^{2+}, and Cl^-, and relatively depleted in Na^+ and K^+, which are incorporated only where water tracks flow through soils containing unfractionated marine aerosols (Levy et al. 2011).

Water-track solutions are typically ~100 times more concentrated than nearby glacier-fed streams (Fig. 9), meaning that they may be major contributors to dry valleys lake geochemical profiles, despite water fluxes ~100 times lower than stream discharges. Notably, water-track solutions entering dry valleys lakes are typically denser than the lake water due to the high total dissolved solids content of water-track discharge: up to 1001.7 kg/m^3 (Levy et al. 2011). Such dense, salty fluids would sink to the bottom of Taylor Valley lakes and may help explain the increase in salinity with depth in Lake Hoare (Levy et al. 2011; Lyons and Mayewski 1993).

Water-track biological and ecosystem effects

Water tracks contribute to the biogeochemical conditions of dry valleys soil habitats (Nielsen et al. 2012). New data indicate that nematodes, a top consumer in the Taylor Valley soil ecosystem (Virginia and Wall 1999), are less abundant in water-track soils than in adjacent dry soils (Table 1). This paucity of nematodes in water-track soils can be best explained by the high pore-water electrical conductivity typical of water tracks associated with high salt contents of water-track fluids (e.g., ~1,000–4,000 μS/cm, ranging as high as 17,000 μS/cm), which exceed the soil moisture conductivity threshold of 1,000–2,000 μS/cm which limits dry valleys nematode distribution (Nkem et al. 2006; Poage et al. 2008). Curiously, water-track soil carbon contents measured via pyrolysis (ash free dry mass) are considerably higher than those of adjacent off-track soils (Table 1). Preliminary measurements of water-track soil microbial biomass indicate that the labile carbon content of water tracks is lower than the labile carbon content of adjacent, off-track soils, suggesting that water tracks may be conduits for transporting refractory, "legacy" carbon (Lyons et al. 2000) through Antarctic hillslopes.

Water tracks are a spatially extensive water transport pathway in the MDV, that move meltwater derived from snow, ground ice, and atmospheric water vapor sources through active layer soils, and ultimately, to dry valleys lakes. Water tracks may facilitate greater landscape

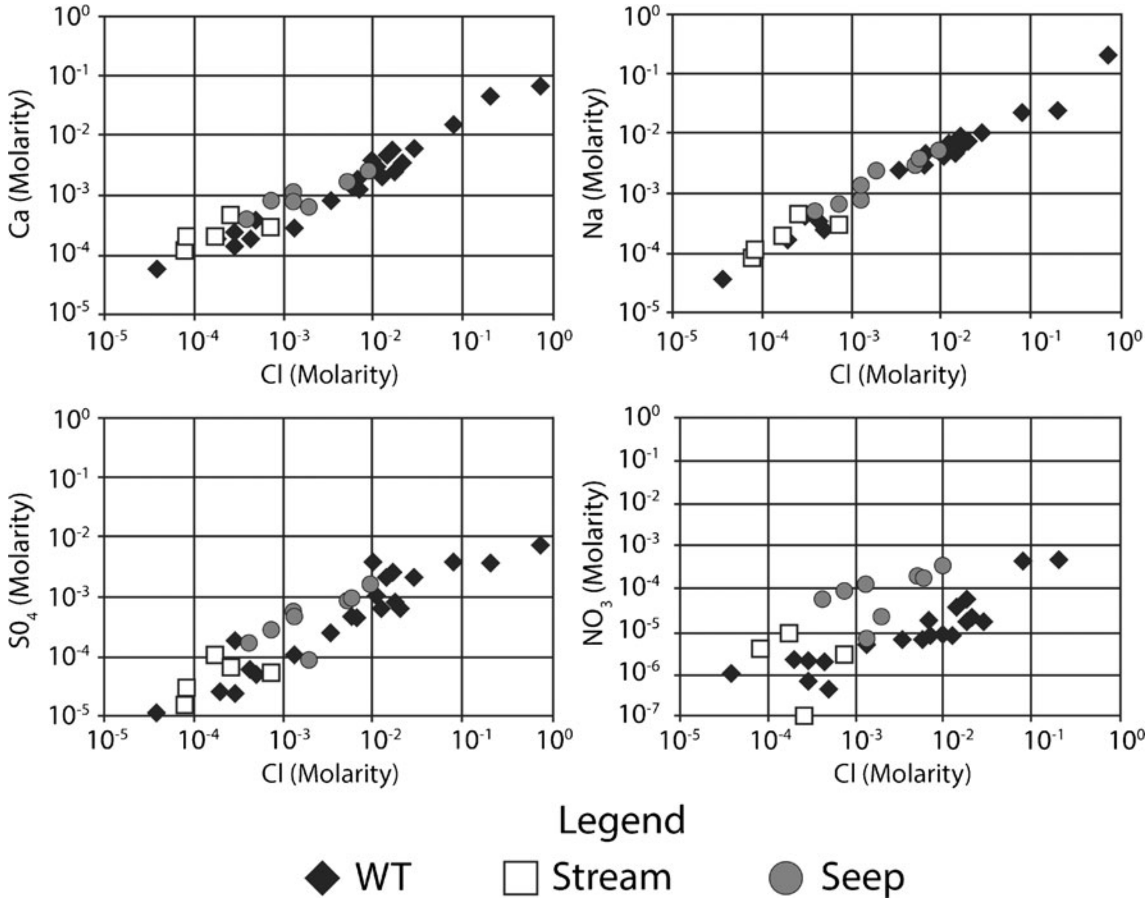

Fig. 9 Major ion data for water tracks (WT, *diamonds*), seeps (*circles*), and streams (*squares*) in Taylor Valley measured using ion chromatography. Total analytical error is <4 % (Welch et al. 2010). Adapted from (Levy et al. 2011)

connectivity in the dry valleys by linking upland areas and valley bottoms through a coupled hydrological and geochemical groundwater drainage system.

Wetted margins of streams and lakes

The fine soil and sediment that make up the active layer adjacent to streams and lakes wick water from the water body through capillary suction (Gooseff et al. 2007). At the surface, these wetted margins of liquid water bodies are distinct during the austral summer (e.g., Fig. 2d), and decrease in soil-water content from the shoreline to the dry edge (Fig. 10). Wetted margins are generally greater in extent where they are adjacent to lakes than streams, extending as much as 11 m from the shoreline (Northcott et al. 2009). Their extent into the dry landscape is dependent upon both sediment grain size and the slope of the shore (Gooseff et al. 2007). Thaw depths are slightly greater at the saturated shoreline, compared to the dry soils, in part due to the higher thermal buffering of the presence of water in the soils across the wetted zones (Ikard et al. 2009). Soil water evaporates across these wetted margins through the austral summer, and evaporative water losses from the soils are replaced by capillary demands of the soils. The enhanced concentrations in the wetted margins of lakes, compared to streams, are caused by more consistent presence of water in the lakes. Liquid water availability at the edges of the lakes occurs for approximately 4 months (even after a thin ice cover forms in February or March), whereas streams flow for 6–10 weeks, often with periods of little to no flow.

The wetted margins of both lakes and streams tend to accumulate salts. Across wetted margins of both lakes and streams, soil major ion concentrations (namely Cl^-, Na^+, NO_3^-, K^+, SO_4^{2-}, Mg^{2+}, Ca^{2+}) increase from shoreline toward the edge of the wetted margin, with peak concentrations within the wetted zone, near the wet-dry transition, and concentrations in lake margins generally 10× those of stream margins (Barrett et al. 2009). The increase in solute concentration with decrease in soil moisture includes nitrate, suggesting that unlike their counterparts in temperate regions, MDV riparian zones do not appear to be enhanced locations of denitrification. Across the wetted margins, ammonium and phosphate generally decrease, potentially due to biological activity in these soils.

The hydrological function and biogeochemical conditions across wetted margins have significant controls on the biological communities found in these soils. Opposite of expectations, bacterial community diversity does not correlate to wetness; rather it is highly correlated to soil

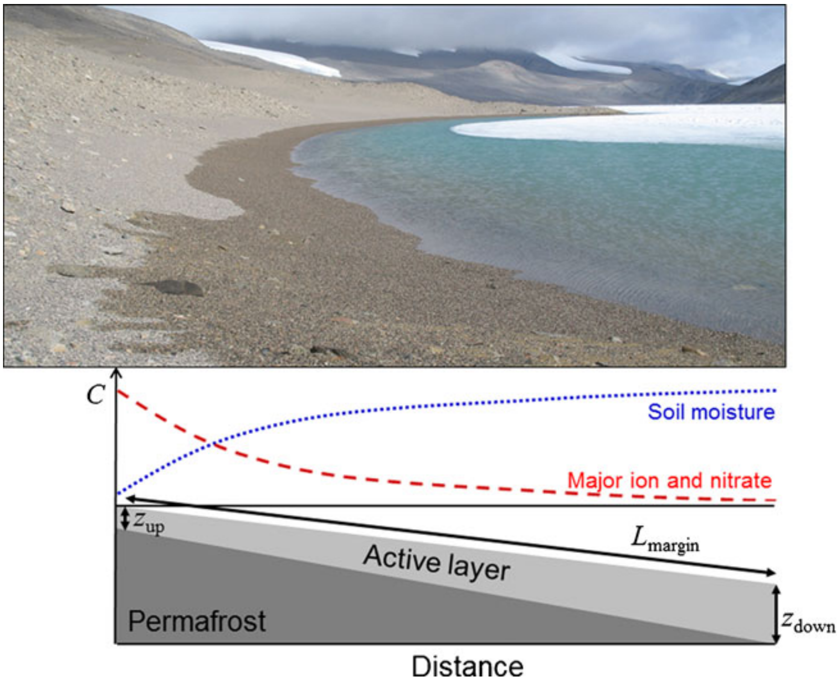

Fig. 10 Lake margin layout on the shore of Lake Bonney. On lake shores, typical thaw depths at the shoreline (z_{down}) are around 0.42 m and 0.31 m at the transition to dry soils (z_{up}); typical margin lengths (L_{margin}) range from 3.9 (±1.96) m on steep shores to 10.01 (±5.44) m on shallow gradient shores (Gooseff et al. 2007). Stream margins have a similar cross-section, with mean thaw depths ranging from 0.12 to 0.85 m, and L_{margin} values ranging from 1.04 to 11.01 m (Northcott et al. 2009)

electrical conductivity (Zeglin et al. 2011). Hence, flowpath and the coincident movement of water and salts influence soil microbial diversity across wetted margins. Microbial community function has been characterized by assessing extracellular enzyme activity potentials, in which no significant relation to soil-water content was observed, but that most of the variance was associated with differences in soil organic matter, pH, and salinity (which exhibit similar patterns to P and N content) of the soils (Zeglin et al. 2009). Soil invertebrate communities vary across these wetted margins of streams and lakes (Ayres et al. 2007; Treonis et al. 1999). Treonis et al. (1999) found that total abundance of invertebrates did not vary across stream-wetted margins, but that taxonomic richness decreased from stream center to dry soils, with distinct habitat preference exhibited by specific taxa.

Hyporheic zones of streams

Adjacent to and beneath streams is a volume of saturated soil and sediment through which stream water exchanges, known as the hyporheic zone. Adjacent to MDV streams, the potential location of the hyporheic zone is fairly evident because of the capillary fringe observed at the surface (Fig. 11). As discussed in the previous section, the surficial soil moisture is held in place by capillary action, but at depth, there is substantial exchange between the saturated portion of MDV hyporheic zones and the stream channel. The active layer beneath and adjacent to streams generally begins to thaw prior to streamflow initiation (though very little), and thaw tends to progress quickly as streamflow begins and both sediment and stream water are warmed by intensive solar radiation (Conovitz et al. 2006). Hyporheic thaw depths have been measured to be as much as ~65 cm, with maximum thaw occurring in January (Conovitz et al. 2006).

The hydrological significance of MDV hyporheic zones is twofold: (1) the seasonal filling of the accommodation space of the streambed sediment that must be satisfied before surface flow can occur; and (2) the exchange of stream water through bed and bank sediments, which can significantly enhance stream-water residence time (compared to water remaining in the channel). The former is a control on streamflow; when little meltwater is generated at the glaciers, it is possible that all of it will infiltrate into the thawed stream sediments and none will reach the lakes at the ends of

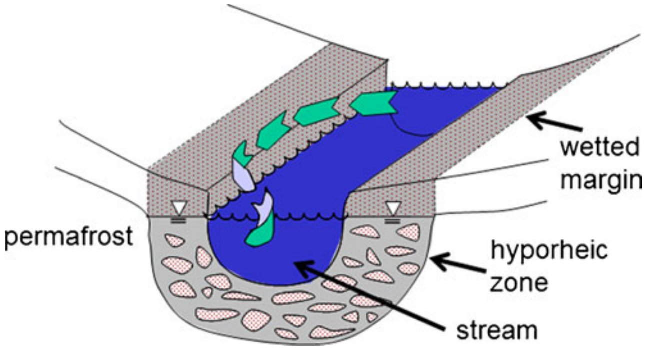

Fig. 11 Conceptual model of hyporheic exchange, stream water moving from the channel, through the sediments and back into the channel as represented with the *green arrows*, in MDV streams (at steady flow), as described in McKnight et al. (1999)

Table 2 Comparison of mean storage residence times and sizes of MDV hyporheic zones determined by several different approaches. All streams noted below are in Taylor Valley

Stream	Mean storage residence time (hr)	Hyporheic zone cross-sectional area (m^2)	Method	Reference
Huey Creek	0.01–20.40	0.2–3.07	Stream tracer experiment, solute transport modeling	Runkel et al. (1998)
Huey Creek	NA (variable)	~2.1–~3.6	Stream tracer exp., coupled surface-groundwater flow model	Koch et al. (2011)
Green Creek	2.53–29.24	0.05–0.40	Stream tracer exp., solute transport modeling	McKnight et al. (2004)
Green Creek	0.01–7.82	0.01–10.4	Stream tracer exp., solute transport modeling	Gooseff et al. (2004b)
Green Creek	804–1550	2.36–4.95	Stable isotope monitoring, transport modeling	Gooseff et al.(2003b)

the streams (McKnight et al. 1999). Hyporheic thaw depth is controlled by the energy balance of the surface of the streambed and there is limited evidence for substantial differences in stream temperatures between short and long streams (Cozzetto et al. 2006). Hence, there is expected to be little variation in the thaw depth of long and short streams in the MDVs and total accommodation space is generally controlled by length of the stream. Thus, long streams are less likely to flow than short streams. As in temperate streams, stream water that exchanges through the hyporheic zone will incur enhanced residence times compared to purely advective time scales. Exchange of stream water through MDV hyporheic zones has been documented at several different time scales, ranging from less than 1 h to ~2 months (Table 2). Stream tracer experiments occurring over hours have identified mean residence times of a few hours (Gooseff et al. 2004b; McKnight et al. 2004; Runkel et al. 1998) likely most sensitive to short flowpaths close to the channel, and simulation of natural distributions of water stable isotopes have indicated mean residence timescale of months (Gooseff et al. 2003b), indicating that there are extensive, distal parts of the hyporheic zone that exchange slowly. After simulating coupled stream groundwater flow dynamics during a stream tracer experiment conducted during unsteady flow conditions, Koch et al. (2011) concluded that bank storage is an important process by which MDV streams exchange stream water through hyporheic zones.

Hyporheic zones of MDV streams actively regulate biogeochemical and thermal inputs to the closed basin lakes on the valley floors. Fluxes of weathering products (primarily Si and K given marine aerosol deposition in this area) in MDV streams are high, rivaling those of temperate watersheds, despite the cold climate and very brief streamflow season (Lyons et al. 1997; Nezat et al. 2001). Modeling of chemical reactions that incorporates the exchange of stream water with hyporheic zones, and informed by synoptic stream water data, further supports these high weathering rates (Gooseff et al. 2002). The sediments of these hyporheic zones can also be locations of enhanced geochemical buffering with cation exchange processes occurring there (Gooseff et al. 2004a). MDV hyporheic zones are also locations of enhanced nutrient cycling. Hyporheic sediments have been documented to retain 15.5 % of removed nitrate during stream tracer experiments that include nutrient enrichment (McKnight et al. 2004), in competition with benthic algal mats in the stream (84–94 % of nitrate removed) (Gooseff et al. 2004b; McKnight et al. 2004). Hyporheic waters are generally enriched in major ions (Fig. 12) and stable isotopes of water (D and ^{18}O) (Gooseff et al. 2003b), and nutrients (McKnight et al. 2004). Further, they also act as thermal regulators for stream water. Underlain by permafrost and influenced by conduction and convection of stream water, they tend to buffer high and low temperatures in streams (Cozzetto et al. 2006).

Comparison of the groundwater systems of the McMurdo Dry Valleys

The dry and cold conditions of the MDVs essentially mean that the active layer soils are conceptually much like a sponge, absorbing and accommodating liquid water when and where it is present. Glacial melt and snowmelt waters are chemically very dilute, whereas stream and lake waters are more enriched chemically, but intermediate between melt water and groundwater. Functionally, these

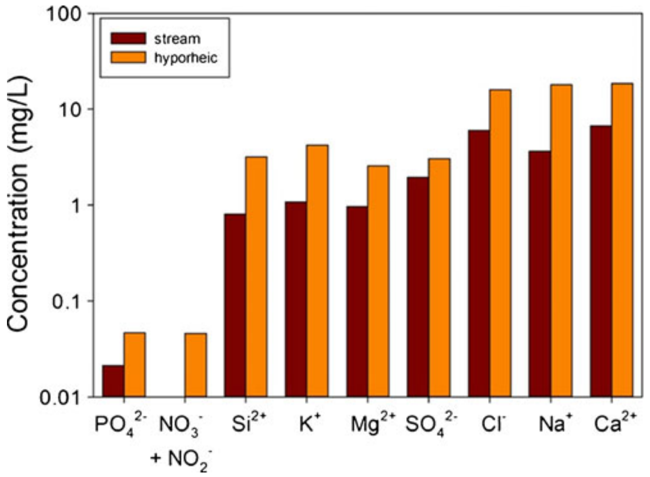

Fig. 12 Comparisons of average Von Guerard Stream nutrient (McKnight et al. 2004) and Green Creek major ion (Gooseff et al. 2003b) concentrations from stream and hyporheic waters (sampled at 10 cm depth)

groundwater systems are common in that the movement of liquid water through the relatively unweathered soils and sediments causes rapid chemical weathering and thus, groundwater is substantially enriched in solutes. Whereas isolated wet patches from snowmelt and wetted margins tend to concentrate these solutes in specific locations, hyporheic zones and water tracks serve as subsurface conduits of water, energy, and solutes across the MDV landscape.

All of the systems discussed in the previous accommodate flows of water at different spatial scales. The most static are the locations around snow patches that are either supply limited (precipitation or aeolian) or topographically limited, such that flow away from that location is not promoted. Wetted margins adjacent to lakes appear to be fairly static in appearance, though the evaporation-forced deficit causes small amounts of flow to move through these sediments. Wetted margins adjacent to streams have the same lateral flow-through as their lakeside counterparts, but due to downstream elevation gradients may also accommodate some downstream subsurface movement of water parallel to the stream and distinct from the hyporheic zone (because the water is not actively exchanging with the stream). Hyporheic zones actively exchange water with the surface stream channel and therefore experience the greatest amount of through-flow in the MDVs. Along with wetted margins, their location is relatively fixed, dependent upon surface-water bodies. Wetted soil patches and water tracks, on the other hand, are supplied by snowmelt and therefore their distribution is dependent upon the distribution of accumulated snow, as well as the dynamics of ablation.

Seasonal evolution and temporal consistency of these systems is somewhat variable. Lake moats (melted edges of lakes in the summer) have been observed to form (i.e., melt) every austral summer season for the past 20+ years of active research in the MDVs. Hence, lake wetted margins form annually because the supply of water is consistently available from season to season. On the other hand, hyporheic zones, stream-side wetted margins, water tracks and soil moisture from snowmelt are more sensitive to weather conditions in a given season and require meltwater generation from either glaciers or snow as sources. In colder or cloudier seasons, less meltwater generation will result in fewer wet soil patches and water tracks forming across the landscape. Hyporheic zones and stream-side wetted margins are intimately linked; though with little to no stream flow, the hyporheic aquifer may fill and provide water for wetted margins, but very little water for streamflow to occur. Soil water and water tracks are dependent on the temporal dynamics of ablation of distributed snow-patch sources. In summers that cool down substantially after a warm spell, there may be a reduction in the potential for meltwater generation, ceasing supply to soils.

Conclusion

The several shallow groundwater systems in the MDVs facilitate and buffer the fluxes of matter and energy at many discrete locations across the MDVs, which also control local patterns of biota. Currently the MDV landscape is discretely hydrologically connected—that is, stream channels and water tracks are fairly well established, and therefore the occurrence of groundwater in hyporheic zones, wetted margins, and water tracks are consistently located as long as liquid water is available. Snow patches generally collect in the same topographic lees each year, such that locally wetted soils will also be consistently located, but they are more likely ephemeral because climatic conditions that influence accumulation and ablation partitioning (sublimation vs. melt) are more likely to change from year to year, significantly influencing the availability of this water in this melt-limited hydrological system. In the coming decades, the MDV region is expected to warm (Walsh 2009), potentially increasing the occurrence and distribution of liquid water across the MDV landscape as increased sensible heat flux drives enhanced melting of ground ice and snow. In such scenarios, groundwater will likely play a more important role in regulating the distribution of matter and energy across the landscape. One possibility is that groundwater may become an accelerant of landscape/ecosystem processes. Increased soil moisture across the landscape (compared to today) will likely increase the rate of ion transport in soils, deepen the thaw depth of ice cemented soils, and increase the rate of chemical and potentially mechanical weathering (through heave/settle cycles). Thus, these processes may produce positive feedbacks (e.g., deeper thaw liberating ground ice into groundwater systems), and thereby an increasing rate of change in groundwater processes in the MDVs would be expected. Both soil biological communities and landscape geomorphic processes are water limited in the MDVs at present, and an increase in shallow groundwater could represent an expansion of activity in both biotic and geomorphic processes.

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