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Role of Snow in the Hydrology of a High Arctic Riparian Wetland

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ABSTRACT
Riparian wetlands are unique strips of saturated and vegetated ground forming important links between terrestrial landscapes and aquatic zones. These linear wetlands are common features in High Arctic landscapes yet their hydrology is not well understood. Woo and Young (2003) provide some information on their hydrology through their study on Cornwallis Island-a polar desert environment. They found that water tables in the wetland continually remain high from seasonal snowmelt runoff and extended over-bank flooding from snow-chocked stream channels. Here, I describe the hydrology of a riparian wetland situated within a polar oasis landscape near Eastwind Lake, Ellesmere Island, Nunavut (80°80'N, 85°35'W) during the 2006 field season. Unlike the Woo and Young (2003) study, snow in the channel does not promote a period of extended over-bank flooding but instead serves as a dam blocking most stream water from entering and flooding the wetland. It is only during a warm, sunny period that the snow dam melts and the wetland becomes recharged. Meltwater from late-lying snowbeds located further upstream is essential for maintaining saturated conditions for the duration of the season.

KEYWORDS
Arctic hydrology, channel snow, High Arctic, permafrost, riparian wetland

1. INTRODUCTION

Riparian wetlands are unique strips of saturated and vegetated ground forming important links between terrestrial landscapes and aquatic zones. They serve to both modify and be modified by fluvial and chemical processes and have been well studied in temperate environments (e.g. Cole and Brooks 2000; Toner and Keddy, 1997; Hauer and Smith, 1998; Vidon and Hill 2006). Cole and Brooks (2000) suggest that these wetlands are the wettest when compared to other wetland-types and with some exception show the smallest range in hydrologic behaviour. They indicate that duration of inundation and saturation for most riparian sites is about 81%. Toner and Keddy (1997) suggest that the duration of flooding and the frequency of flooding is important for determining plant type structure. Woody plants succeed herbaceous plant in areas with both infrequent flooding and duration. Vidon and Hill (2006) and others have focused on defining the biogeochemistry of these zones and their ability to deplete nitrogen-rich waters draining from upslope agricultural fields.

These linear wetlands are also common features in high arctic landscapes running along streams and rivers, yet their hydrology is not well understood. Woo and Young (2003) provide some information on their hydrology through their study on Cornwallis Island-a polar desert environment. Here, these researchers found that water tables in the wetland continually remain high from seasonal snowmelt runoff and extended over-bank flooding from snow-choked stream channels. Due to diluted conditions, cation levels remain low, in comparison to groundwater-fed depression-type wetlands. Here, I describe the hydrology of a riparian wetland situated within a polar oasis landscape near Eastwind Lake, Ellesmere Island, Nunavut (80°80'N, 85035'W) during the 2006 field season. Unlike the Woo and Young (2003) study, snow in the channel does not promote a period of extended over-bank flooding but in fact initially serves as a dam, blocking stream water from entering and flooding the wetland prior to its disintegration. This study investigates how the wetland responds to these conditions along with contributions of meltwater from late-lying snowbeds which exist in the stream channel and along steep slopes and valleys. A combination of field data (climate, hydrology) and a snowmelt model (Woo and Young 2004) are employed to explore the dual role of snow (blockage/recharge) in the hydrology of a High Arctic riparian wetland.

2. STUDY AREA

This study took place from early May to early-August 2006 near Eastwind Lake, Ellesmere Island, Nunavut ($80^{\circ}80'$N, $85^{\circ}35'$W). The wetland is situated about 20 km inland from Eureka, a government weather station (Figure 1). The wetland site is composed of a broad flood-plain characterized by a main stream channel running through it and a series of water pathways or streamlets. Elevation ranges from 142 m at its inlet to 136 m at its outlet-a gradient of 0.05. The wetland shows a high degree of variability. Some areas are well vegetated and contain much wet meadow-type vegetation (e.g. *Cotton-grass, Moss, Sedges, and Graminoids*), while other zones are void of plant life and are better described as gravely mud-flats. These latter areas are routinely subjected to stream waters which deposit much silt and detritus here, as the current slows through the area. A soil profile dug in the middle of the wetland indicates a thin, organic layer over a saturated, gravely-silty soil grading to clay with depth. Orange iron stains indicative of water-logged conditions occur throughout the soil profile. The area is below the marine-limit, set at 150 m a.s.l. The stream which floods and recharges this wetland originates near the peak (~590 m) of Black Top Ridge, a ridge which runs in a southwest to northeast direction across the Fosheim Peninsula, from Eureka Sound to Greely Fiord. This stream, referred here as Black Top Ridge Creek (BTRC), is just one of many which drain this high ridge and empty into adjacent wetland zones. Snow typically persists on the ridge and in steep gullies much longer than the lowland wetland, owing to the cooler conditions here.

The area can be described as having a polar-oasis type climate (Woo and Young 1997 and Woo and Guan 2006). It typically experiences warmer and drier conditions than elsewhere in the High Arctic, as it is sheltered by near-by mountains from low pressure systems that originate in the Arctic Ocean (Maxwell 1980; Young and Woo 2004a, b and Woo and Guan 2006). Summers are warmer than the coastal Eureka station (see Woo and Guan 2006). In 2006, snow cover was low over the landscape with much of the snow blown into low-lying areas (i.e. stream channels and depressions). However, due to a cool and cloudy spring, snowmelt was delayed until May 24 and persisted 21 days, 11 days longer than in 2005. The 2006 season was also much cooler (~400 thawing degree-days) and wetter than 2005, which was one of the warmest on record for this area (over 500 thawing degree-days at Eureka, see Woo and Guan 2006). Summer rainfall in 2006 amounted to 39 mm up until Aug. 8 (end of fieldwork) and then an additional 30 mm fell between Aug 9-14 at Eureka (Woo and Guan, 2006). Only 27 mm fell in 2005 at the study site, in comparison to 19 mm at the Eureka weather station. Growing conditions were less favourable in 2006 than 2005. In 2006, growing- degree days totalled 138 versus 224 in 2005. This resulted from 17 fewer growing days (>5°C) in 2006 than 2005, when the same time span is considered.

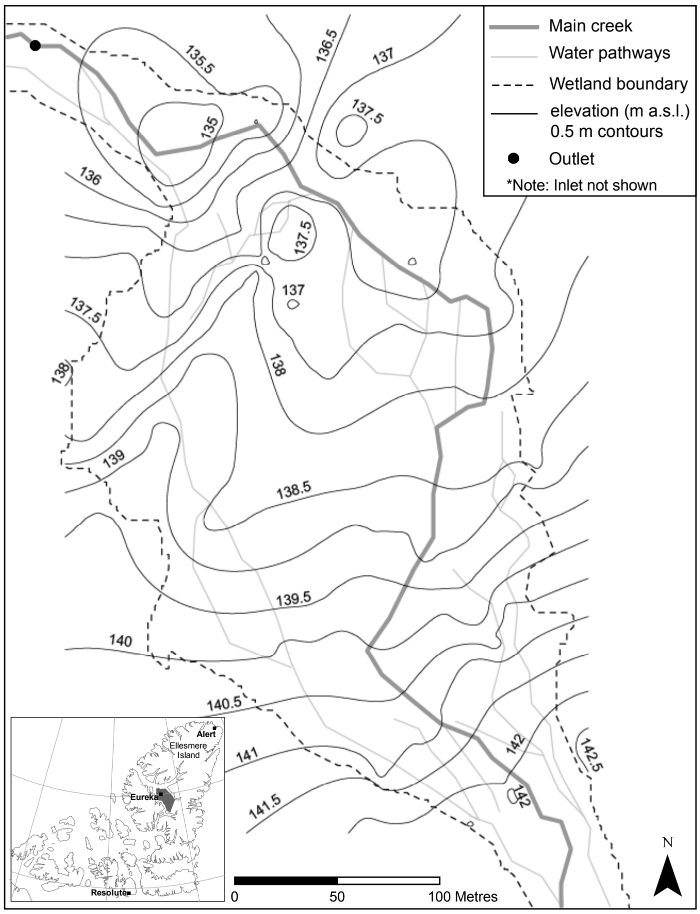

Figure 1. Topographic map of the riparian wetland ($80^{\circ}80'$N, $85^{\circ}35'$W) located 20 km north of Eureka, Ellesmere Island, Nunavut, Canada (see inset map). Fosheim peninsula is shaded.

3. METHODOLOGY

3.1 Field

Five transects were laid out across the riparian wetland and a snow survey was conducted following after Woo (1998). Snow depth measurements were made every 10 m and snow density was determined at the beginning and end of each transect with an Environment Canada MSC snow tube. On occasion, snow depth was too deep for the snow rod, leading to an underestimate in snow water equivalent (mean SWE = 106±50 mm). Considering this error and the fact, that reasonable snow information for this site was needed to model melt elsewhere along the incised stream channel (see section 3.2), a decision was made to increase this initial value by 50% (new SWE=159 mm-see Table 1). Direct measurements of snowmelt followed after Heron and Woo (1978). In 2005, three permanent transects were established across the wetland (see Figure 2) and a series of perforated and screened water wells (3 to 4) per transect were installed. In the post-snowmelt period (2006), daily water levels were measured at wells and depth of thaw was measured weekly at 10-12 locations along each transect (see Figure 2). The approach by Cole and Brooks (2000) was followed to assess different moisture conditions within the wetland; here the 15 cm depth was set as the limit of the rooting zone. I defined inundation as occurring when water tables were >0 cm, saturation (0 to -15 cm) and dry conditions (< -15 cm). Soil moisture was also determined at two locations in the middle of the wetland using the gravimetric approach (Figure 2). These measurements were taken in association with others (e.g. wet meadow, tundra upland, mesic ground, pond rim), as part of a broader wetland study. An Automatic Weather Station (AWS) (elevation = 138 m) situated over a wet meadow provided hourly meteorological information (Q*, K↓, K↑, Ta, RH, U). Summer precipitation was measured with a recording tipping-bucket raingauge and verified with four manual raingauges, with one of them in the middle of the riparian wetland. A stilling-well was situated near the outlet of the riparian wetland in the stream channel and an Ecotone water level recorder measured stage here (±10 mm). Stage levels were corrected routinely with direct depth measurements. Current metering occurred at both the inlet and outlet locations (see Figure 1) usually 2 to 3 times per day during high flows and once per day in low flow conditions. This allowed rating curves to be determined for each site: inlet location-$Q = 4.98H^{2.23}$, $r^2=0.93$, n=38; and for the outlet- $Q= 4.98H^{2.14}$, $r^2= 0.94$, n=38. A continuous record of reliable discharge was determined for both locations from June 29 (JD 180) onwards. A topographic survey of the study site occurred in late July using a transit level and stadia rod. Elevations were tied to a known benchmark.

3.2 Snowmelt model

For this study I wanted to identify and understand the processes which were driving the stream flow pattern passing through this riparian wetland. An initial comparison of stream discharge to both air temperature and net radiation proved inadequate. A snowmelt model (Woo and Young 2004) was then employed to assess the processes (energy receipt vs. rain input) modifying sreamflow. The utility of this model was recently confirmed at another wetland site on Somerset Island (Young and Abnizova 2005). Inputs to the model include both climate and snow information. Hourly climate data came from the AWS (K↓, Ta, RH, U, and PPT) except for P (station pressure) which was obtained from the Eureka weather station, 20 km to the south. Initial snow information was limited to the study site. Given that most streamflow was likely generated from snow further upstream, snow information for this valley zone was required. Using a series of photos from 2005, obtained from students hiking up the creek to the top of Black Top Ridge on July 1 (JD 182), I dissected the stream channel into a series of sections (slope, aspect, elevation) and snow amount (i.e. I compared snow conditions in the photo to initial wetland snow to derive an estimated snow index) (see Table 1). Indices were kept to reasonable levels based on previous surveys of snow-filled valleys (Woo and Young 2004). Photographs taken during both 2005 and 2006 also indicated that most snow was constrained to the main stream valley and near-by slopes. This information helped to define areas for the different contributing zones (m^2). Here, a 1:50 000 topographic map of the Black Top Ridge area (340 B/3) was employed. Normally, extensive snow surveys should have been conducted along the stream channel but this was not logistically possible. Modelled streamflow was generated from both simulated melt and measured rainfall inputs obtained from the AWS. These data were areally weighted for each terrain unit.

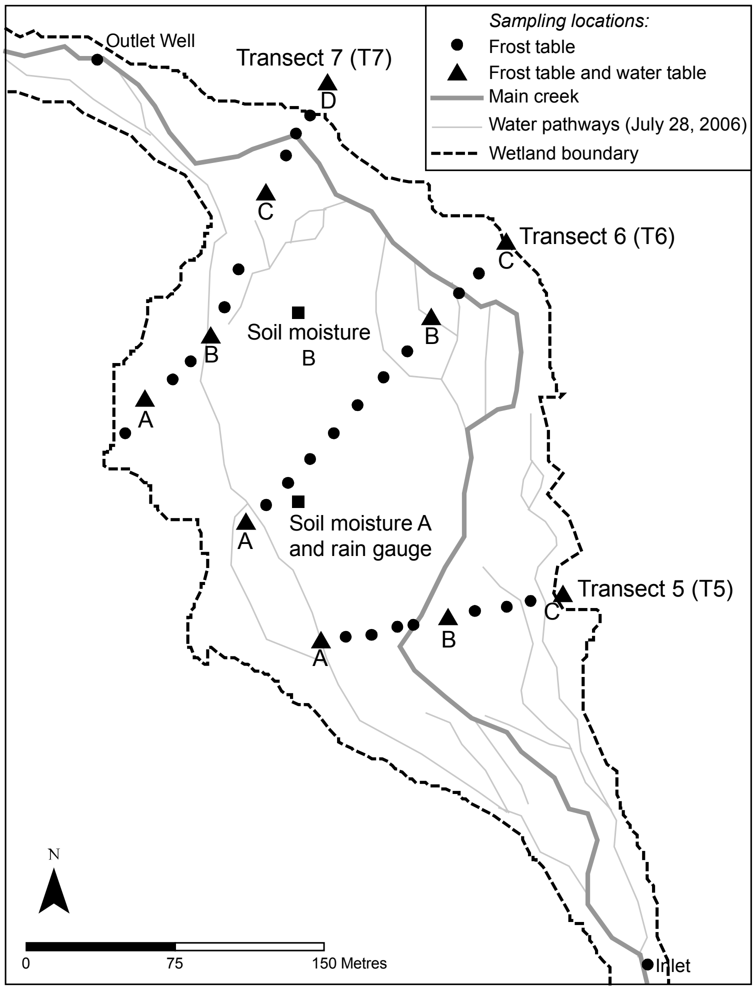

Figure 2. Series of transects across wetland indicating water wells and frost table locations. Stream gauging locations at the inlet and outlet are also indicated.

Table 1 provides the site conditions for the base and the series of valley terrain units. Isothermal conditions were assumed for the base station since the seasonal snow pack had largely disappeared from the low-land and only snow in the stream channel and valleys remained.

Table 1 Initial conditions for the snowmelt model (see Woo and Young 2004).

Terrain	Snow Index	Mean Elevation (m)	Aspect (degrees)	Slope Angle (degrees)	Area (m^2)
base (swe=159 mm)	1.00	138	–	–	
valley 1	1.00	134	315	0.01	97 656
valley 2	3.00	160	315	4	97 656
valley 3	4.5	220	315	19.7	317 383
valley 4	6.0	350	315	19.7	195 312
valley 5	6.0	500	315	19.7	67 139

4. Results and Discussion
4.1 Model results
A reasonable relationship between measured and modeled stream flow (see Figure 4b) at the outlet (within 5%) provides confidence in the initial conditions selected and the types of processes controlling stream

flow through the wetland (see below). Differences in results can be attributed to lags in the system, e.g. the snow dam in the channel delaying flow, a situation which cannot be reproduced by the model. Both over and under-estimates of measured stream flow also arise from errors in assessing initial snow amounts and areal coverage. Overall, this adequate performance is to be expected given the lack of snow information for this mountain stream.

4.2 Snow-dam period

Figure 3a indicates the saturation conditions of the wetland prior to the large flood event of July 9 (JD 190) (see Figure 4a). During this period the saturation levels are reduced with water tables falling below the ground surface and the absence of water in other wells (see Figure 5). Soil moisture levels while limited in extent confirm this drying pattern (i.e. θ_s < 100% vol. water content). Electrical conductivity values are also variable, especially for the wetland zone which had much higher and erratic values than channel water and minor flow paths (see Figure 6). Dall'O *et al.* 2001 indicates that dry intervals are common for riparian wetlands and are not considered critical (e.g. these episodes help to aerate the soil), yet Toner and Keddy (1997) indicate that saturated conditions are required for germination and infrequent flooding can lead to a change in plant structure. They discovered that for temperate wetlands, the duration of floods and the duration between initial and secondary floods were key factors in preventing woody substrates from succeeding herbaceous species. Drier conditions in the Athabaska Delta after a water diversion led to a shift in vegetation from herbaceous to woody plants (see Toner and Keddy 1997).

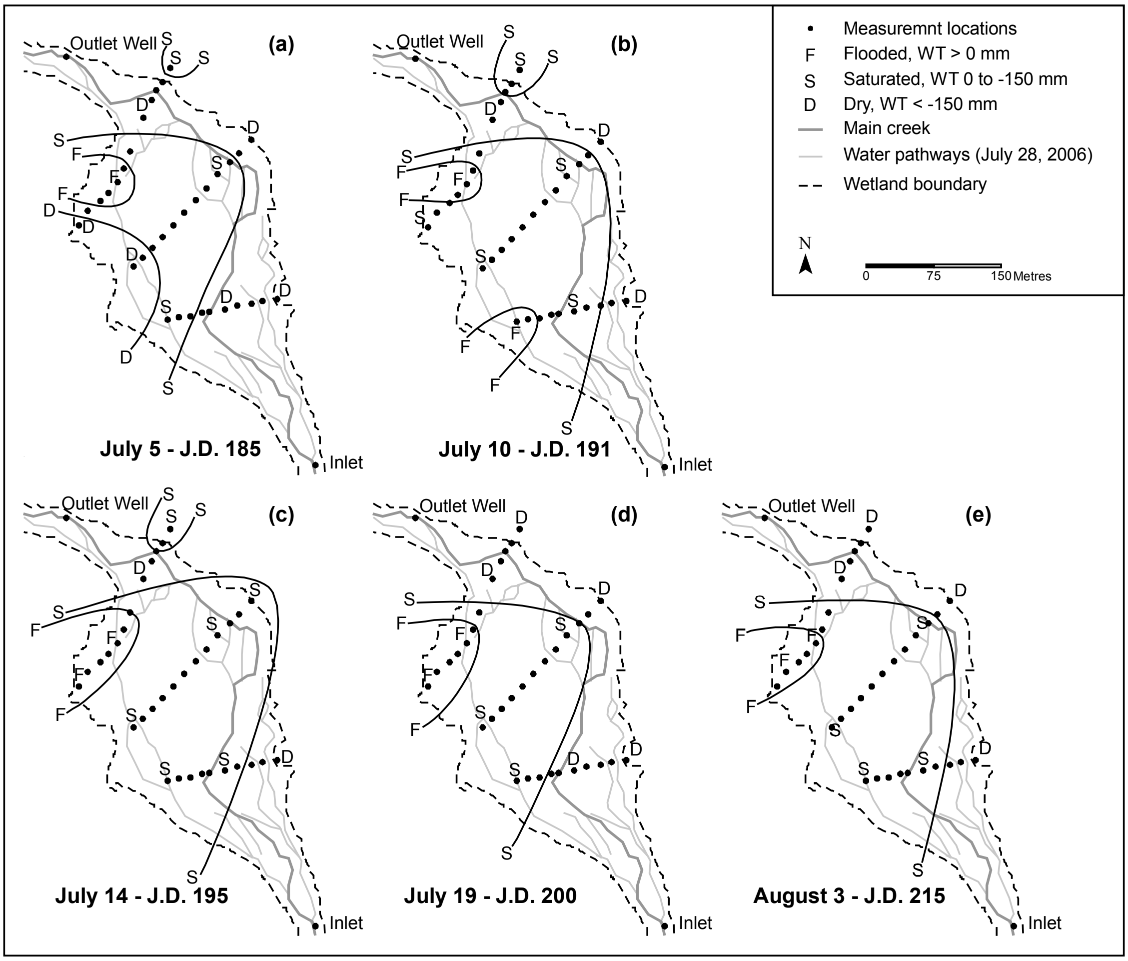

Figure 3. Water saturation patterns in the riparian wetland, 2006.

4.3 Flood period

A significant discharge event (see Figure 4a) did not occur until a snow dam diverting most seasonal snowmelt flow (**A**) from the riparian wetland was finally destroyed on July 9 (JD 190) (labeled here as, **B**). This large release of water was triggered by a stretch of sunny (□Q^*), warm and windy conditions (□Q_H fluxes), which enhanced melting after an unusually long and cool melt season. This pronounced flood event allowed water tables to rise (Figure 5) often above the ground surface, expand the saturated zone (Figures 3b, c) and dilute the wetland (see large drop in electrical conductivity, Figure 6a). This event which rapidly recharged the wetland occurred about three weeks later than in 2005. The occurrence of snow dams and snow-choked channels and their ability to delay and impound water levels is common in High Arctic environments (Woo and Sauriol 1980; Xia and Woo 1992). The surge of water after release followed by a dramatic drop in discharge can be described as a jökulhlaup (Blachut and McCann 1981).

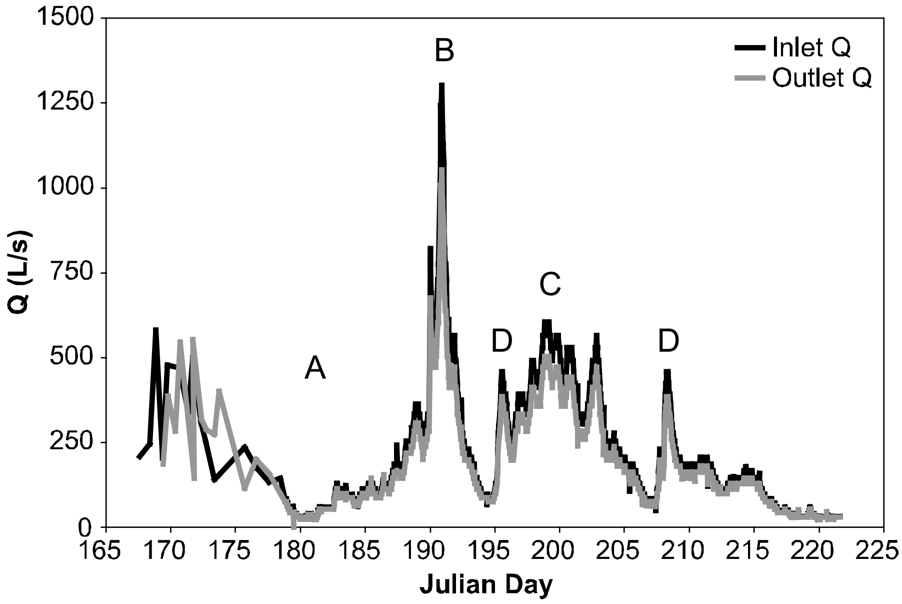

Figure 4a. Seasonal streamflow pattern of Black Top Ridge Creek (BTRC), 2006. Letters in the diagram are referred to in the text.

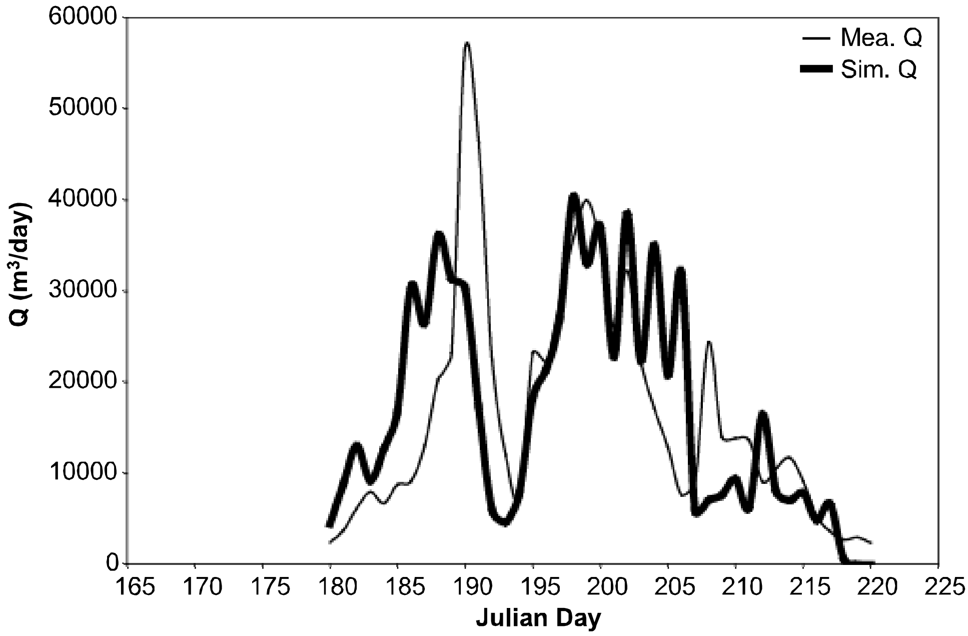

Figure 4b. Simulated and measured streamflow, Black Top Ridge Creek (BTRC), 2006.

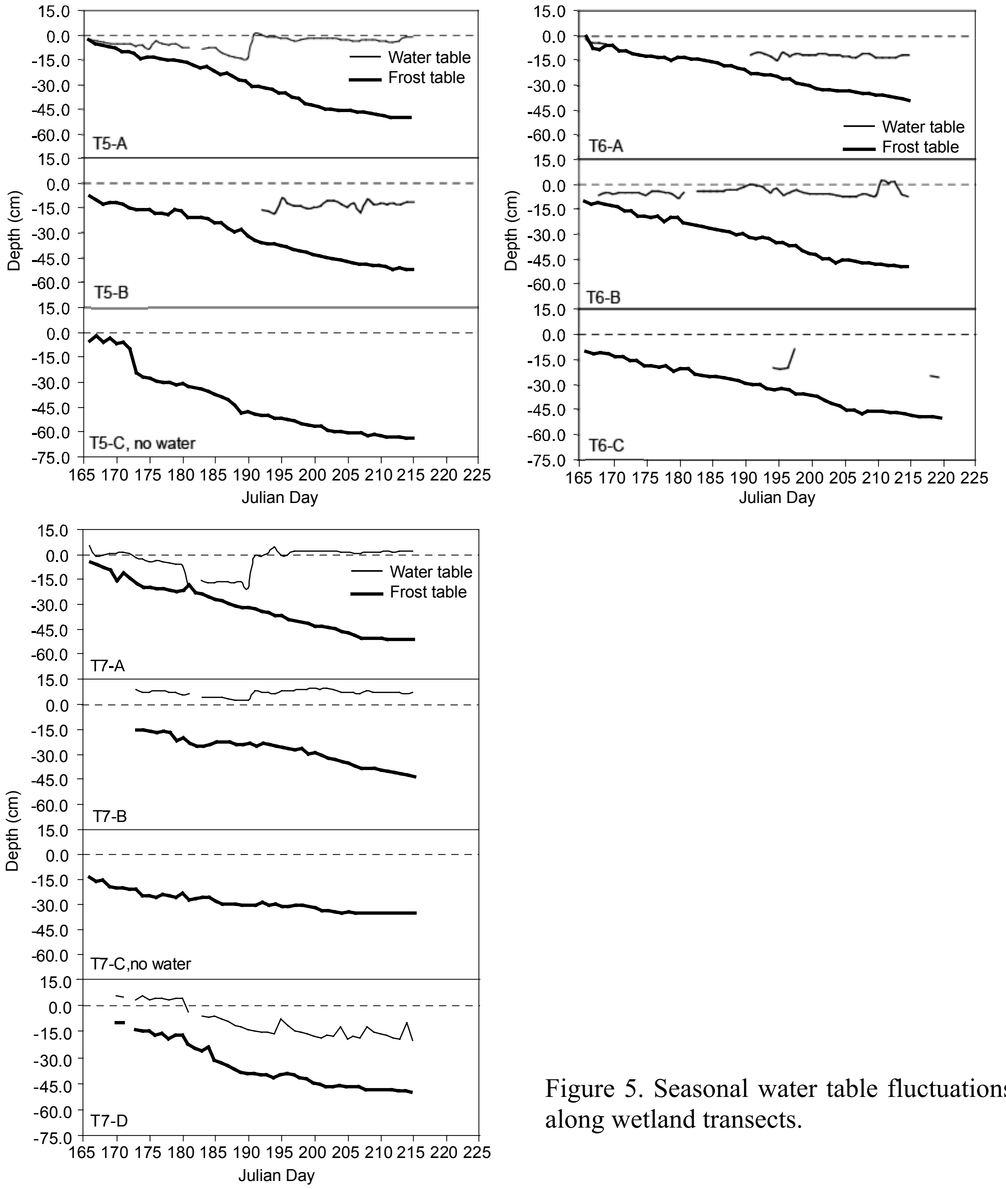

Figure 5. Seasonal water table fluctuations and frost table pattern along wetland transects.

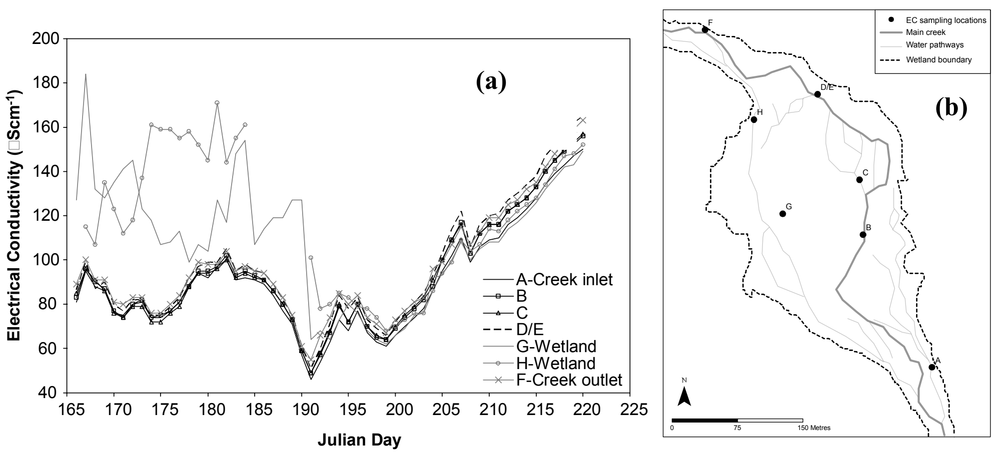

Figure 6. Seasonal pattern of electrical conductivity (a) at selected locations in the wetland (b).

4.2 Late-lying snowmelt period

Figure 4 (a) indicates that discharge levels were steady throughout July and did not drop off until early August when cooler and cloudy conditions became more frequent. The snowmelt model indicates that this period of enhanced flow (indicated by **C**) arises from the melting of channel snowbeds and lingering snow on steep slopes. The pulses or sharp increases are induced by sunny weather along with warm and windy conditions which enhance fluxes of Q_H. Young and Lewkowicz (1990) similarly found that Q* and Q_H dominated melt at a large perennial snowbank, near Ross Point, Melville Island and highest discharges occurred on clear, warm and windy days. Stream flow peaks labeled as **D**, are driven by rain and the melt generated by rain-on-snow (Q_P). Energy levels were low (cloudy, cool) for these days but rain helped to elevate the importance of Q_P and its ability to melt snow. These residual snowbeds and the meltwater that they produced were important for keeping the wetland saturated for the remainder of the summer. Figure 5 reveals that most water tables remain elevated and overall, the wetland continues to be saturated (see Figures 3d and e). The persistence of elevated soil moisture values (i.e. θ_s = 100% vol. water content) also confirms this pattern.

Comparable observations at this site in 2005, suggest that this period of "secondary flooding" is a regular event. Electrical conductivity values start rising during this post-peak period but increases are similar amongst sites suggesting stable moisture conditions throughout the wetland (Figure 6). Without these additional water inputs it is doubtful whether the wetland would have remained saturated given the potentially high losses of evaporation (ca. 4 mm/d) which can occur from wetland surfaces (see Woo and Guan 2006).

5. CONCLUSIONS

Dall'O *et al.* 2001 indicates that riparian wetlands are inherently complex, interface systems where different types of systems interact and where gradients can be high. They suggest that two main problems arise when dealing with riparian buffer zones: high temporal variation and extremely high spatial heterogeneity. For this riparian wetland which is found in a polar-oasis type climate snow plays a leading role in controlling this variable pattern. In summary,

1) The snow-choked channel initially deprives the wetland of much stream water, a delay of three weeks over the previous year. Delay in the arrival of these meltwaters results in the shrinkage of the saturated zone as the water table falls below the ground, often below the rooting zone. The water chemistry pattern also becomes altered (see Figure 6).

2) Contributions from flood waters and meltwater are important for these riparian wetlands. Water recharges the wetland and nutrients and matter (e.g. carbon), which are important for continued plant growth (Fellman and D'Amore 2007), are carried here in solution. During these events, water tables rise, often above the ground surface and some areas become inundated while saturated areas expand. Conductivity levels drop indicating diluted conditions.

3) A snowmelt model (Woo and Young 2004) was effective in helping to identify the reasons behind the stream discharge pattern. Much of the stream flow in the post-peak flow period is due to the melting of late-lying snowbeds either in the channel itself or on steep channel slopes. Net radiation (Q*) and sensible heat flux (Q_H) were the main drivers behind this melt, confirming what others have found (e.g. Young and Lewkowicz 1990). Rain was important in triggering stream flow by its control on the Q_p flux.

4) Considering that this is a one-time only study and its applicability to other riparian wetlands is limited, more attention should focus on channel snow and the role of this snow in steep catchments. Snow storage in these zones is important in providing meltwater to low-lying areas long after the seasonal snowpack has disappeared (Young 2006). Our study showed that this meltwater was essential for keeping a riparian wetland saturated for most of the summer. Loss of this snow and its ability to recharge the wetland on a regular basis might lead to drier conditions and eventually, a shift in vegetation-type (e.g. *Sedges* to *Salix arctica*) (Toner and Keddy 1997).

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