Hillslope hydrological linkages: importance to ponds within a polar desert High Arctic wetland

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ABSTRACT

Arctic wetland environments are considered to be sensitive to ongoing climate change but they have received limited attention despite their ecological importance. To understand and quantify better the hydrologic processes which are leading to the sustainability and demise of High Arctic ponds, a water balance framework was employed on several ponds situated in two broad geomorphic areas near Creswell Bay, Somerset Island (72°43′N, 94°15′W). These ponds are also linked to an upland area through a range of linear features: stream, late-lying snowbeds and frost cracks. This study assesses the importance of these features with respect to the sustainability of these wetland ponds.

A pond's position in the moraine landscape was important in determining its connectivity to a nearby stream and late-lying snowbed. Close proximity to a stream draining a large upland snow-covered catchment ensures steady water levels during the snowmelt period. Once discharge slows, a late-lying snowbed continues to supply the pond and others nearby with meltwater. The deeply thawed, sandy coastal zone is characterized by frost cracks, which contribute to the patterned ground of this wetland zone. These cracks, when situated downslope of ponds, function primarily as 'sinks' and serve to deprive small and medium-sized ponds of water during dry periods, often leading to their desiccation.

Key words | High Arctic wetland complexes, hydrologic linkages, permafrost landscape, polar desert environments, sustainability

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INTRODUCTION

High Arctic wetlands are important ecosystems in Northern Canada, given their ability to store, regulate, and cleanse water flow. They provide homes and resting grounds for northern fauna and migratory birds. While our understanding of small, patchy wetlands existing in polar desert environments has been improved recently (e.g. Woo & Young 2003), our understanding of extensive wetland systems in polar oasis and polar desert regimes is still limited (e.g. Woo & Guan 2006).

Various types of patchy wetlands exist and are governed by different aspects of topography, hydrology, vegetation and frost conditions (Woo & Young 2006). Through surface depressions some wetlands are able to capture and retain sufficient quantities of spring snowmelt, maintaining a prolonged saturation long after snowmelt. Other wetlands have hydrologic linkages to late-lying snowbeds, streams and subsurface ground ice melt. These sources of water are critical in sustaining these wetlands during short-term shifts in climate (warm, dry summers) but are themselves vulnerable to shifting climatic conditions, particularly the loss of late-lying snowbeds and near-surface ground ice supplies during persistent warm summers. Woo & Guan (2006) recently investigated the hydrology of tundra ponds existing in a polar oasis environment (warm/dry). They found that meltwater inputs from the surrounding landscape were important in replenishing ponds during a high

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snow year but this role diminished during a year with little snow. The tundra thaw ponds instead relied on late summer rains to rejuvenate water levels to near snowmelt levels.

It has recently been suggested that climate change will influence numerous hydrological and ecological processes in wetlands (e.g. Bridgham *et al.* 1995; Rouse *et al.* 1997; Prowse *et al.* 2006). In fact, it has been documented that ponds and lakes are disappearing in Alaska and Siberia in response to recent climate warming (Fitzgerald & Riordan 2003; Hinzman *et al.* 2005; Smith *et al.* 2005). Alterations in water movement due to climate change will impact on the delivery of carbon and nutrients to ponds, ultimately influencing their productivity levels and ecology. Limited understanding about the hydrology of larger wetland complexes found in the High Arctic islands makes it difficult to predict how these systems will sustain themselves under a changing climate (Woo & Young 2006).

In this study we examine the role of different modes of lateral water inflow into a low-gradient wetland from adjacent hillslopes and uplands and discuss their importance in the sustainability of a suite of ponds situated here. These linear features can take a variety of forms: streams draining uplands, meltwater from late-lying snowbeds, and frost cracks which can channel water from hillslopes into wetlands and/or capture water back from ponds (reversal of flow), thereby depriving ponds of water during drought conditions. A sound understanding of the interactions between wetland ponds and upslope linkages is critical as we begin to anticipate how High Arctic wetland systems will respond to future climate warming.

STUDY AREA

The study occurred within an extensive, low-gradient wetland lying south of Creswell Bay on Somerset Island (72°42′N 94°15′W). The area can be described as having a polar desert climatic regime (cool/wet) comparable to Resolute Bay, Cornwallis Island about 100 km to the north. Here a government weather station exists. The study spanned two seasons: May to mid-August 2005 and May to late July 2006. While three study sites were selected within this glacial till terrain, only two are discussed here (Figure 1).

The Moraine site contains lakes and ponds that formed as a result of glacial action, remnants of ponds formed behind an ancient lagoon and ponds likely created by thermokarst action (Brown & Young 2006). Here two ponds were selected, one fed by a late-lying snowbed and the other fed by a stream and a late-lying snowbed (Table 1 and Figures 2 and 3). The Coastal site with numerous ponds and lakes evolved over time, being subjected to continual isostatic rebound. It contains very distinctive hydrological features, notably frost cracks, running both horizontally and linearly throughout the area. One medium-sized pond with a frost crack running beside it is discussed in detail in this study (Table 1 and Figures 2 and 3). Supplemental pond information (one small, one large pond) is included.

METHODOLOGY

Snow

Snow comprises a large percentage of the annual precipitation in High Arctic regions and seasonal snowmelt remains one of the most important sources of water to wetland systems and consequently to ponds (Young & Woo 2004). At the end of the winter period, a snow survey at each pond site (see Woo 1997) was conducted to derive the water content of the snowpack in water equivalent units (mm). A series of transects ($n = 6$) were laid across each pond and surrounding catchment and snow depth was taken every 2 m with a metric ruler or a longer snow rod if the snow depth > 1 m. Snow density was taken at three to four locations along each transect with a Meteorological Survey of Canada (MSC) snow corer and then averaged. Snow ablation lines were installed to measure daily lowering of the snow surface, which was converted into water equivalent units using the surface snow density (Heron & Woo 1978). Snowmelt was also estimated with a snowmelt model described thoroughly by Woo & Young (2004). Young & Abnizova (2005) had previously applied this snowmelt model to this wetland site in 2004 and found it worked well. Once the snowmelt season ceases, patches of late-lying snow often remain in the lee of slopes, these features being common in these wind-swept environments (Young & Lewkowicz 1990). One of these late-lying snowbeds persisted adjacent to one of the study ponds and a detailed

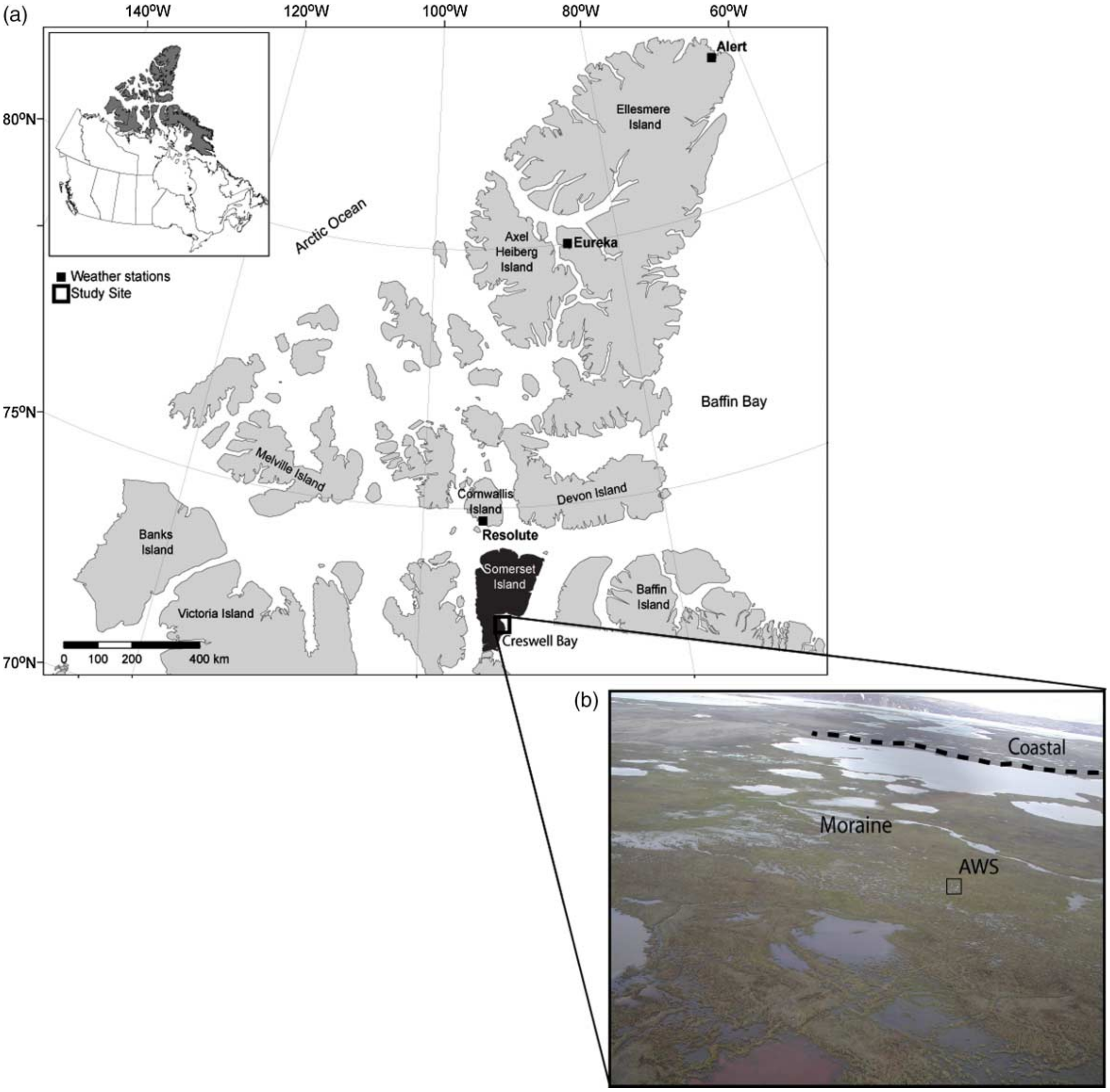

Figure 1 | Location of the study area south of Creswell Bay (a) and a photograph of the general study area, August 2004 (b). The main Automatic Weather Station (AWS) is indicated and a dashed line separates the Moraine wetland zone from the Coastal area.

snow survey was made of it. Rate of retreat was monitored daily along 11 transects and photographs were taken weekly to track shrinkage of the snowbed.

Water balance framework

To better understand the hydrologic dynamics of ponds and their sustainability in a polar desert climatic setting, a detailed water balance framework was used during the summer seasons of 2005 and 2006. Here

$$\Delta S = P - E \pm Qs, \qquad (1)$$

where ΔS is used to describe the change in storage (here we consider volume of water in the pond), P is precipitation: the sum of snowfall (Sn) and rainfall (R), E is evaporation loss and Qs is inflow or outflow to the pond (both surface and subsurface) (Woo *et al.* 1981). If lateral flow is absent, then the water storage can be estimated as the difference between vertical water fluxes (Woo & Guan 2006):

$$\Delta S_{(P-E)} = P - E. \qquad (2)$$

The change in water storage ΔS was estimated by examining pond stage dynamics on a daily basis using (1)

Table 1 | Location and general characteristics of study ponds

	Moraine zone		**Coastal zone**
Soil type and texture (%)	Organic layer (ca. 140 mm thick) overlying sandy-silty materials (fine sand (0.125 to 0.25 mm, 80%) and silt (<0.125 mm, 20%)		Organic matter (<10 mm thick) overlying coarse sandy materials (>0.25 mm, 100%)
Study site	Snowbed-fed pond	Stream and snowbed-fed pond	Frost crack pond
Hydrological linkage	Late-lying snowbed	Stream and/or late-lying snowbed	Frost crack
UTM coordinates easting//northing (National Topographic Database, Map Series 58B11)	458700//8067248	458450//8067386	458712//8067948
Surface area (m^2) 28 June–1 July 2005	441	149	1386
SWE (mm)			
2005	280	148	163
2006	255	115	122
Mean water depth (m) 28 June–1 July 2005	0.22	0.34	0.22
Mean frost table depth (m) 12 August 2005	0.65	0.50	0.83
Mean volumetric soil moisture ± standard deviation, sample size (n)			
2005	44.1% ± 11.1 ($n = 90$)	53.2% ± 11.0 ($n = 92$)	32.2% ± 2.9 ($n = 102$)
2006	41.2% ± 14.8 ($n = 6$)	51.8% ± 15.6 ($n = 10$)	40.3% ± 2.7 ($n = 11$)

water level recorders (WLRs) placed at the center of medium ponds; (2) by frequent water table measurements (every second day) and (3) weekly monitoring of pond expansion and shrinkage. Water tables were monitored in a series of perforated and screened PVC wells (diameter 51 mm), which were installed down to the permafrost table in 2004 (ca. 600 mm). In areas where water wells could not be easily inserted (e.g. frost cracks), wooden dowels allowed surface water tables to be assessed. Owing to detailed data collection, water balance components are evaluated in detail for the stream, snowbed-fed and the frost crack ponds. As required, additional information from other studied ponds is provided (e.g. small and large frost crack ponds).

Summer precipitation, P, was measured with a tipping bucket raingauge connected to a CR10X datalogger at the main automatic weather station (AWS) (Figure 2 and Table 2). Manual raingauges were placed near each study site and regularly checked. The rainfall record is used to estimate the amount of precipitable water that is available to the pond's basin (catchment and open surface).

Evaporation, E, was evaluated using the Priestley–Taylor approach which has been found to work well in a range of arctic environments (e.g. Young & Woo 2003; Woo & Guan 2006). Its robustness was recently evaluated in a recent study where it was found to perform surprisingly well in comparison to other techniques (Rosenberry *et al.* 2004). In our study, α, the Priestley–Taylor coefficient, was set equal to 1.26, which is a value widely accepted for saturated surfaces. Data required in the calculation of E was obtained from both the main and roving automatic weather stations and included such variables as: net radiation ($Q*$, W/m^2), ground heat flux (Q_g, W/m^2), air temperature (T_a, °C), pond water temperature (T_p, °C), substrate temperature (T_s, °C) at 1 and 10 cm, relative humidity (RH, %) and wind speed (U, m/s) (see Table 2). In order to consider the changing surface area of open water in the pond, pond water

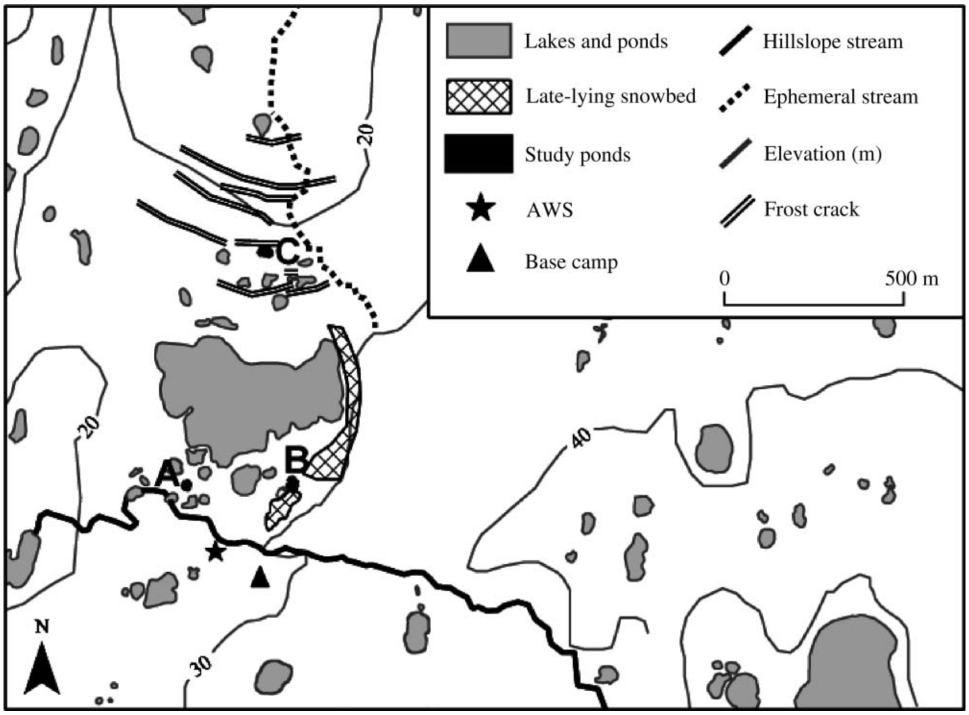

Figure 2 | Site map and location of the study ponds: snowbed-fed pond (A), stream and snowbed-fed pond (B) and frost-crack pond (C).

shrinkage and expansion was monitored routinely and daily evaporation and precipitation were expressed in volumetric units following Woo & Guan (2006). Here

$$E = E_w A_w \tag{3}$$

where E (m^3) is total evaporation from the pond, E_W is evaporation from water (m) and A_W is the pond's respective area (m^2). Both stations also provided climate data to estimate snowmelt and ground thaw at the pond sites.

To identify the subsurface connectivity of the coastal pond to the adjacent frost crack, groundwater flow (Q_s) per unit width (m^3/d) was determined using the following equation:

$$Q_s = k\,ds(dh/dx) \tag{4}$$

where k is the saturated hydraulic conductivity (m/d), dh/dx is the hydraulic gradient estimated elevation differences of the water table in the adjacent wells (pond, frost crack) and ds is the thickness of the saturated zone (m), obtained daily as the elevation difference between the frost and the water table positions (Young *et al.* 1997). Water and frost tables were monitored regularly on a weekly basis. To measure location of the frost table a metal rod was pushed into the ground until the frozen surface was reached. Hydraulic conductivity estimates (after Luthin 1966) were carried out at each site at least once per season. Near-surface soil moisture (0–60 mm) in the pond catchment was measured with a Theta probe and confirmed with direct volumetric soil moisture measurements. These data quantified the degree of saturation in the pond catchment, which is important in hydrological studies of northern wetlands (Rouse *et al.* 1997).

Moraine stream input monitoring

The stream draining the upland area (7 ha catchment, ca. 45 m a.s.l) emptied into the moraine wetland area (ca. 28 m a.s.l). The stream carved a well-defined channel for about 100 m within the wetland and then it spilled into a wet meadow zone. Stream discharge at the entry of the wetland complex was monitored in both years using the area–velocity approach. Stage measurements together with current metering allowed discharge to be determined. In 2005, no water level recorder was available, so only two to three daily estimates of discharge were available. In 2006, water level in the stilling wells was monitored continuously

Figure 3 | Photographs of the study ponds showing (a) snowbed-fed pond; (b) stream and snowbed-fed pond; (c) snowbed link to the frost crack and (d) frost crack pond. Linear features (late-lying snowbed, frost crack) are also indicated.

with Ecotone water level recorders. During high flow periods, the floatation approach was used to determine stream velocity (Dunne & Leopold 1978). Again, two to three discharge measurements were made daily during the high flow period and less frequently during low flow.

Coastal frost crack monitoring

To estimate the hydrological role played by frost cracks in pond sustainability, one frost crack located in close proximity to the study pond and two additional frost cracks beside smaller- and larger-sized ponds were also monitored during 2005 and 2006. The selection of the frost cracks was associated with their proximity to the observed ponds at the Coastal site and included both minor (1 m in width) and major cracks (up to 2 m in width). Monitoring consisted primarily of regular measurements of water and frost tables. Finally all sites were surveyed in July 2005 with a Leica Total Survey System.

RESULTS AND DISCUSSION

Climatology

Weather conditions near Creswell Bay in 2005 and 2006 were very similar to those of Resolute Bay (see Figure 4), confirming a polar desert climate designation (Woo & Young 2003). Mean temperature at Creswell Bay was slightly higher than at Resolute Bay in 2005 (3.7°C vs. 2.7°C) and in 2006 (2.8°C vs. 1.5°C). Summer precipitation was slightly lower in 2005 (47 mm) than in 2006 (68 mm) and there were differences in the timing of rainfall. Overall, a monthly comparison showed that rainfall was greater in July 2005, but higher in June 2006. Winds were generally from the west and averaged 3.6 m/s. End-of-winter snowcover at the main weather station was 162 mm of snow water equivalent (SWE) in 2005 and only 108 mm in 2006. Snowmelt was delayed in 2006 due to poor weather conditions and steady snowmelt did not commence until 12 June and lasted for 10 d (Figure 4). Growing degree-days

Table 2 | Climatologic and hydrologic instrumentation

Variable/parameter	Instrument	Location and height (m)	Field accuracy
Net radiation (Q^*, W/m^2)	Kipp and Zonen Net Radiometer*, NR Lite*	RWAS (1 m)	± 5%
	Middleton Net Radiometer*	AWS (1 m)	± 5%
Incoming ($K\downarrow$, W/m^2) and outgoing solar	Kipp and Zonen Pyranometer* CMP21	AWS (1 m)	± 5%
radiation ($K\uparrow$, W/m^2)	LI-COR Pyranometer LI-200*	RAWS (1 m)	± 5%
Ground heat flux* (Q_g, W/m^2)	Middleton Heat Flux Plate*	AWS and RAWS (0.05 m)	± 3%
Wind speed (U, m/s)	R.M. Young 05103 Wind Monitor	AWS (1.5 m)	± 0.2 m/s
	Davis Anemometer 7911	RAWS (1.5 m)	± 5%
Air temperature (T_a, °C) and relative humidity (RH, %)	CSI Probe	AWS (1 m)	± 2°C and 5%, respectively
Air temperature (T_a)	StowAway® TidbiT®	RAWS (1 m)	± 0.2°C
Water temperature (T_w, °C)		Pond water	± 0.1°C
Soil temperature (T_s,°C)	Type T Thermocouples	Near-surface soil (0.01 and 0.05 m)	± 0.1°C
Rain (R)	RG600 Tipping-bucket raingauge	AWS	± 0.25 mm
Water table (WT)	Water table recorders	Pond	± 2 mm
	Manual water beeper	Pond	± 2 mm
Surface flow velocity	OTT C2 (OTT)*	Input stream	± 5%
	Pygmy Meter*		± 5%
Soil moisture	ThetaProbe Sensor ML2x (DeltaT)	Pond catchment	± 1%
Elevation	Lecia Total Survey Station	Pond basin	± 1%

*Instruments were calibrated prior to going in the field. AWS and RAWS refer to the main and roving automatic weather stations.

were greater in 2005 (187) than in 2006 (102) when the same time period was compared.

Hillslope linkages

Single: moraine zone – a late-lying snowbed-fed pond

This snowbed-fed pond is located near the lee of a slope and receives more snow than exposed ponds (280 mm of SWE in 2005 vs. 255 mm in 2006). Deeper snow here delayed snowmelt until 21 June 2005 and 24 June 2006. Snowmelt persisted here for 14 d in both years. Figure 5 indicates that water tables remained stable in both years (189 ± 19 mm in 2005 and 175 ± 35 mm in 2006) largely due to steady water contributions from the melting late-lying snowbed during favorable weather conditions (sunny, warm periods) and episodes of significant rainfalls (6.6 mm from 2–6 August in 2005). Soil moisture in the adjacent catchment was also high, varying between 32 to 62% in both years due to prolonged meltwater contributions (Table 1). However, some water loss from the pond did occur as the snowbank and water supplies diminished.

Young & Woo (2003) have previously shown the importance of late-lying snowbeds in providing meltwater to downslope patchy wetlands long after the seasonal snowmelt has ended. They noted that these snowbeds buffer wetlands from variable climatic conditions, especially during warm, dry summers. However, snowbeds are also vulnerable to shifts in climate and can shrink dramatically during warm, dry summers (Woo & Young 2006). Future climate warming may see the disappearance of these features along with their ability to sustain nearby ponds and their adjacent wet meadows. Brown & Young (2006) used historical air photos to show that, in the past, ponds

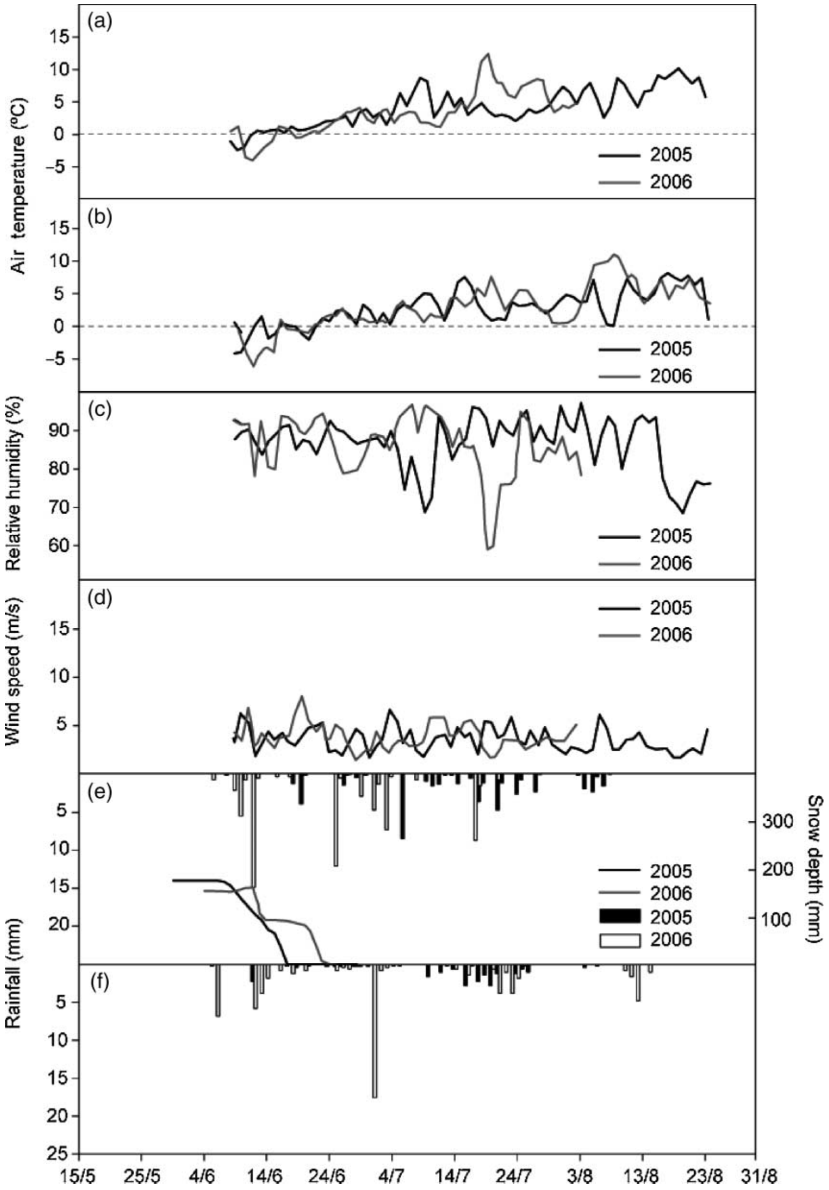

Figure 4 | Seasonal pattern of mean daily air temperature at (a) Creswell Bay; (b) Resolute Bay; (c) mean daily relative humidity; (d) mean daily wind speed: (e) daily total snowmelt and precipitation at Creswell Bay; and (f) daily total precipitation at Resolute Bay. Note: data collected at Creswell Bay were not complete in 2006 (data extend from 1 June to 26 July only).

disappeared from a nearby rocky landscape when adjacent late-lying snowbeds also disappeared.

Multiple: moraine zone–stream-fed and late-lying snowbed-fed pond

Evaluation of the water balance components of a second moraine pond demonstrated the importance of multiple water sources in this wetland system (Table 1 and Figure 6). Initially, linkage of the pond with the upland stream contributes to elevated water levels during the spring flood (Figure 3(b)). Large amounts of end-of-winter snow in 2005 in comparison to 2006 (Table 1) generated high stream discharge, resulting in significantly increased pond volumes during snowmelt (Figure 6). Once snowmelt waters are drained from both the lowland and upland, the pond loses its connectivity with the stream and its water level drops to its seasonal level (see Figure 6).

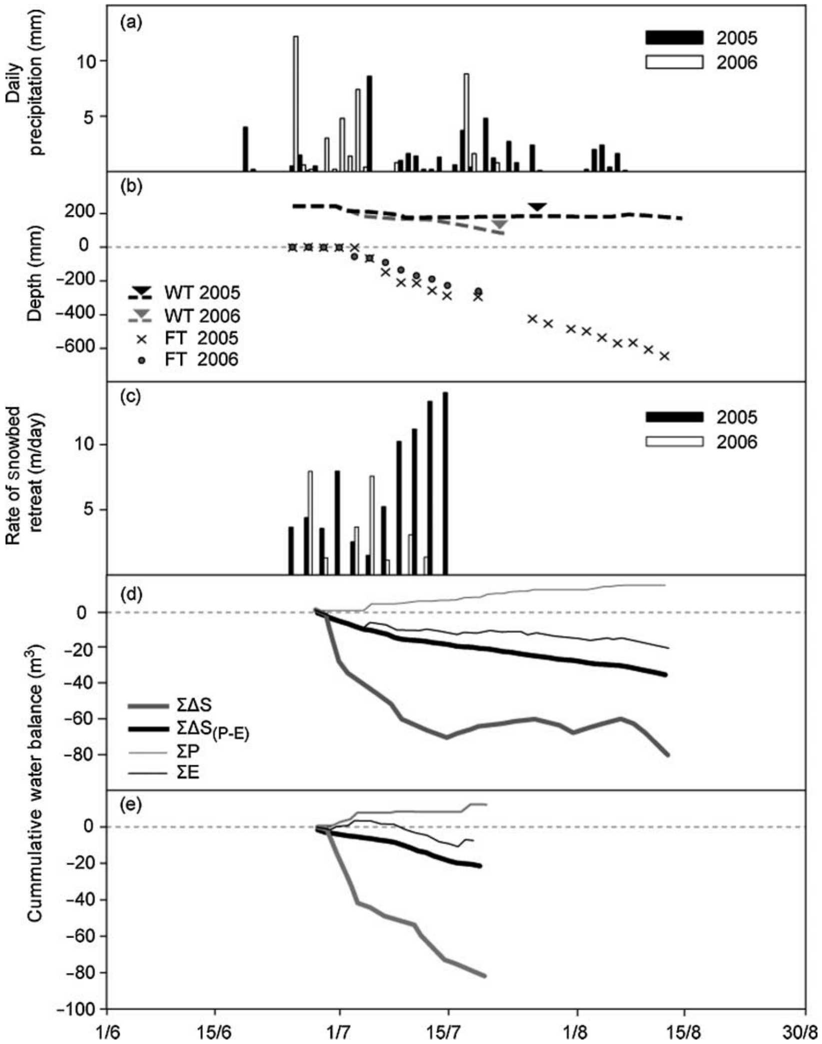

Figure 5 | Seasonal hydrology of the Moraine snowbank-fed pond in 2005 and 2006 showing (a) daily total precipitation amounts (mm); (b) ground thaw (FT, mm) and water table (WT, mm); (c) late-lying snowbed retreat (m/d); and (d) and (e) cumulative water balance components 2005, 2006 (m^3). Note: data collected at Creswell Bay were not complete in 2006 (data extend from 1 June to 26 July only).

However, meltwater inputs from a late-lying snowbed (ca. 180 m away) continue to provide additional meltwater as the season progresses, ensuring steady water levels in the pond. Soil moisture observations also confirm saturated conditions for the adjoining catchment (Table 1). Water storage remains relatively stable despite high surface outflow during the snowmelt season, deep thaw which would encourage vertical seepage, and evaporation losses during the post-snowmelt season (Figure 6).

The timing and magnitude of rain events coupled with the degree of connectivity of a pond to its landscape is another important consideration in terms of recharge. A late season rain event of 10.4 mm in 2006 elevated measured pond water volume $\Sigma\Delta S$ higher than that estimated by $\Sigma\Delta S_{(P-E)}$, suggesting that additional water inputs came from the surrounding landscape (i.e. stream, late-lying snowbed and saturated catchment) (Figure 6).

Other wetland researchers (e.g. Soranno *et al.* 1999; Van Hove *et al.* 2006) have also remarked on the importance of linkages with the landscape to buffer the losses of water due to climatic influences. Ponds which are isolated, have limited connection to their surrounding basin (snowbeds, streams, saturated ground), are generally more dependent on meteorological conditions (snowfall, summer rains) for

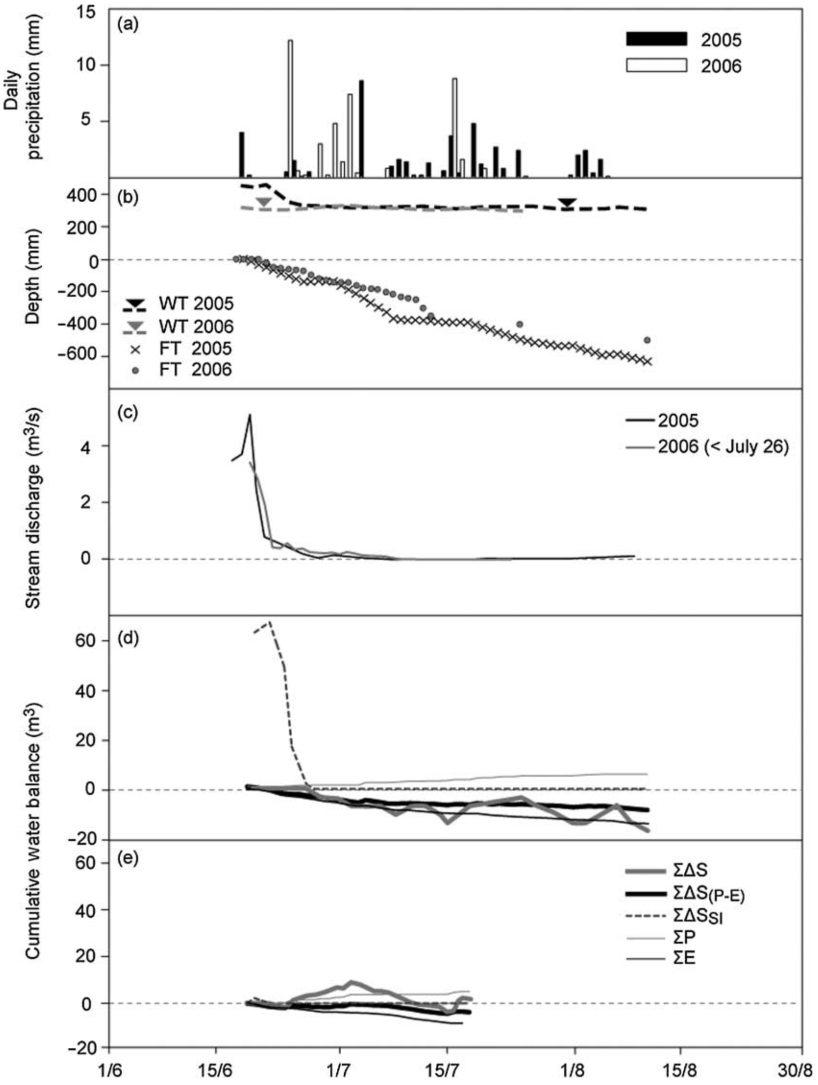

Figure 6 | Seasonal hydrology of the Moraine stream and snowbed-fed pond in 2005 and 2006 showing (a) daily total precipitation amounts (mm); (b) ground thaw (FT, mm) and water table (WT, mm); (c) stream discharge into the wetland (m^3/s); and (d) and (e) cumulative water balance components 2005, 2006 (m^3). Cumulative measured change in pond volume during the snowmelt season ($\Sigma\Delta S_{SI}$) provides an indication of stream input in comparison with cumulative pond volume change after the snowmelt season where no linkage to the stream ($\Sigma\Delta S$) occurred. Note: data collected at Creswell Bay were not complete in 2006 (data extend from 1 June to 26 July only).

their survival. Seasons with little snow and rain result in these ponds drying out quickly (Woo & Guan 2006). Large rainfall events occurring at critical periods may recharge the ponds if storage deficits can be satisfied. Without adequate inputs, these ponds can be viewed as intermittent and in time may cease to exist. Multiple water linkages appear to be one of the best strategies for Arctic ponds to survive changing climatic conditions. In this study, the overlapping contributions of streamwater and late-lying snowmelt water inputs allow this particular pond to maintain stable water storage despite variable climatic conditions.

Dual role: coastal zone–frost crack pond

The coastal zone is characterized by coarse sandy soils which thaw rapidly after snowmelt in comparison to the Moraine ponds. Sandy soils of the coastal site possess good water conductivity under saturated conditions. Estimated hydraulic conductivity was higher than in the moraine soils (2.60 m/d, $n = 2$ vs. 0.95 m/d, $n = 1$) and is typical of sandy soils.

Numerous frost cracks at this site are formed in response to isostatic rebound and to the maximum ground temperature gradient arising from the contrast between land and sea (Lachenbruch 1962). These frost cracks appear to play a dual role in a pond's hydrology. At the time of snowmelt and large rainfall events they are conduits for water draining from slopes and are effective in funneling this water further out into the coastal zone (Figure 3(c)). Their major role in the post-snowmelt period, especially if they are situated downslope of small and medium-sized ponds, is to serve as 'sinks' and enhance pond drainage and desiccation (Figure 3(d)). Decline in the medium-pond water volumes in 2005 and 2006 occurred as a result of increased groundwater flow from the pond to the frost crack, occurring quite rapidly once the frost crack become desiccated. Estimated values of groundwater flow from the pond to the frost crack were calculated using Darcy's law (Equation (4)) with saturated hydraulic conductivity equal to 2.60 m/d. Seasonal increase in saturated thickness zone was observed to range from 0.1–0.8 m in 2005 and 0.1–0.5 m in 2006. The initial groundwater losses were low, with the hydraulic gradient below 0.07 m/m in 2005 and 0.04 m/m in 2006 (Figure 7)). The groundwater flux increased with the hydraulic gradient during frost crack

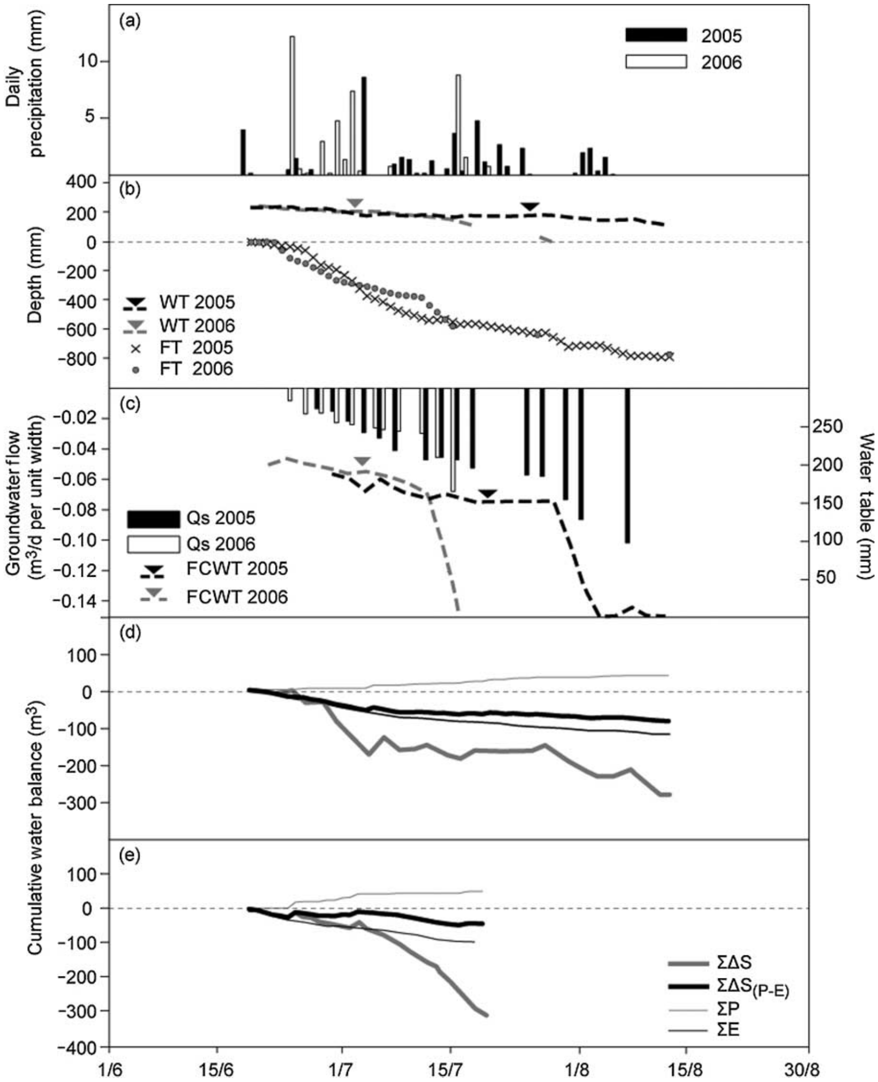

Figure 7 | Seasonal hydrology of the Coastal Frost Crack pond in 2005 and 2006 showing (a) daily total precipitation amounts (mm); (b) ground thaw (mm), FT and water table (mm), WT; (c) pond ground water flow to the frost crack (m^3/d per unit width) and frost crack water table (FCWT); and (d) and (e) cumulative water balance components (m^3). Note data collected at Creswell Bay were not complete in 2006 (data extend from June 1 to July 26 only).

desiccation and reached its peak with a hydraulic gradient ranging from 0.08–0.09 m/m in late June 2005 and 0.05–0.07 m/m in the middle of June 2006, leading to rapid decline in pond water storage (Figure 7).

A similar drainage pattern occurred for a small pond (area $= 232\,\mathrm{m}^2$) in association with a frost crack. After the desiccation of the frost crack adjacent to the small pond, water levels declined rapidly ($R^2 = 0.87$, $p < 0.05$). However, large groundwater losses were not observed for a large pond (area $= 1519\,\mathrm{m}^2$). Here, water tables were equivalent in the pond and the nearby frost crack, suggesting little water exchange ($R^2 = 0.75$, $p < 0.05$) (Abnizova 2007).

In general, the presence of nearby frost cracks is just one more feature compounding water losses from these coastal-type ponds. These ponds have little relief and cannot capture as much snow as other pond sites (163 mm of SWE in 2005 vs. 122 mm in 2006). Shallow water (seasonal mean depth = 0.16 m, 2005, 19 June–11 August) and warm conditions (6.64°C, 2005) triggered by a dark blue-green substrate which can absorb much radiation (Oke 1987) enhances evaporation losses (about 2.2 mm/d, 2005). Furthermore, the sandy texture contributes to much groundwater flow by allowing for deep thaw (0.89 m) and vertical seepage, along with a high hydraulic conductivity (ca. 2.60 m/d).

The role of frost cracks in pond hydrology was recently described by Woo & Guan (2006). At their study site a frost crack was formed due to thermokarst processes after an exceptionally warm summer with little rain. They concluded that a warmer climate increases the probability for thermokarst occurring along pond rims, helping to create natural channels for pond drainage. This response is a slightly different situation than in our study but does help to provide additional evidence of the numerous roles played by frost cracks in High Arctic wetland environments.

SUMMARY AND CONCLUSIONS

There are many factors which determine a pond's ability to sustain itself in polar desert environments. Some of these are position in the landscape and size, with large ponds generally receiving water from larger catchment areas. Topography and soil texture are also critical. Depression-type ponds can capture and hold onto more snow than broad, shallow ponds which tend to be windswept. Ponds with sandy soil will have deeper and earlier thaws than silty soils with high ice contents. Here, we consider a few selected ponds in the context of hillslope linkages (i.e. late-lying snowbed, stream and frost cracks). Our study has shown that connectivity to a water source is important in sustaining ponds during variable climatic conditions (2005 vs. 2006) and can help buffer ponds against seasonal water losses (runoff and evaporation). Multiple water linkages provide the best strategy for ponds to sustain themselves over the long term. Streamwater together with meltwater from late-lying snowbeds provide overlapping sources of water which sustain pond water levels throughout the summer season. A pond dependent on only one water source (e.g. late-lying snowbed) could be vulnerable in the future if this supply disappears in response to a warmer climate (Woo & Young 2006). Ponds not well connected to a reliable hydrological system are the most vulnerable to climatic shifts and are prone to desiccation (e.g. small and medium-sized coastal ponds). Here, landscape features such as frost cracks also serve as 'sinks' rather than water 'sources', helping to deprive ponds of even more water.

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