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Water tracks in the High Arctic: a hydrological network dominated by rapid subsurface flow through patterned ground[1]

Michel Paquette, Daniel Fortier, and Warwick F. Vincent

Abstract: Water tracks play a major role in the headwater basin hydrology of permafrost landscapes in Alaska and Antarctica, but less is known about these features in the High Arctic. We examined the physical and hydrological properties of water tracks on Ward Hunt Island, a polar desert site in the Canadian High Arctic, to evaluate their formation process and to compare with water tracks reported elsewhere. These High Arctic water tracks flowed through soils that possessed higher near-surface organic carbon concentrations, higher water content, and coarser material than the surrounding soils. The water track morphology suggested they were initiated by a combination of sorting, differential frost heaving, and eluviation. The resultant network of soil conduits, comparable to soil pipes, dominated the hydrology of the slope. The flow of cold water through these conduits slowed down the progression of the thawing front during summer, making the active layer consistently shallower relative to adjacent soils. Water tracks on Ward Hunt Island, and in polar desert catchments with these features elsewhere in the High Arctic, strongly influence slope hydrology and active-layer properties while also affecting vegetation distribution and the quality of runoff to the downstream lake.

Key words: Patterned ground, permafrost hydrology, polar desert, sorted stripes, water tracks.

Résumé : Les nappes d'eau (« water tracks ») jouent un rôle important au niveau de l'hydrologie des bassins d'amont des paysages de pergélisol en Alaska et en Antarctique, mais on en connait moins sur ces caractéristiques dans le Haut-Arctique. Nous avons examiné les propriétés physiques et hydrologiques de nappes d'eau sur l'île Ward Hunt, un site de désert polaire dans le Haut-Arctique canadien, afin d'évaluer leur processus de formation et de comparer avec les nappes d'eau documentées ailleurs. Ces nappes d'eau dans le Haut-Arctique coulaient à travers des sols dont les concentrations en carbone organique proche de la surface et la teneur en eau étaient plus élevées, et dont le matériau était plus grossier que celui des sols environnants. La morphologie de nappes d'eau laisse entendre qu'elles ont été engendrées par une combinaison de triage, de soulèvement par le gel différentiel et d'éluviation. Le réseau de conduits de sol (comparables à des tuyaux de sol) qui en résulte dominait l'hydrologie de la pente. L'écoulement d'eau froide par ces conduits ralentissait la progression du front de dégel pendant l'été, entraînant la diminution systématique de l'épaisseur de la couche active par rapport aux sols adjacents. Les nappes d'eau sur l'île Ward Hunt, et dans les bassins hydrologiques de désert polaire ayant ces caractéristiques

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ailleurs dans le Haut-Arctique, influent fortement sur l'hydrologie des pentes et les propriétés de la couche active, en plus d'avoir des effets sur la répartition de la végétation et la qualité d'écoulement au lac en aval.

Mots-clés : sol à, figures géométriques, hydrologie du pergélisol, désert polaire, traînée avec triage, nappes d'eau (« water tracks »).

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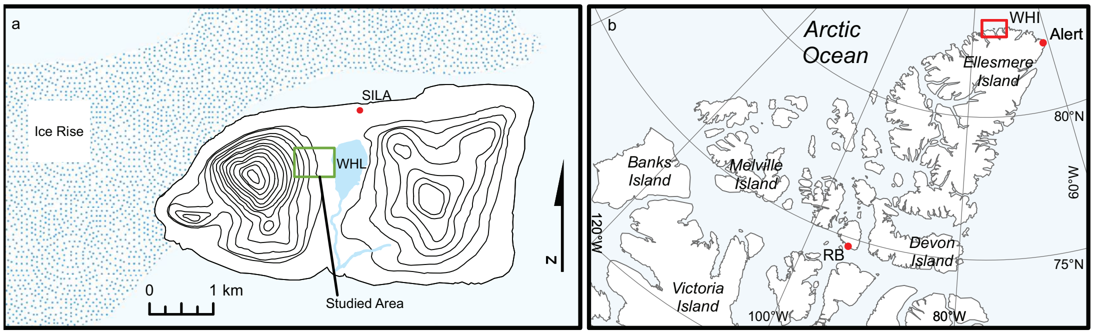
Introduction

Water tracks are widespread features of high-latitude watersheds (Kane et al. 1991). As preferential subsurface flow paths, they are often the only surface indicators of drainage patterns on nonincised permafrost slopes, yet the periglacial literature makes little mention of water tracks as an important feature of high-latitude landscapes. The term itself is relatively recent and is not defined in permafrost glossaries (Harris et al. 1988; Van Everdingen 2005). Overall, there is no consensus on the specific characteristics of this landform feature, and authors have adapted their definition according to their specific research interest or study site (Walker et al. 1982; Chapin et al. 1988; Kane et al. 1991; Hinzman et al. 1993; McNamara et al. 1998; Stieglitz et al. 2003; Jorgenson et al. 2008; Levy et al. 2011). An encompassing definition is provided by Gooseff et al. (2013) who defined water tracks as a regional feature of permafrost areas, forming "narrow bands of high soil moisture that route water downslope, in the absence of overland flow, through permafrost dominated soils in polar regions."

Water tracks in periglacial regions have been the subject of research in two contrasting polar environments: the foothills of the Brooks Range, northern Alaska, and the Taylor Valley, Antarctica. The Brooks Range Arctic tundra water tracks are broad, highly vegetated hillslope depressions fed by a mix of snowmelt and rainfall, while the water tracks in Antarctica are narrower and located on polar desert soils, devoid of vegetation and of organic matter accumulation (Chapin et al. 1988; Levy et al. 2011). Mainly by comparison with intertracks (areas between water tracks), studies have shown that water tracks have multiple physical, chemical, and biological effects on landscape slope properties. In Alaska, primary production was 40% higher in water tracks than in intertrack soils (Hastings et al. 1989). The superior soil moisture conditions in water tracks reduced water stress on plants, allowing higher photosynthetic rates during periods of drought (Matthes-Sears et al. 1988) and influencing CO_2 efflux in late summer (Oberbauer et al. 1991). Nutrient supplies may increase in water tracks (Cheng et al. 1998), partly as a result of the deeper active layer beneath them (Oberbauer et al. 1989; Gooseff et al. 2013). Vegetation, microfauna, and bacterial assemblages are also modified by the presence of water tracks (Walker 1983; Walker et al. 1989; Levy et al. 2013; Steven et al. 2013). The greatest effect of water tracks is on the hydrology of their watersheds, where they decrease the delivery time and increase the outflow response of catchment basins (Kane et al. 1991). They achieve this by remaining at levels close to soil water saturation and by acting as potential contributing areas that extend considerable distances upslope; this reduces the need for basin storage pools to fill up before initiating their input to storm runoff events (McNamara et al. 1998).

The studies in Alaska and Antarctica showed pronounced contrasts in morphologies and other physical properties of the water tracks between the two sites, underscoring the need for wider geographical coverage to understand the full diversity of these features. In the present study, we focused on water tracks in the High Arctic to determine their morphological and flow characteristics in a polar desert landscape. We undertook this study on Ward Hunt Island at the northern limit of the Canadian Arctic Archipelago, which is a slightly wetter polar desert landscape than in the McMurdo Dry Valleys of Antarctica but that still sits far from the widespread vegetation cover of Arctic tundra water tracks. The aims of our study were to identify the geomorphological context and properties of water tracks and the role of these features in slope hydrology.

Fig. 1. (*a*) Topographic map of Ward Hunt Island. (*b*) Location at the northern tip of the Queen Elizabeth Islands. Isolines are 30 m apart. RB, Resolute Bay; SILA, weather station; WHI, Ward Hunt Island; WHL, Ward Hunt Lake.



Methods

Study site

Ward Hunt Island (83.08°N, 74.14°W) is located 6 km off the north coast of Ellesmere Island near the northern limit of the Canadian High Arctic (Fig. 1). A description of the physiography, geomorphology, and ecology of the island and the surrounding areas is given in Vincent et al. (2011). Our study focused on the slopes of Ward Hunt Lake watershed, a headwater catchment of 1.82 km^2 feeding the 0.35 km^2 lake, which is located 26 m above sea level (a.s.l.). The lake drains to the south and its watershed is delineated by a beach ridge to the north (40 m a.s.l.) and by two hills to the east (Ward Hunt Hills, unofficial name; ~165 and ~245 m a.s.l.) and one to the west (Walker Hill, 436 m a.s.l.). The geology of the island includes mostly limestone to the west (Walker Hill) and some igneous and volcanic rocks to the east (Trettin 1991). Surficial deposits on the island are a mix of glacial drift and gelifracted parental material that probably pre-date the last glacial maximum (Lemmen 1988), along with some sandy gravel beaches below the Holocene marine limit. The mean annual air temperature is −17.9 °C (1995–2015), with average air temperature of −33.4 °C in February and 1.5 °C in July (CEN 2016). The freeze–thaw regime at this location is sensitive to slight changes in temperatures, and year-to-year variation can cause a threefold increase in the number of thawing degree-days as measured by air temperatures (Paquette et al. 2015). Hourly snowmelt was measured using a Sonic SR50 sensor connected to a CR10X data logger (Campbell Scientific, Edmonton, Alberta) and precipitation was measured using a metric rain gauge read twice a day (0700 and 1900 local time zone). Total precipitation has not been measured but is likely to be slightly lower than the average of 158 mm $year^{-1}$ measured at Alert, located 170 km to the southeast (Environment Canada 2016), as rainfall events are rarer. The study site is an eastward-facing slope located at the base of Walker Hill; water tracks are the final component of a succession of coarse gelifracts (angular rock fragments produced by frost action), nivation hollows (depressions created by snowpatch erosion), and solifluction landforms (produced by the downslope deformation of saturated or thawing soils) down the slope.

Morphology and soil properties of water tracks

Water tracks on Ward Hunt Island most commonly take the form of regularly spaced, linear vegetated depressions similar to nonsorted stripes. They expand upslope into a network of elongated patterned ground (polygons and stripes) that becomes increasingly bare farther up the slope. In a few cases, water tracks seep to the surface as return flow and become rills. In order to cover the widest range of conditions, measurements were performed at multiple sites in contrasting morphologies. General slope topography and profiles were first measured using a GNSS station and a VX station (Trimble, Sunnyvale, California), geo-positioned by a survey-quality geodesic point (*x*, *y*, *z* precision of 5, 5, and 18 mm).

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Microtopographic profiles transverse to the water tracks were measured at six locations along the slope using a clinometer (1° precision) and measuring tape. A point-transect survey of vegetation was conducted along a 100 m transect (10 cm intervals), perpendicular to the water tracks, 20 m up from (and parallel to) the edge of the lake.

To describe the fine-scale morphology of the soil, five soil pits were excavated in contrasting positions across the sorting pattern and water tracks. Pit Sp-1 was in a vegetated water track near the lakeshore, pits Sp-2 and Sp-3 were in the patterned ground network, with Sp-2 slightly upslope, in a mostly bare section of the network, and pit Sp-4 was under a seeping stream emerging from a water track. A final pit, "Backslope", was also dug upslope from the patterned ground area of Sp-2 and Sp-3, outside the water track network, where a small snowdrift laid until midsummer. All pits were along a transect perpendicular to the slope, covering both a water track and an intertrack and down to the frost table. Identification and delimitation of organic matter, soil morphology, and gravel concentrations were performed in the field. Each profile was photographed and then its morphology was digitized over a mosaic of the pictures. Sediments were sampled using a 250 cm^3 sampling ring in Sp-1, allowing the measurement of volumetric soil parameters, but the high gravel concentration in other pits prevented the use of the rings, and grab samples were collected instead.

A total of 17 pairs of water tracks and intertracks were probed for active-layer depth (depth to refusal) using a manual earth auger. Triplicate measurements were performed each time. In addition to samples from the soil pits, soil from these pairs was sampled at the surface (0–5 cm depth) and subsurface (5–10 cm depth) by grab sampling. Each sample collected in the field was analyzed for water content by oven drying at 105 °C until stable mass was reached. The samples were then crushed and dry sieved for grain size analysis following a modified ASTM D6913 standard to include subsampling. Fractions of the sediments <2 mm were subsampled and were processed by lost on ignition for organic matter and carbonate content (Dean 1974; Heiri et al. 2001). Electrical conductivity and pH measurements were also conducted in the laboratory using a 2:1 water to sediment ratio for mineral soils and 5:1 ratio for organic-rich soils.

Water track hydrology

The flow and hydraulic conductivity characteristics of the water tracks were determined with in situ monitoring, point measurements, and laboratory tests. The hydrological regime of water tracks was compared to that of a rill located 20 m from a perennial snowdrift in order to evaluate its similarity with an open channel flow regime. A cut-throat flume (length, width, and throat width of 91, 26, and 5.25 cm, respectively) was installed in the seeping area just downslope of a water track, and a second one was installed in the rill. The flumes were secured by excavation and fitting them into the soil so that no water flowed underneath them. They were each equipped with a Hobo U20 pressure sensor (accuracy of ±0.14 cm) (Onset, Bourne, Masschusetts) to measure water levels (h_u, cm), which were converted to free flow discharge (Q_f, $cm^3\ s^{-1}$) with the equation

$$(1) \quad Q_f = K_f \times C_f \times h_u^{n_f}$$

where K_f is a free flow correction factor calculated from the specific dimensions of the flume, C_f is the free flow coefficient, and n_f is the free flow exponent, both of which can be extracted from tables according to flume standard dimensions (Siddiqui et al. 1996). These measurements were performed for 30 days in 2013, covering the early melt season until after peak discharge.

Hydraulic conductivity of the soil as well as flow velocity in vegetated water tracks were also evaluated in 2014 for comparison. Four flow velocity tests were performed using a salt tracer and a conductivity probe, using the slug centroid method described in Whiting

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(2005). To measure hydraulic conductivity (*k*) of the sediments, undisturbed material in the first 15 cm of soil in the water tracks and intertracks was sampled by inserting 250 cm^3 sampling rings horizontally; the samples were then analyzed using a KSAT apparatus (UMS, München, Germany) and a laboratory permeameter. Hydraulic conductivity tests in the field usually measure downward conductivity of the soil material, but by inserting the sampling rings horizontally in the soil, these tests provided the downslope hydraulic conductivity, in the direction of water flow.

All statistical analyses were performed using R 3.1.1 (R Core Team 2014). Paired *t*-tests with 95% confidence intervals were used when comparing specific water tracks with their intertracks, while unpaired *t*-tests were performed when comparing undifferentiated sets of measurements. The Shapiro–Wilkes test was used to verify normality of distribution or of paired differences, and if the data failed to pass this test even after transformation, the nonparametric Wilcoxon test was used to evaluate differences.

Results

General slope morphology

Below its rounded top, the eastern slope of Walker Hill could be differentiated into three sections with distinct geomorphic features. The upper section (>150 m a.s.l.) was characterized as a steep, 22.5°–29.5° angled slope covered with coarse glacial debris and gelifracts. This section showed little slope variation except for the occasional poorly developed nivation niches and also contained isolated fractured bedrock exposures. The middle section (150–65 m a.s.l.) had a concave morphology, with slopes irregularly decreasing downslope from 21.6° to 11°. Its uneven topography retained multiple annual and semipermanent snowdrifts. The latter had the typical characteristics of well-developed nivation hollows: coarse and bouldery backslopes followed by a small field of sorted material often overlain by snow and solifluction lobes a few tens of metres downslope of the snowdrifts. These snowdrifts (>1 m depth) were usually the only remaining snow patches a few days after snowmelt had begun and were likely to be the main contributors of freshwater to Ward Hunt Lake (Paquette et al. 2015). This section of the slope was also mainly covered by coarse glacial debris and gelifracted colluviums, but without clear bedrock exposures. The third, lowermost section was demarcated by the upper limit of the toe of the slope (65–26 m a.s.l.) corresponding to the upper limit of the marine transgression for the sector (≥62 m a.s.l.) (Lemmen 1988). This lower section contained the patterned ground formations and water tracks observed in the present study (Fig. 2*a*). It had low, steady angles between 3.5° and 9.7° and was covered with muddy gravel and sand. Snowdrifts in this section were sparse, <70 cm deep, and usually underlain by coarser material than the rest of the slope toe.

Water track physical characteristics

The water tracks stretched from 20 m to nearly 100 m long, with their length increasing toward the northern edge of their zone of occurrence. They were readily discernable from the rest of the soil because of their organic cover, which contrasted with the dominantly bare or darkened appearance of the intertrack soil (Fig. 2*c*). The survey of vegetation showed that the water tracks, as demarcated by thick moss-coated ground, covered 19.8% of the surface of the slope near the lake. The rest of the slope section was mostly dominated by black cryptogamic crust (61.5% of total cover), with rocks (5.3%), white crusts (3.4%), *Saxifraga oppositifolia* L. (2.9%), or bare ground (2.7%) as other recurrent types of soil surface. The spacing between the moss-covered water tracks averaged (±SD) 1.5 (±0.9) m along the transect. Whenever water tracks ended with a seeping section, the above ground water flowed along a rill containing pink and orange cyanobacterial mats, mosses, *Phippsia algida* (Sol.) R. Br., gravel, and cobbles (Fig. 2*d*). These seeping rills were short, and the water

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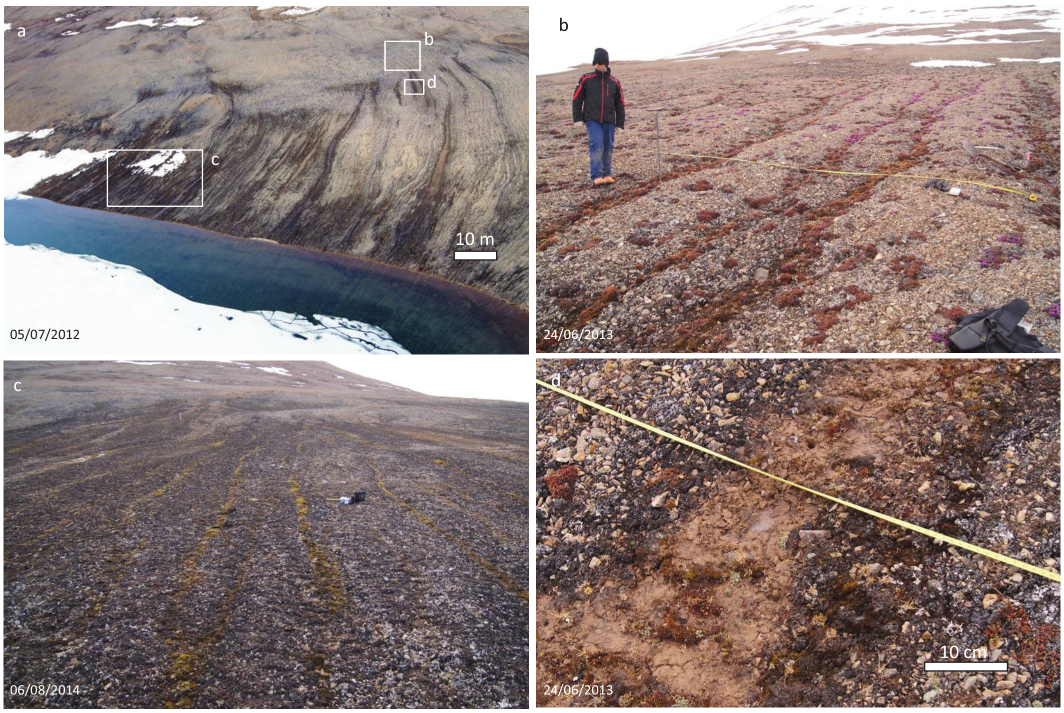
Fig. 2. Photographs of water tracks and intertracks. (*a*) Lower slope of Walker Hill and water tracks flowing and extending into Ward Hunt Lake. (*b*) Transect F–F′, located 9 m downslope of Sp-3. The transition between sorted nets and nonsorted stripes are covered with *S. oppositifolia*. Note the bare soil instead of black crusts in the intertracks. (*c*) Sp-1 site, near the edge of the lake. The contrast between the moss cover on the linear water tracks and black crust on the intertracks makes the features stand out. The bag on the picture is 30 cm wide. (*d*) Location of Sp-4 and of transect G–G′, where cyanobacterial mats covered a seepage (dry at the time of the photograph) streambed downslope of a water track, as opposed to the black crust on the edges and on the intertracks.



usually dissipated into the ground within <50 m. Other water tracks terminated by discharging into the lake, and some could be seen extending across the lake bed of the littoral zone, possibly reflecting periods of lower lake levels (Fig. 2*a*).

The mapping of a patterned ground network and the measurements of microtopographic transects showed the organization of the water tracks and their changes down the slope (Fig. 3). The network began at the upper part of the lower slope section, with sorted, elongated patterned ground. This section had irregular microtopography (transects D–D′ and E–E′), where the depressions were occupied by clean gravel and cobbles, while the highest sections possessed a sandy and muddy matrix. Downhill from this area, the nets and polygons stretched and merged into stripes. The depressions in the patterned ground (transect F–F′) were covered with *S. oppositifolia* and mosses, indicating near-surface water availability. As the stripes coalesced, seepage occurred and the microtopography was progressively gentler (transects G–G′ to I–I′), ending the striped pattern.

The physical characteristics of the moss-covered water tracks, 20 m from the edge of the lake, are summarized in Table 1. One conspicuous feature was a 10.2 ± 4.8 cm thick washed-out gravel layer of mean grain size 12.7 mm and with less than 5% sand content (mostly coarse) immediately beneath the wedge-shaped moss cover. Lifting up the moss cover revealed that this gravel layer, at the interface of the organic and mineral layer, contained free-flowing water. The intertracks were on average 4.5 cm (±3.1) (maximum = 10 cm) higher than the water tracks.

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Fig. 3. (*a*) Map of sorted nets and stripes network with locations of soil pits and of microtopographic profiles (insert). The extent of the mapped features corresponds to the "divide" of the network to the north and south and to a coarse backslope deposit to the west. (*b*) Microtopographic profiles with a 3.5:1 vertical exaggeration. The microtopography gradually becomes less pronounced downslope, and no trace of a pattern is visible in H–H′ and I–I′.

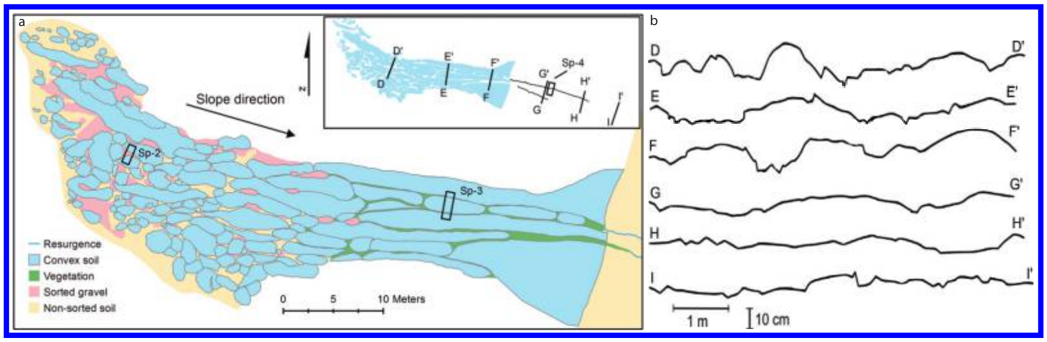

Table 1. Morphological characteristics of water tracks on Ward Hunt Island.

Characteristic	Width or depth (cm)			n
	Mean ± SD	Min	Max	
Width	29.7 ± 9.9	14.0	55	17
Organic matter thickness	6.2 ± 2.8	2.0	17	17
Gravel layer thickness	10.2 ± 4.8	0.0	>30	18
Active-layer depth (2014)	48.9 ± 7.1	32.0	61.5	17

The soil properties across the water tracks and intertracks are given in Table 2. The most striking difference was in organic matter content, which was significantly higher in the first 5 cm of the water track soils than in the intertrack, reaching 26.4% ± 3.2% compared to 9.0% ± 1.2% ($t = 5.4$, $p < 0.001$, $n = 17$). This difference was also observed at 5–10 cm depth, where the organic matter was twice as high in the water tracks compared to the intertracks. The water content was also much higher (factor of 8.3, $W = 264$, $p < 0.001$) in the water tracks than in the intertracks in the upper 5 cm of the profile, while the difference at 5–10 cm depth was less pronounced (1.9 times higher) but still highly significant ($W = 255$, $p < 0.001$). Grain-size analysis at these depths revealed a clear difference between the two locations. In the water tracks, the top 5 cm layer of the soil was almost equally composed of gravel and sand (43% and 47% of the sample weight, respectively) mixed with organic matter. It was underlain by the gravel layer noted above but also included some sand and organic matter in the 5–10 cm sample. In contrast, the intertracks were always dominated by gravel, and their surfaces contained the highest concentration of gravel: 67.8% versus 52.7% in the 5–10 cm range ($W = 280$, $p < 0.001$). There were also more fines in the 5–10 cm depth of the intertrack sections than in other locations or depths sampled (15.0% versus ≤10.0% elsewhere).

The active layer depths for water tracks and their intertracks in 2014, immediately prior to freeze-back, are shown in Fig. 4. The active layer was significantly deeper ($W = 268.5$, $p < 0.001$) in the intertracks, on average by 7.5 cm. This difference was consistent, except for a small number of measurements where local conditions, such as the presence of rocks, may have affected the measurements. The difference was smaller but still significant ($t = 3.4$, $p < 0.01$) after correcting for microtopographic differences between the water track and intertrack in order to put all measurements on the same datum: this adjusted

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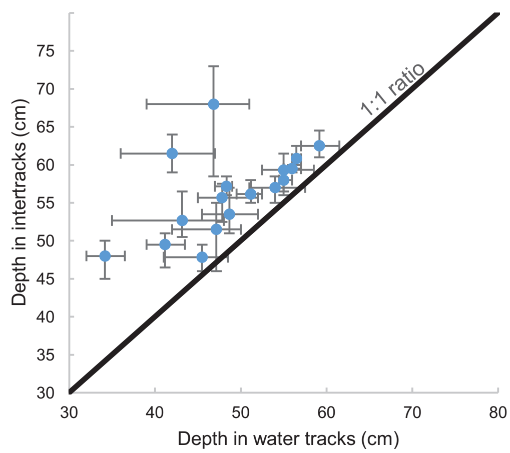
Table 2. Physical and chemical properties of water track and intertrack substrates at two depths (n = 17).

	Water track		Intertrack		*t*-test	
Properties	0–5 cm	5–10 cm	0–5 cm	5–10 cm	0–5 cm	5–10 cm
OM (% dry weight)	26.4 ± 3.2	8.3 ± 0.6	9.0 ± 1.2	4.4 ± 0.2	WT***	WT***
Carbonate (% dry weight)	3.9 ± 0.5	6.6 ± 0.6	7.9 ± 0.4	8.0 ± 0.4	IT***	IT*
SpC (μS cm^{-1})	611.5 ± 38.9	374.5 ± 29.0	487.2 ± 52.1	210.1 ± 11.7	WT	WT***
pH	7.42 ± 0.06	7.86 ± 0.05	7.76 ± 0.06	8.11 ± 0.03	IT***	IT***
GWC (%)[a]	159.3 ± 30.8	33.8 ± 7.1	19.3 ± 1.5	17.8 ± 3.6	WT***	WT***
Mean particle size (mm)[a]	1.9 ± 0.5	4.0 ± 1.0	3.8 ± 0.4	1.7 ± 0.2	IT**	WT*

Note: OM, organic matter; SpC, specific electrical conductivity; GWC, gravimetric water content; WT, water track value is greater; IT, intertrack value is greater. *significance of the *p*-value: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. All ± values are standard errors.
[a]Wilcoxon test for nonnormal data.

Fig. 4. Active-layer depth measurements in water tracks and their intertrack. Circles are the mean of triplicate measurements, while bars represent minimum and maximum values.

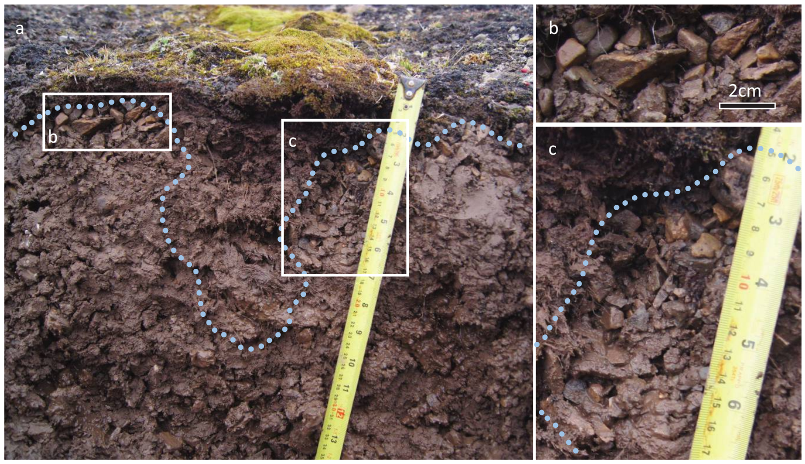


active-layer depth beneath the water tracks was on average 2.5 cm (4.6%) shallower relative to adjacent soils.

Subsurface morphology

In soil pits Sp-1 to Sp-4 (locations in Figs. 2 and 3), the intertracks had a coarse surface layer, along with varying proportions of biological soil crust and bare ground. The intertrack profiles showed no obvious structure, with the soil always composed of a gravelly, angular diamict. In contrast, the water track sections of the soil all had distinct morphologies that differed from one soil pit to the next. In Sp-1, the vegetated water track contained a wedge of fibrous organic matter associated with the moss cover and mixing with the diamict to form a gravelly, organic-rich soil (Fig. 5). On each side of the wedge, a zone of washed-out gravel marked the transition between the organic cover and the rest of the soil, and their dimensions indicated the maximum area available for free water flow. The section shown in Fig. 5*b* was located just below the organic cover and had a rectangular shape 9.5 cm wide and 3.5 cm high, while that in Fig. 5*c* followed the right edge of the wedge of organic matter, measuring 13.5 and 4 cm in its long and short axis, respectively. Summer was almost at an end at the time of the excavation of the pit (8 August 2014), which was performed around 2200 when discharge was near its lowest daily rates. Even

Fig. 5. Soil structure at Sp-1. The blue dotted line marks the separation between the wedge of fibrous organic matter and the mineral soil. Rectangles are locations of clean, washed-out gravel concentration on each side of the wedge and are magnified in Figs. 5*b* and 5*c*.



under those conditions, seepage was observed at the base of the gravel zone (Fig. 5*c*), with evidence of wetting throughout the rest of the soil profile downward.

The physical structure of Sp-2 and Sp-3 is given in Fig. 6. In Sp-2, the washed-out gravelly section was much greater than in other pits and had the form of an inverted wedge, with a width of 15 cm at the surface and 62 cm at the thaw front. The configuration of the active layer ranged from 30.5 cm at its minimum to 56 cm, as shown on the left side of Fig. 6. These properties might have been expected to favor water flow laterally from the gravel section toward the intertrack following the steepest microtopography. Instead, however, water was seen flowing at the bottom of the active layer in the coarse section only. Sp-3 covered two water tracks instead of one and showed two wedge-shaped gravel concentrations just beneath the vegetation wedges of the water tracks. Once again, the thaw front was shallower underneath the water tracks. Sp-4 and Backslope are not shown because their profiles were relatively uniform: Sp-4 showed a coarse diamict throughout the profile, while the first 25 cm of Backslope (the entire thawed region) was composed of washed-out gravel and stones.

Soil properties of the sampling pits are given in Fig. 7. Compared to the adjacent intertrack, the water track of Sp-1 had higher organic matter and water content throughout its profile, along with higher mean particle size and specific conductance and lower bulk density and pH. However, there were large variations in these soil properties, particularly near the surface, and overall, there were no significant differences between the intertrack and water track locations. In Sp-3, the mean particle size showed a large increase between approximately 25 and 50 cm in the water track. The organic matter content was also larger at the top and at 15 cm depth in the water track than it was in the intertrack, and this in turn was reflected in the higher water content of the soil.

Backslope properties show the dominance of clean, washed-out gravel in the soil profile. The sample taken just below the thaw front of at the Backslope site showed higher fine sediment content, with little organic matter. This sample also had the highest carbonate content, likely caused by the absence of wash in the frozen ground. Sp-4 also showed distinct profile properties, with grain size increasing with depth, while water content and organic matter content diminished. The 45 cm depth marked a sharp change in all

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Fig. 6. Soil structure at sites (*a*) Sp-2 and (*b*) Sp-3. Vertical axes begin at the highest point of the soil.

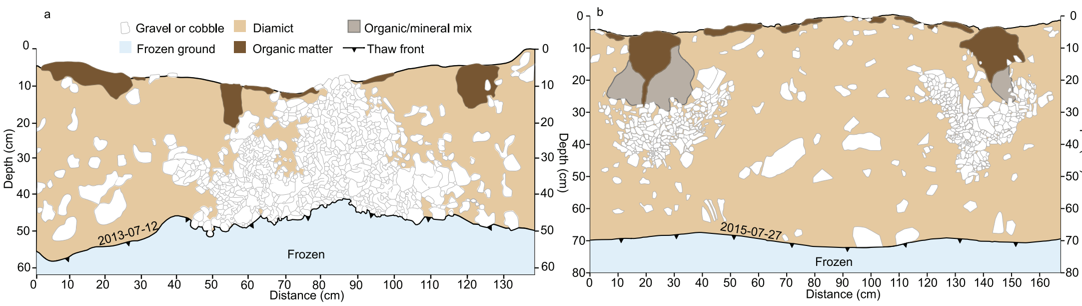
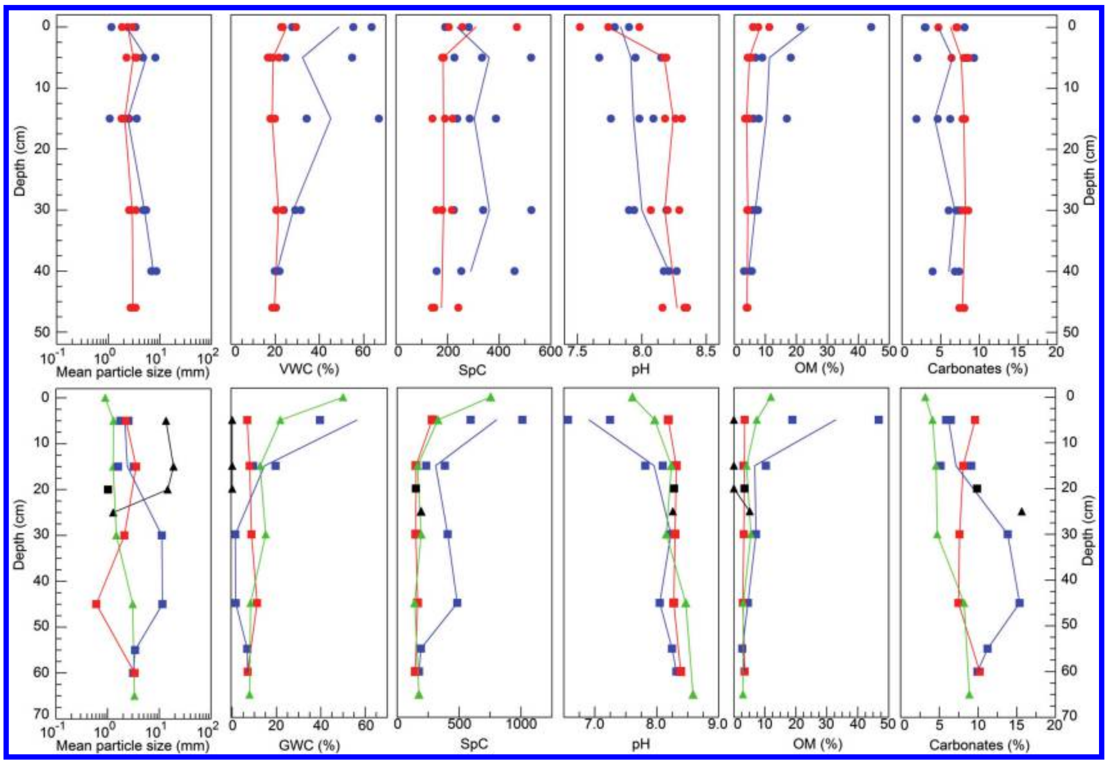


Fig. 7. Soil properties of soil pits. Points are individual samples and lines connect the means at each depth. Blue circles, Sp-1 water track; red circles, Sp-1 intertrack; black squares, Sp-2 intertrack; blue squares, Sp-3 water track; red squares, Sp-3 intertrack; green triangles, Sp-4; black triangles, Backslope site; VWC, volumetric water content; GWV, gravimetric water content; SpC, specific conductivity (µS cm−1); OM, organic matter content (% of dry weight of sediments <2 mm).

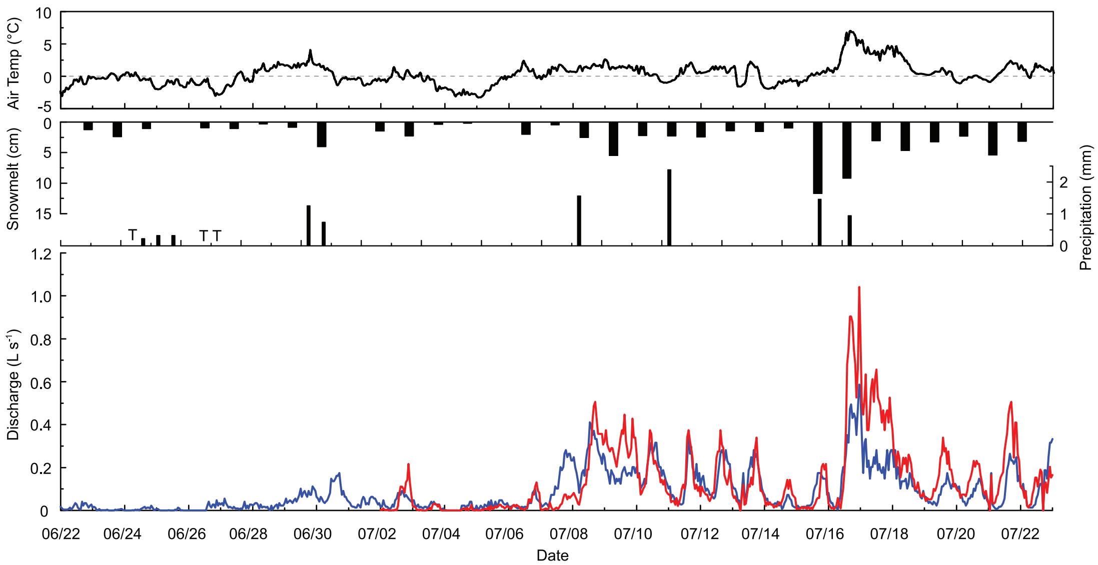


variables, with the percentage of organic, fine and sandy material as well as the SpC all dropping, while pH, gravel content, and carbonate concentrations increased.

Hydrology

Water flowed below the surface in the water track sections of the slope, while at another site on the slope, several hundred metres to the south, the water flowed at the surface in distinct rills that extended from a perennial snowdrift. Figure 8 shows the discharge measurements in a water track and one of these rills in 2013, along with snowmelt and air temperature data from the weather station. The onset of snowmelt and flow was late

Fig. 8. Air temperature, daily snowmelt (snow thickness), precipitation (T for trace), and discharge in a rill (red line) and in a seep fed by a water track (blue line) in 2013. Discharge rates responded rapidly to snowmelt, with almost no delay between the water track and the rill.



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during the 2013 summer, reflecting the cold air temperatures (Paquette et al. 2015). While the rill registered greater discharge than the water track, both exhibited a strong diurnal variation. Peak flows were attained around the same time in late afternoon in both sites, between 1500 and 1700, while low flows were usually between 0100 and 0700 in the rill and between 0300 and 0800 in the water track. Maximum discharges were recorded in both flow paths on 17 July, at midnight in the rill and at 0100 in the water track, as part of a discharge event that had begun during the afternoon of 16 July. This event lasted longer in the rill than in the water track and was followed by a return to flows similar to previous conditions after July 19.

The samples taken at the junction of the gravel and organic layer in the water track had the highest hydraulic conductivity, with values that were an order of magnitude higher than in the organic material (Table 3). By comparison, the diamict had a low hydraulic conductivity, seven orders of magnitude less than in the subsurface flow path. This low value was mostly due to the low porosity typical of gravel–fine mixtures (Dunn and Mehuys 1984). Our tracer velocity tests indicated a flow speed that was two times higher than that measured in the laboratory, with values that range within the theoretical conductivity of gravel-dominated layers (Fetter 2001).

Discussion

Formation of the water tracks and significance for slope hydrology

Linear water tracks are an important feature of the Ward Hunt Lake watershed. These landscape features correspond to the definition of nonsorted stripes (Washburn 1956), a patterned ground with regular spacing, downslope orientation, and a vegetation cover that contrasts with the relatively bare ground of the intertracks. The wedge shape of the vegetation, their width, and the concentration of stones at the surface of the soil were all consistent with this description. Upslope from these nonsorted stripes, however, the network of gravel and vegetation patches between elevated grounds was more of a hybrid between sorted (segregation of coarse and fine sediments) and nonsorted stripes.

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Table 3. Hydraulic properties of water tracks and an intertrack.

Location, type	k_s m d^{-1}	k_s cm s^{-1}	Bulk density (g cm^{-3})	Porosity (%)
WT, semi-organic	2.4 (0.62) × 10^2	2.7 (0.07) × 10^{-1}	1.29	37.9
WT, organic	4.0 (0.44) × 10^1	4.6 (0.5) × 10^{-2}	0.64	54.6
IT, diamict	2.4 (1.3) × 10^{-5}	2.7 (1.5) × 10^{-8}	1.95	25.4
WT, vegetated	5.3 (1.4) × 10^2	6.1 (1.6) × 10^{-1}	N/A	N/A

Note: k_s is the saturated hydraulic conductivity, with standard deviation in parentheses. The first two samples were measured with the ksat device, the third was measured with a permeameter, and the fourth was based on tracer tests. WT, water track; IT, intertrack.

In patterned ground, the shape of the pattern is generally affected by the slope gradient and the availability of fines (Washburn 1979). The patterns at the upper end of the water track network corresponded to a series of debris islands followed by circles or polygons, nets, and finally stripes that form the logical succession of patterned ground along an increasing slope. In this case, however, the slope did not increase along the succession; instead, it decreased from values between 5° and 17° to more steady values between 3.6° and 9.3°. The reason why the patterned grounds were better developed and became elongated downslope is still uncertain, but our observations suggest two potential reasons: a downslope decrease in winnowing and the existence of a gradient of sorting potential in the material.

The first reason, decreased winnowing, relates to soil morphology and to the organization of the hydrological network. As the inverse wedge shape of the gravel layer in Sp-2 and the complete absence of fine particles in the active layer at the Backslope site suggest, leaching of fine sediments likely accounted for most of the concentration of gravel, with this process enlarging the wedge as the thaw front progressed in spring. Sp-2 and Sp-3 exhibited a clear separation between the washed-out, coarse sections of the patterned ground and the finer grained areas in between. This distribution of sediments, with their contrasting hydraulic conductivity, indicated the preferential flow in the coarse section, as observed. The presence of a binding organic layer at Sp-3 and the slightly lower slope at Sp-1, decreasing velocities in this water track, could account for the differences between the structures of both water tracks. The network formed in the upslope part of the network as shown in Fig. 3 also likely played a role channeling water toward the vegetated water tracks. In a classic study of sorted stripes, Caine (1963) observed that most of the drainage along a network of patterned ground occurred in the coarse section of the stripes, eluviating fine material along the process. Horwath et al. (2008) also hypothesized that the coarse sandy and loamy gravel accumulation observed along vegetation and sand wedges at their site favored slope drainage but did not mention winnowing as part of the formation process. The erosion of soil particles is likely favored by decreased sediment cohesion following freeze–thaw (Dagesse 2013) or by localized high velocities caused by factors such as a steeper local hydraulic head, turbulent flow through gravel layers, or interception of the thaw front with ice lenses (Dyke and Egginton 1988). These particles may then be transported through the network until the emergence of the water track as overland flow. Leaching of fines from gravel-rich slopes is known to occur in polar deserts (Woo and Xia 1995), and evidence from Antarctica suggests that water tracks can create favorable flow conditions when sufficient flow velocities are reached, through either large enough hydraulic gradients or high conductivities (Schmidt and Levy 2017). At that point on the slope, the surface flow becomes a losing stream, dissipating water into the surrounding soils and depositing the suspended sediments along the slope. This deposition process could explain the absence of sorting in Sp-4 as well as the increasing amounts of fines and the decreasing amount of carbonates

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towards the soil surface. Similar stratigraphic evidence was found where surface runoff and seepage occurs (Woo and Steer 1986; Woo and Xia 1995) and has also been reported at another site on Ward Hunt Island (Verpaelst et al. 2017).

The second reason explaining the shape of the pattern ground is the gradient of sorting potential in the slope caused by changes in soil material, where the coarser deposits in the upslope section would be less easily sorted than the finer material downslope. Continuous eluviation (removal of material by running water) of fines at the Backslope site along with irregular slope angles would have prevented the formation of continuous and regular elongated polygons and stripes by removing the frost-susceptible sediments. Kessler and Werner (2003) showed that availability of coarse material and the sorting capacity of the soil can affect sorting and result in the formation of nets or polygons. The Goldthwait (1976) chart classifies patterned ground transitions according to the relation between grain size fraction <0.074 mm and slope gradient; according to this classification, the soils at Sp-2. Sp-3, and Sp-4 would possess the grain size and slope for the sorted stripes category, while Sp-1 soils would be at the transitional boundary between stripes and nets and the Backslope would fall into the nonsorted category. A sorting potential gradient could therefore partially explain the difference in patterned ground shape between these areas. While the accumulation of gravel or stones at the interface of peaty layers has been previously observed in the Low Arctic (Nicholson 1976) and High Arctic (Horwath et al. 2008), the origin of this feature is not clear, and both studies attributed it to differential frost heave. At Ward Hunt Island, the stones showed no evidence of preferential vertical orientation, which would be expected in any periglacial concentration of rocks by mass movement and sorting (Watson and Watson 1971; Washburn 1979; Van Vliet-Lanoë 1991). The higher organic matter content measured at all depths in Sp-1 and Sp-3 and the high gravel content present at the surface in all intertracks suggest, however, that some freeze–thaw sorting occurs. This process can be responsible for carrying organic matter to depths and burying it, and frost-pushing and pulling may create a gravelly soil surface (Mackay 1984; Hallet and Prestrud 1986; Bockheim and Tarnocai 1998; Bockheim 2007; Horwath et al. 2008). Whether the vegetated water tracks were initiated by eluviation or by sorting remains unresolved, but a case can be made for the latter as the starting point because of the general appearance of the network.

The genesis of water tracks on Ward Hunt Island contrasts with their formation process at Imnavait Creek, Alaska, where the water tracks are interpreted as rudimentary channels that never completely developed due to the restricting effect of permafrost on soil erosion (McNamara et al. 1999). For the Ward Hunt Island water tracks, a combination of periglacial and azonal processes caused the formation of a drainage network that was not linked to the formation of a classical drainage network. The formation process for these water tracks resembles that for soil pipes, except for their retention of a gravel lag because of the coarse nature of the parental material. Soil pipes are usually initiated by eluviation at the peat–soil interface, where the difference in conductivity between two materials favors the erosion of the finer, less porous material (Jones 1971). On permafrost slopes, a shallow thaw front and the presence of thick organic mats create ideal conditions for high-velocity flow at and just below the interface of the organic and mineral layers (Carey and Woo 2000). Our hydrographic comparison of a seeping water track with that of a rill shows that the behavior of both channels were similar, responding rapidly to snowmelt by exhibiting a strong diurnal cycle and receding quickly when temperatures or insolation dropped. Such dynamics are typical of surface flow on polar desert slopes during snowmelt periods (Woo and Steer 1983). The registered flow velocities, the rapid response of the hydrograph to input of meltwater from the upslope snowdrifts, and the limited storage in the surrounding soils make the water tracks on Ward Hunt Island behave more like a rill than simply a zone of preferential soil water flow. This is also the behavior proposed by Woo (2012, p. 245) for sorted stripes, but it differs from the behavior of the water tracks in Imnavait (saturation excess flow up to 14 L s^{-1}, but usually less than 1 L s^{-1}; McNamara et al. 1998) and in the Antarctic Dry Valleys (groundwater flow averaging 5.4×10^{-3} L s^{-1}; Levy et al. 2011).

The maximum difference between the measured hydraulic conductivity of water tracks and intertracks at Ward Hunt Island was seven orders of magnitude; this shows that intertracks play a negligible role in groundwater flow within the studied slope section. Soil pipes regularly become the dominant flow pathway in nonpermafrost environments, greatly affecting the hydrographic characteristics of small catchments (Uchida et al. 1999), and can even account for 100% of total runoff down slopes during precipitation events (Uchida et al. 2005). Our observations show the strong, controlling relationship between patterned ground and slope hydrology, a link rarely highlighted in periglacial regions. This type of landscape feature is widely distributed throughout the vast landscapes of the High Arctic, and geomorphological processes involved in the formation of patterned ground are likely to play a central role in the establishment of drainage patterns. Although strict nomenclature is not always respected, similar links have been established in periglacial landscapes. Woo et al. (1994) witnessed rapid flow through blockstreams and stone stripes, where alpine conditions (coarse sediment, steep slopes) favored free subsurface flow. In a study of rill flow and erosion in polar desert conditions, Wilkinson and Bunting (1975) identified flow through stone stripes as an important provider of water to rillwork. Hodgson and Young (2001) measured a three order of magnitude increase of hydraulic conductivity between the top of frost mounds, composed mainly of fine-grained material, and the low-lying gravelly channels in between the frost mounds. Areal weighting of these features modified their modeled groundwater flow output by 28%–48% as opposed to a general calculation of groundwater flow. Quinton et al. (2000) also measured a similar scale variation of soil hydraulic properties between earth hummocks and interhummocks of the Arctic tundra, where the relative contribution of interhummock flow reached upwards of more than 99% of the total subsurface flow on the studied slope sections. In the case of Ward Hunt, surface conditions are closer to polar desert or alpine environments than Arctic tundra, and hydraulic properties do not depend on the presence of living peat but rather on sediment properties and organization. Nonetheless, at Ward Hunt Island, the ubiquity of water tracks on the slopes and the presence of multiple snowdrifts upslope imply that most of the meltwater reaching the lake from the snowdrifts of Walker Hill transits through patterned ground as preferential subsurface flow.

Thermal role of running water

On Ward Hunt Island, the active-layer depth of water tracks was consistently and significantly shallower than in intertracks, on average by 7.5 cm (13%). A similar behavior where shallower thaw occurred in preferential flow zones has been reported in cold-room simulations when air temperatures were higher than water temperatures (Veuille et al. 2015). The dominant paradigm in permafrost environment is that running water has a warming effect on the active layer because of convective heat transfer to the underlying ground. For instance, running water can initiate thermokarstic features such as thermo-erosion gullies (Fortier et al. 2007; Bowden et al. 2008), thermo-erosional niches (Kanevskiy et al. 2016), or retrogressive thaw slumps (Burn and Lewkowicz 1990) and can damage buildings, roads, and other infrastructure by increasing the active-layer depth (de Grandpré et al. 2012; Zottola et al. 2012). In the polar desert water tracks of Taylor Valley, Antarctica, the active layer was more than twice as deep as in the rest of the slope (45 versus 19 cm; Levy et al. 2011), while in Alaska tundra, it was over 50% greater than in intertrack soils (Hastings et al. 1989). A combination of factors prevented running water from preferentially thawing the

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active layer in the water track on the slopes of Ward Hunt Island. Firstly, the cold air temperatures and the short residence time of water through the slope allowed little opportunity for the flowing water to warm up. This water came from snowdrifts, and it entered the hydrological network at or near 0 °C, reducing the amount of heat available for advection. Secondly, the structure of the water tracks kept water moving near the surface of the soil, preventing effective thermal exchange with the thaw front and acting as a buffer for conductive exchanges by cooling the soil near the surface. The structure of the water track thus created a two-layer system, with the near-surface layer dominated by convective heat transfer and setting the boundary conditions for the conductive heat transfer in the deeper soil column. Thirdly, the thermal conductivity (k) and the heat capacity ($C\rho$) of the porous peat or gravelly layers created different conductive heat transfer conditions than in the regular soil. Calculation of these parameters was done using the following values: our data for porosity and density, parameters from Farouki (1981, pp. 12 and 42) for $C\rho$ in soils and peat as well as k for gravel, equation 2.5-12 and fig. 2-28 in Andersland and Ladanyi (2004, p. 46–51) for k values in the soil and peat respectively, and average values of Schön (2004, p. 373) for $C\rho$ in limestone gravel. Assuming saturated conditions, the peat, gravel, and intertrack had $C\rho$ values of 2.84, 2.86, and 2.50 J g^{-1} K^{-1}, respectively, and k of 0.25–0.4, 1.79, and 3.24 W m^{-1} K^{-1}. Thermal conductivity is therefore much higher in the intertrack, while heat capacity is only slightly lower in the intertracks. These differences between water track and intertrack near-surface thermal properties were enough to prevent the heat conduction in the water tracks, at least early during the period when the thaw depth was still shallow. This thermal behavior is common in patterned ground, which often exhibit thicker thaw penetration under the finer or barren sections (Shilts 1978; Mackay 1980; Van Vliet-Lanoë 1991).

Water tracks in the High Arctic

Water tracks have been described at only a few locations with most information from either the North Slope of Alaska or the McMurdo Dry Valleys, Antarctica. The observations from these two contrasting landscapes (Arctic tundra versus polar desert) illustrate how water tracks can vary in morphology and functioning (Table 4), but all studies to date agree on the dominant role that water tracks can play in headwater basin hydrology (Kane et al. 1991; McNamara et al. 1997; Levy et al. 2011). The water tracks of Ward Hunt Island also played such a role. They did not carry water across the entirety of the slope but were important for rerouting that water and concentrating it in highly conductive soils. They began near the front of every snowdrift where patterned ground and washed-out deposits were observed. Figures 9*a* and 9*b* show the front of a nivation hollow similar to the "wetlands" described in Woo and Young (2003) and a patterned ground network on Ward Hunt Island, with their vegetated water tracks. The water tracks in Fig. 9*a* further fed into a block stream but in other cases, where the slope angle permitted, led to solifluction lobes. In all cases, water was channeled underground and the groundwater flow velocities were controlled by these features.

In addition to the reported occurrences mentioned above (Wilkinson and Bunting 1975; Woo et al. 1994), similar features have been observed in other areas of the Canadian Arctic, for example, on southern Melville Island (Cape Bounty, 74.94°N, 109.61°W) and near Resolute Bay on Cornwallis Island (74.73°N, 94.96°W) (Figs. 9*c* and 9*d*), near a site where polar desert hillslope hydrology was extensively studied in the early 1980s (Woo et al. 1981; Woo and Steer 1982, 1983, 1986). In both of those locations, water flow is likely to occur preferentially through the coarse section of patterned ground and to exit the soil at the break of slope. There was also a small alluvial fan showing evidence of recent sedimentation in a small resurgence downslope of the site in Fig. 9*c*, demonstrating the potential of the

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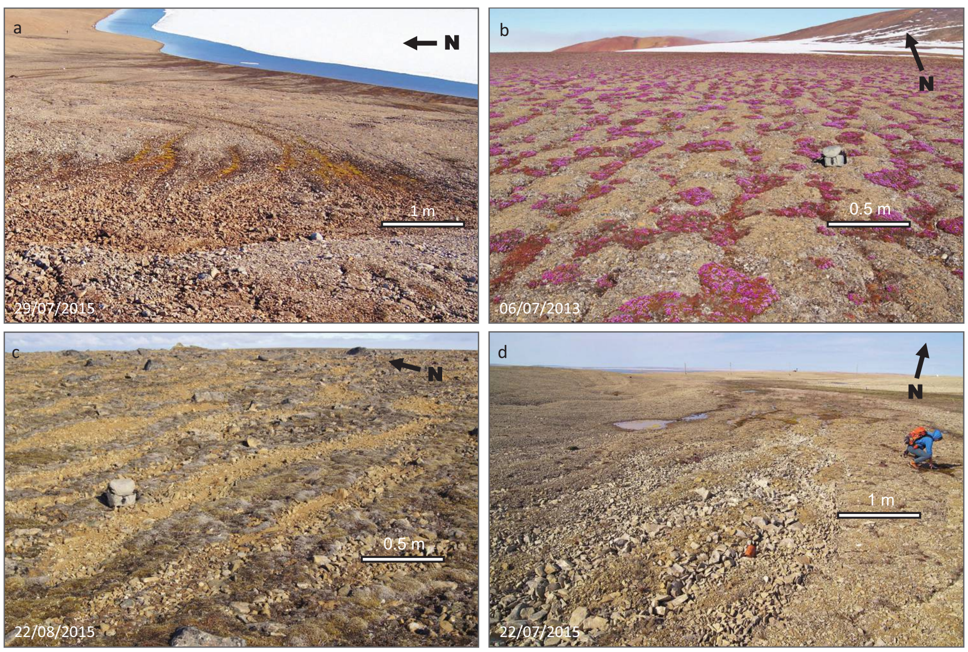
Table 4. Morphology of water tracks at three sites in the polar regions.

Site	Width (m)	Length (m)	Spacing (m)	Reference(s)
Imnavait Creek (Alaska)	5–20	~250	10–20	Chapin et al. 1988; Stieglitz et al. 2003
Taylor Valley (Antarctica)	1–3	200–1900	nd	Levy et al. 2011
Ward Hunt Island (High Arctic Canada)	0.2–3	<100	1–2	This study

Note: nd, no data provided.

Fig. 9. (*a*) Patterned ground and water tracks at the front of a nivation hollow on Ward Hunt Island feeding into a block stream (not pictured). (*b*) Water tracks on gently sloping terrain. The high gravel and organic matter content allowed water to drain efficiently in the coarse section of the patterned ground. (*c*) Patterned ground on sloping terrain on Melville Island, where the very coarse, stony sections were devoid of fines and were covered by vegetation (moss), giving an unsorted appearance. A small fan of recently deposited sandy sediments was observed downslope, indicating both a channelled flow and fine sediment removal. (*d*) Sorted patterned ground on Cornwallis Island followed the typical elongation sequence along an increasing slope angle. Water can be seen seeping farther downslope at the junction of multiple stripes.



underground network for soil erosion. These small-scale features strongly influence hillslope hydrology and water quality by rerouting flow and by supplying fine sediments to downslope soils, streams, lakes, and wetlands. The presence and properties of patterned ground on sloping terrain, whether it is sorted or nonsorted in appearance, are likely to have a controlling effect on the hydrologic properties of unincised hillslopes in permafrost landscapes.

Conclusions

Water tracks are a common feature of high-latitude environments, but their characteristics differ greatly among regions. Our study at Ward Hunt Island in a High Arctic polar desert catchment describes a new geographic setting for such features. The water tracks in this catchment were initiated by the combination of sorting processes linked to

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patterned ground formation and of fine material eluviation. They were part of a regularly spaced network of patterned ground acting as small-scale watersheds, channelling snowmelt water down the slope in highly conductive gravel layers. In addition to increasing the velocity of groundwater transfer from snowbanks to the lake, they were also a mechanism of underground erosion and sediment transport. They were widespread along low-angle slopes and collected meltwater from snowdrifts and were therefore the dominant flow paths for the water traveling downslope to the lowlands. The water tracks were characterized by soil conditions of increased water and organic matter content, lower pH, and higher dissolved solid concentrations. These hydrological features also had a thermal effect by cooling the near surface with fast-flowing snowmelt water, thereby restricting the extent of active-layer deepening.

Some uncertainties exist on the definition and role of water tracks in the periglacial landscape. As shown here, water tracks can possess different characteristics and thermal behaviors according to their morphology and location. Their formation can be the result of multiple processes, and the origin of water tracks may vary according to local conditions. Our results show that patterned ground can play a controlling role in slope hydrology by forming water tracks that greatly modify soil properties, ground thermal regime, and drainage pathways.

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