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The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post-restoration

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ABSTRACT

Restoration measures (ditch blocking, bund construction, etc.) were applied to a cutover part of the Bois-des-Bel (BdB) bog peatland in autumn 1999; since then a near complete cover of *Sphagnum rubellum* (~15 cm) has developed over the old cutover peat, along with a suite of bog vegetation. This research assesses the restored site's (RES) hydrological condition after 10 growing seasons (May 15th–August 15th, 2010) through comparison with an adjacent unrestored site (UNR) and a natural site (NAT) located elsewhere in the peatland. Evapotranspiration (ET) from RES (242 mm) has not noticeably changed since the first 3 years post-restoration (2000–2002) still maintaining lower ET rates than UNR (290 mm). The highest ET occurred at NAT (329 mm), dissimilar to RES despite similar vegetation cover. UNR generates more runoff (37 mm) than RES (7 mm), similar to the initial assessments. However, since the initial assessments the average water table has continued to rise, from −35.3 (±6.2) cm (2000–2002) to −27.3 (±14.9) cm (2010) below the cutover peat surface but still fluctuates predominantly within the cutover peat and not the regenerated *Sphagnum*. The regenerated *Sphagnum* at RES has increased the surface elevation by ~15–20 cm, and with respect to its surface the average water table was at ~−42.3 (±20.9) cm. However, its water table was still lower (and more variable) than at NAT (33.2 ± 9.0 cm), with respect to the moss surface. Average soil water pressures in 2010 were similar to the early post-restoration condition at depths of 10 cm (−43.0 ± 12.2 and −44.1 ± 13.1 mb) and 20 cm (−41.4 ± 13.0 and −40.6 ± 10.5 mb) below the cutover surface at RES and UNR, respectively. Volumetric soil moisture contents (θ) at 2.5, 7.5 and 17.5 cm depths were higher in the *Sphagnum* moss at NAT (0.23, 0.31, and 0.71) compared to RES (0.12, 0.11, and 0.23), where the underlying cutover peat had a relatively high θ of 0.74. The low moisture content in the new moss overlying the relatively moist cutover peat indicates there was restricted connectivity between the two layers. Ten years following the implementation of restoration measures and the development of a near complete 15 cm thick *Sphagnum* moss layer, further time is required for the moss layer to develop (increase in thickness and bulk density, hence water retention capacity) and more consistently host the water table, so that the average water content more closely mimics NAT.

1. Introduction

Peatlands depend on a combination of large scale (water table, evapotranspiration, runoff, etc.) and small scale (capillary flow, soil water retention, etc.) processes to function and sequester carbon (Waddington, 2008; Waddington et al., 2001). The removal of *Sphagnum* and peat through peat harvesting disrupts the hydrology (Price, 1996) that supports carbon sequestration; turning the peatland from a carbon sink into a source (Waddington et al., 2001). Spontaneous re-vegetation can occur; however, this is often relegated to vascular plants and not the more important peat forming *Sphagnum* mosses (Girard et al., 2002; Lavoie et al., 2003). Successful peatland restoration is defined by not only the successful return of target species (generally identified through the use of a natural reference site), but also the net sequestration of carbon within a peatland (Poulin et al., 2012). Both of these restoration milestones depend on specific hydrological conditions. Target peatland plants (i.e. *Sphagnum* moss) require high water tables to suitably raise the soil water pressures within the moss matrix to facilitate re-colonization, which Price and Whitehead (2001) suggested should be greater than −100 mb. To achieve this, ditch blocking, bund construction and straw mulch application (Rochefort et al., 2003) has been used to raise the water table, soil water pressures and reduce evapotranspiration (Gorham and Rochefort, 2003; Price et al., 1998; Rochefort et al., 2003; Shantz and

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Price, 2006a; Williams and Flanagan, 1996). Lucchese et al. (2010) and Waddington et al. (2011) suggest that a critical stage in the restoration process will occur when the water table fluctuates primarily within the newly regenerated *Sphagnum* moss layer, during which the conditions will be suitable for net carbon sequestration.

Restoration measures (Rochefort et al., 2003) applied to the previously harvested Bois-des-Bel (BdB) bog in autumn 1999 included blocking ditches, constructing bunds along elevation contour lines and reintroducing bog vegetation (see Rochefort et al. (2003) for a more detailed description). Hence, we consider the first year post-reclamation (i.e. first growing season) to be 2000. The donor material used in the restoration contained approximately the same amount of *Sphagnum fuscum* and *Sphagnum rubellum*; however, *S. rubellum* dominates the site (Poulin et al., 2012). The high water tables that occurred initially after restoration created suitable conditions for *S. rubellum* to outcompete other *Sphagnum* species (i.e. *S. fuscum*), which resulted in the current species composition (Poulin et al., 2012). Poulin et al. (2012) believe that *S. fuscum* will become more prevalent as larger hummocks develop at the site; conditions which are better suited to *S. fuscum* than *S. rubellum*. After 10 years since restoration measures were implemented, the restored section of BdB is dominated by peatland species (see Poulin et al. (2012) for a complete description) with some other wetland species resulting in higher a biodiversity than the natural reference site.

A detailed description of the hydrology during the first 3 years following restoration (2000–2002) is provided by Shantz and Price (2006a). The construction of bunds and blocking of ditches led to a decrease in runoff by 25% compared to the unrestored section during the post-snowmelt period (Shantz and Price, 2006b). Although runoff decreased post-restoration, the discharge peaks were greater due to wetter antecedent conditions compared to the unrestored section (Shantz and Price, 2006b). Total growing season runoff from the restored and unrestored sites maintained an average ratio of ~1:2.6 mm during the first 3 years following restoration (Shantz and Price, 2006b) where the average growing season water tables were −32.5 cm and −42.5 cm, respectively (Shantz and Price, 2006a). Evapotranspiration decreased at the restored site by ~25% compared to the unrestored site, initially due to the straw mulch application covering the bare soil and plant material (Petrone et al., 2004b; Shantz and Price, 2006a). Both the soil water pressure (greater than −100 mb) and soil moisture content (0.73 ± 0.05) 5 cm below the peat surface were significantly higher in the restored section of the peatland (Shantz and Price, 2006a), thus providing greater water availability for the newly regenerated vegetation. Although only a few cm of patchy *Sphagnum* had regenerated during the initial assessment, the conditions were suitable for it to regenerate across the site in the ensuing years (Poulin et al., 2012).

Notwithstanding the successful reintroduction of bog vegetation, the site remained a net exporter of carbon in 2000 and 2001 (Petrone et al., 2003, 2004b) and 6 years (2006) after restoration (Waddington et al., 2010). Strack and Zuback (2012) found the restored site was still a net carbon source in 2010, but so was the natural site in this relatively dry summer. Rewetting has caused higher surface soil moisture during the growing season which has resulted in enhanced photosynthesis; however, in the early post-restoration period this was offset by high soil respiration due to low water tables and high carbon export from mulch decomposition (Petrone et al., 2003, 2004a,b; Waddington et al., 2010).

It remains uncertain, therefore, whether the hydrological conditions in the moss have recovered the potential to support net carbon accumulation, and how the hydrology of Bois-des-Bel has evolved since the initial assessment in 2000–2002 by Shantz and Price (2006a). With respect to this last point, this study aims to determine (1) the current hydrological state of the Bois-des-Bel restoration; (2) identify how it has evolved since the initial assessments; and (3) determine the hydrological progression towards a reference bog peatland.

2. Study site

BdB is located 10 km northwest of Riviére-du-Loup, Quebec (47°57′47N, 69°26′23W, 28 masl), with an average temperature and precipitation of 14.6 °C and 366 mm, respectively, from May–August (Environment Canada, 2012). The ombrotrophic peatland is approximately 189 ha with ~2.2 m of peat thickness in the natural (NAT) site (47°57′35N, 69°27′00W) and 1.8 m in the cutover section (restored (RES) and unrestored (UNR) sites) (Lavoie et al., 2001). Based on a paleoecological study Lavoie et al. (2001) determined that the cutover peat still comprises typical bog peat, notwithstanding oxidation and consolidation processes (Price, 2003). The unrestored (1.9 ha) and restored (8.1 ha) sites are located adjacent to each other with a buffer of ~30 m between them, whereas NAT is ~2 km away in the same peatland (Fig. 1). NAT has large open areas dominated by *S. rubellum* and represents a set of hydrological (McCarter and Price, submitted for publication) and ecological (Lavoie et al., 2001; Poulin et al., 2012) conditions that are a target for successful restoration. Since restoration a near complete ~15–20 cm carpet of *Sphagnum* moss, chiefly *S. rubellum*, has covered RES (Poulin et al., 2012). The interface depth (i.e. where the regenerated *Sphagnum* and cutover peat meet) is variable over the site with small hummocks being ~20 cm, while other areas ~15 cm below the top of the *Sphagnum* moss. In contrast to NAT, where the dominant vascular vegetation are specific peatland plants, RES's vascular species are a mix of peatland and non-peatland wetland plants (Poulin et al., 2012).

3. Methods

Field monitoring at BdB occurred from day-of-year (D) 145–245 in 2010. Meteorological data, water table depth and volumetric soil moisture (θ) were averaged every 30 min (60 min for θ) between D 145 and 245. Manual water table measurements were made twice weekly. For the comparison to early post-restoration results (2000–2002) reported by Shantz and Price (2006a), only twice weekly manual well measurements were used to determine average water table. Samples (4) of the cutover peat and *Sphagnum* moss were taken from each site in 2.5 cm depth increments starting 1 cm below the surface to determine bulk density. The top 1 cm was taken individually to determine the evaporative surface (capitula) bulk density.

Micrometeorological stations were installed and instrumented at RES and NAT with net radiometers, tipping bucket rain gauges, temperature/relative humidity probes, and two copper–constantan thermocouples measuring soil temperature at 1 and 5 cm. Ground heat flux (Q_g) was determined using Fourier's Law (1).

$$Q_g \cong -k_s \left(\frac{T_2 - T_1}{z_2 - z_1} \right) \tag{1}$$

where Q_g (W m^{-2}) is the ground heat flux, k_s (W m^{-1} K^{-1}) is the thermal conductivity, T (°K) temperature, and z (cm) is the depth. k_s was determined hourly based on θ reported from the 2.5 cm TDR probe and an assumed thermal diffusivity of 0.12 m^2 s^{-1} × 10^{-6} (Oke, 1987).

The Priestley–Taylor combination model (2) (Priestley and Taylor, 1972) was used in conjunction with soil lysimeters (Price and Maloney, 1994) to calibrate the coefficient of evaporability (α);

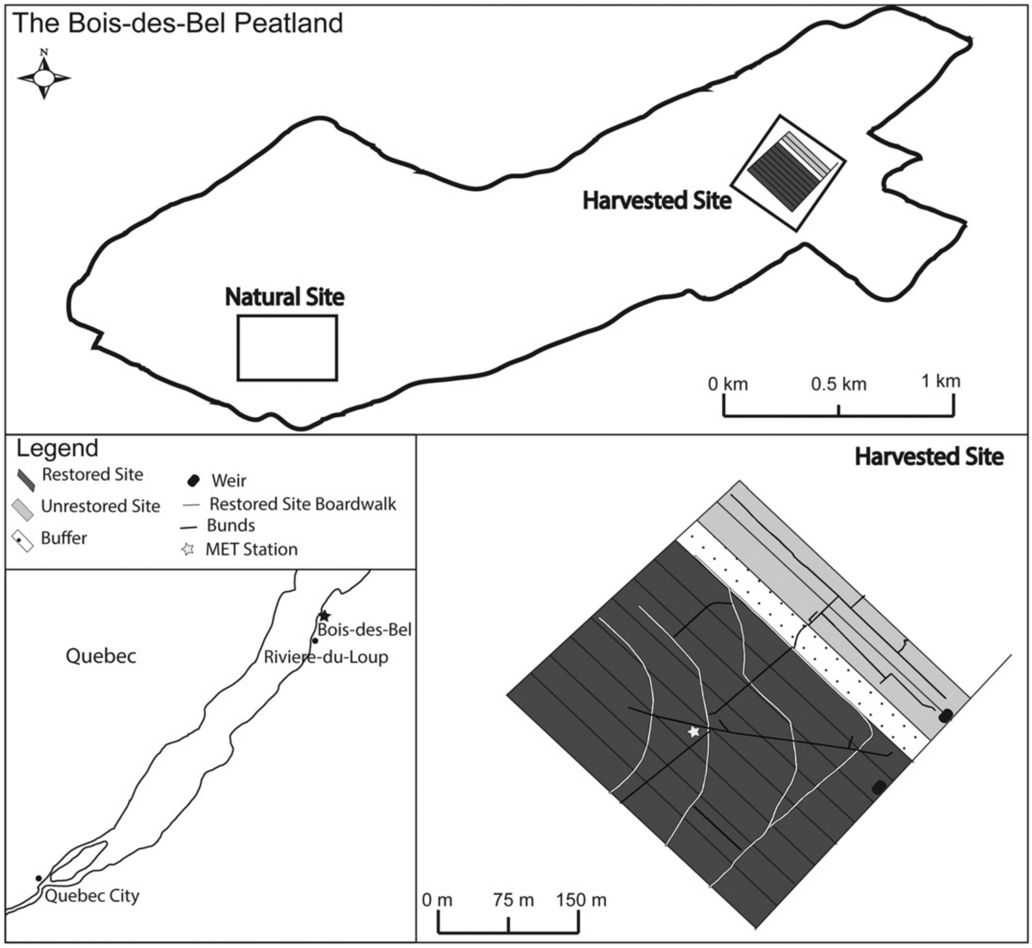

Fig. 1. A map of the Bois-des-Bel peatland and the hydrological monitoring locations within the restored, unrestored and natural sites.

(unrestored – 1.72, restored – 1.44, natural – 1.63) to obtain unique evapotranspiration (ET) values for all three sites;

$$ET = \alpha \left[\frac{s}{s+q}\right] \left[\frac{Q^* - Q_g}{L\rho}\right] \qquad (2)$$

where Q^* is net radiation, s is the slope of saturation vapour pressure–temperature curve (Pa °C^{-1}), q is the physchrometric constant (0.0662 kPa °C^{-1} at 20 °C), L is the latent heat of vaporization (J kg^{-1}), ρ is the density of water (kg m^{-3}). Four 30 cm diameter, 40 cm deep lysimeters were installed at both NAT and RES; while two 12.5 cm diameter, 20 cm deep lysimeters were installed at UNR (due to the high volume of roots and woody debris in the peat that limited the practical size of the lysimeter). Lysimeters were weighed twice weekly.

Soil water pressure (ψ) was measured twice weekly using tensiometers at both RES and UNR. Due to the poor contact surface in the upper portion of *Sphagnum* moss, the tensiometers were unable to provide measurements at NAT or in the regenerated *Sphagnum* moss at RES. A total of 12 tensiometers (6 at each site) were installed 10 and 20 cm below the level of the cutover peat. Thus, the tensiometers were installed 30 cm and 40 cm below the *Sphagnum* surface at RES.

Two perpendicular ~200 m transects of 10 wells (70 m transects of 5 wells at UNR) (100 cm slotted intake, 2.54 cm I.D. PVC pipes) were measured twice weekly at RES and NAT. Averages of all manual well measurements were used to compare to those collected by Shantz and Price (2006a). One logging pressure transducer was installed per site for a continuous record of water table from D 145 to 245. The hydraulic conductivity of the peat was determined using the Hvorslev (1951) method in each well. In addition to measuring the height of the well above the surface, a DGPS survey of the well tops and ground elevations was conducted to determine the elevations and distance between wells. Groundwater in (GW_{in}) and out (GW_{out}) was determined assuming flow was parallel to the water table, with hydraulic gradients calculated between the ends of each transect to the micrometeorological station (central study area) at NAT using average water table measurements. The central study area is ~10 m × 10 m with a peat depth of 209 cm; these measurements were used to calculate the flow face into the study area, based on Darcy's law. There are no GW_{in} measurements at RES and UNR because a drainage ditch intercepts all incoming water and exports it off site and GW_{out} was collected in the culvert, which drains the site. Weirs were installed on the culverts at both RES and UNR; a bucket and stopwatch were used to derive a stage–discharge relationship for each site. Due to weir malfunction at UNR, data are unavailable until D 180.

θ was measured using time domain reflectometry (TDR) with uniquely derived calibrations for each peat type following the calibration method of Topp et al. (1980). Two pits per micrometeorological station (RES and NAT) were dug in the *Sphagnum* moss (the approximate cutover peat/*Sphagnum* interface was 20 cm below the surface at RES) and four TDR probes per pit were installed horizontally at depths below the *Sphagnum* surface of 2.5, 7.5, 17.5, and 27.5 cm. The pits were backfilled with peat and covered with the intact *Sphagnum* moss.

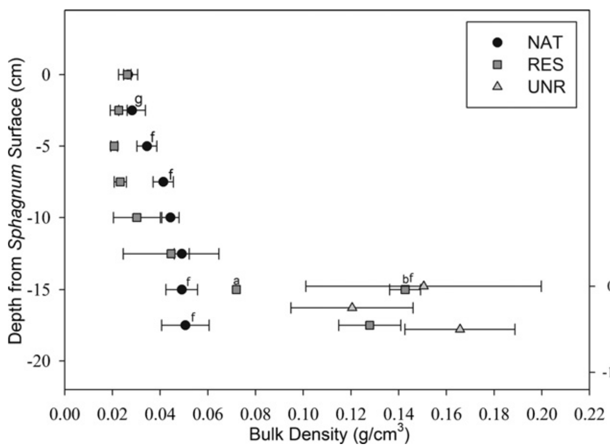

Fig. 2. Bulk density of the *Sphagnum* moss in 2.5 cm increments. The capitula (upper 1 cm) are represented by the 0 depth sample. The average cutover peat/*Sphagnum* interface is ~15 cm below the surface and is apparent through the larger standard deviations in the 15 cm samples at RES. [f] Significantly different than RES at $p = 0.001$. [g] Significantly different than RES at $p = 0.01$. The 15 cm RES samples were split into two groups of 2 (denoted by [a] or [b]) based the dominant material type (*Sphagnum* or cutover peat, respectively). $n = 4$.

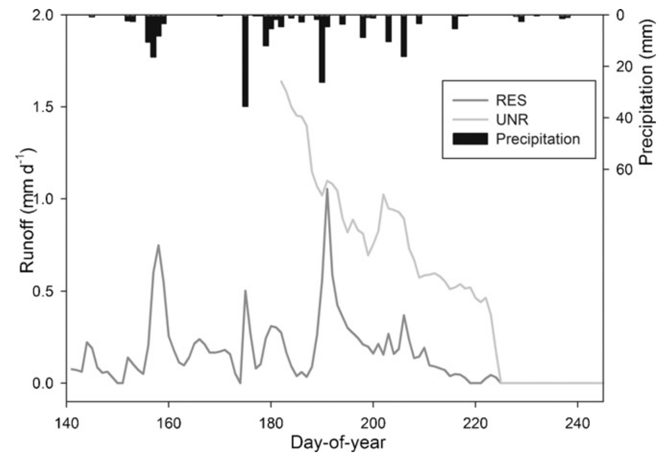

Fig. 3. Runoff depth (mm) over time from RES and UNR from D 140 to 245. UNR started on D 182 due to the site outflow being blocked.

Change in storage (ΔS) comprises both the water lost due to water table fluctuations and decreases in soil moisture, with

$$\Delta S = \Delta S_{\mathrm{wt}} + \Delta S_s, \quad (3)$$

where ΔS_{wt} is the change in storage related to the decrease in water table, given by

$$\Delta S_{\mathrm{wt}} = S_y \cdot h_{\Delta \mathrm{wt}} \quad (4)$$

where S_y is the specific yield (determined by McCarter and Price (submitted for publication) through monolith experiments) and Δh_{wt} is the change in water table height during the study period. ΔS_s is the change in soil water storage determined as

$$\Delta S_s = z_{\Delta\theta} \cdot \Delta\theta, \quad (5)$$

where $z_{\Delta\theta}$ is the height of the layer associated with a given change in moisture content and $\Delta\theta$ is the change in moisture content in $z_{\Delta\theta}$. Given the lack of θ measurements for UNR, the field ψ measurements were converted into θ values using the $\theta(\psi)$ relationship derived by McCarter and Price (submitted for publication) to determine ΔS_s.

The water budget encompasses all the inflow and outflow measurements from each study site, calculated as

$$\varepsilon + \Delta S_s = P + \mathrm{GW_{in}} - \mathrm{ET} - \mathrm{RO} - \mathrm{GW_{out}} \quad (6)$$

where RO is the runoff and ε is the residual term. $\mathrm{GW_{in}}$ and $\mathrm{GW_{out}}$ were minimal at RES and UNR (see above), thus were precluded from the water budget analysis for those sites.

One-way ANOVA was used to test the statistical differences between water table, soil water pressure and between sites, and the differences of average water table and θ between this study (2010) and the initial assessment (2000–2002).

4. Results

The regenerated *Sphagnum* moss (upper 12.5 cm) at RES had slightly lower average bulk densities than the mosses at NAT (Fig. 2). Although similar ($p > 0.05$) capitula bulk density (NAT 0.027, RES 0.026 g/cm^3) were observed, the regenerated mosses underneath the capitula show statistically significant (except at 2.5 cm) lower bulk densities until 12.5 cm (Fig. 2). The average position of the cutover peat/*Sphagnum* interface was between 15 and 20 cm (depending on microtopography) and was apparent through the large range of bulk density values in the 15 cm layer at RES. For this reason the 15 cm samples were split into two distinct groups, one consisting of *Sphagnum* and the other of cutover peat. Both samples were statistically different than NAT ($p < 0.001$) at the same depth. Below the interface region, the bulk density of RES (0.13 g/cm^3) is statistically different than NAT (0.05 g/cm^3) ($p < 0.001$) and the overlying *Sphagnum* ($p < 0.001$), while not statistically different than UNR (0.13 g/cm^3) ($p > 0.05$) (Fig. 2).

The spring and summer of 2010 were unusually dry with 201 and 206 mm of rainfall at RES and NAT, respectively, compared to the 30 years average of 366 mm; however, precipitation in 2010 was similar to the initial assessment in 2000–2002 (Table 1) which was also relatively dry. Most of the precipitation fell during large storm events >30 mm, with few smaller events in-between. ET was largest at NAT (329 mm) followed by UNR (290 mm) and lastly RES (242 mm). Runoff at RES was less than at UNR (Table 1 and Fig. 3) as was also reported by Shantz and Price (2006a) for the early post-restoration period.

Low horizontal hydraulic gradients observed at NAT for both $\mathrm{GW_{in}}$ and $\mathrm{GW_{out}}$, 2.75E−5 and 1.00E−5 cm/cm respectively, account for 12 mm of $\mathrm{GW_{in}}$ (from the adjacent treed bog section of BdB) and 1 mm of $\mathrm{GW_{out}}$ during the study period (Table 1). As noted by Shantz and Price (2006a) and corroborated in this study, there was negligible groundwater exchange at RES and UNR due to active drainage ditches surrounding the harvested site, so no values are reported.

The ΔS observed at UNR (Table 1) is an estimate due to the absence of soil moisture measurements (Table 2) due to equipment malfunction and extrapolated soil water retention curves generated by McCarter and Price (submitted for publication) and field ψ values (Table 2). This method resulted in a decrease in θ of 0.08 over the study period. Change in ΔS during the study period equated to −51, −62 and −57 mm of water lost over the study period at RES, UNR and NAT respectively (Table 1).

The water tables from the manual measurements (D 147–245) at NAT (−33.2 ± 9.0 cm) were higher than both RES (−42.3 ± 14.9 cm) and UNR (−42.3 ± 20.9 cm) (Fig. 4). Furthermore, both NAT and UNR had significantly different average water tables than RES ($p < 0.001$) during the study period. Note that the depth at RES is referenced to the new moss layer surface which is ~15–20 cm above the interface of the cutover peat. Thus, with respect to the old cutover peat surface the water table depths at RES and UNR were −27.3 ± 14.9 and −42.3 ± 20.9 cm, respectively.

Table 1
Comparison of 2010 water budget data to first 3 years post restoration. Measurements were taken from D 147–245 (runoff D 181–245).

Year	2000[a]		2001[a]		2002[a]		2010		
Site	RES	UNR	RES	UNR	RES	UNR	RES	UNR	NAT
Precipitation (mm)	220		254		210		201		206
ET (mm)	248	334	374	501	253	257	242	290	329
Runoff (mm)	15	18	13	43	2	17	7	37	0[b]
GW_{in}	–	–	–	–	–	–	–	–	12
GW_{out}	–	–	–	–	–	–	–	–	1
ΔS (mm)	–	–	–	–	–	–	−51	−23	−57
Residual (mm)	–	–	–	–	–	–	3	−103	−55

[a] Data from Shantz and Price (2006a,b).
[b] Assumed to be zero because no steams or visible surface outflows were present.

The water table at RES fluctuated almost entirely within the cutover peat and not within the regenerated moss layer (Fig. 5).

The water table at all sites generally decreased throughout the summer with the final water table (D 245) at NAT (−50.3 cm) being the highest followed by RES (−60.9 cm) and lastly the UNR (−86.3 cm) (Fig. 5). Generally, NAT had a higher water table than RES and UNR (Fig. 5), and less variability (Fig. 4). RES was most responsive to drying and precipitation events (Fig. 5) and thus showed the greatest water table variability (Fig. 4).

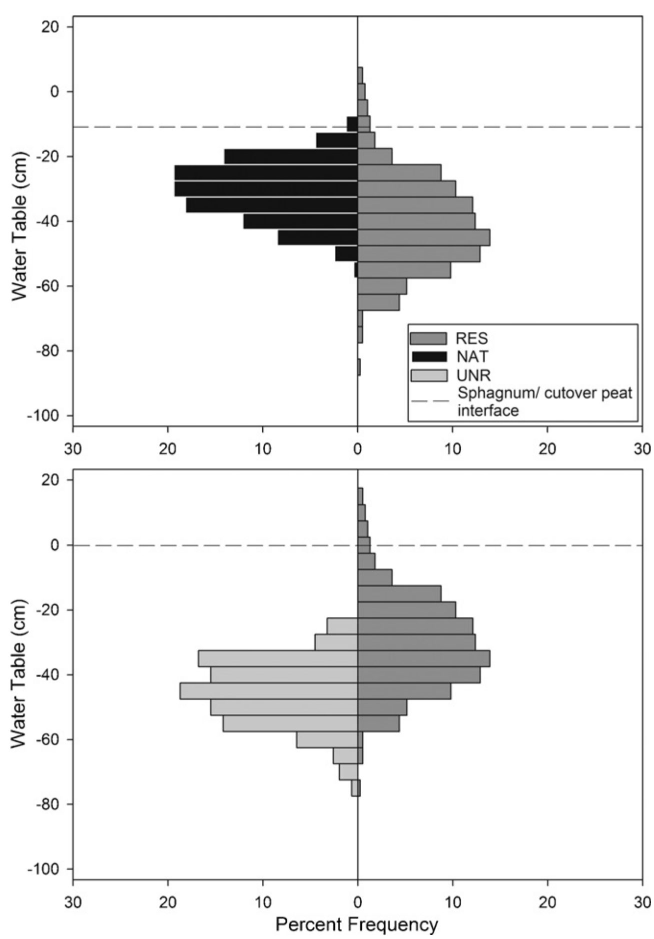

Fig. 4. Histograms of the manual measurement water tables. NAT (−33.2 ± 9.0 cm) had the highest and least variable average water table, followed by RES (−27.3 ± 14.9 cm) and UNR (−42.3 ± 20.9 cm). RES and NAT's datum (water table = 0) are referenced to the top of the *Sphagnum* moss, which represents the current surface of RES and NAT. The bottom panel's datum (RES and UNR) is analogous to the datum used by Shantz and Price (2006a) and is currently the *Sphagnum*/cutover peat interface (dashed grey line), ∼15 cm below the top of the regenerated *Sphagnum* moss at RES (as seen in the upper panel).

ψ at both 10 and 20 cm below the cutover peat show similar distributions and were not statistically different between RES and UNR (Table 2 and Fig. 6). There are no soil water pressure data for NAT, however, average θ within the moss layer at NAT was significantly higher ($p < 0.001$) than in the moss layer at RES at all depths (Table 2 and Fig. 7). θ in the cutover peat (i.e. 27.5 cm probe) at RES was not statistically different ($p > 0.05$) than the initial study (Shantz and Price, 2006a). Only the probes within the cutover peat (27.5 cm) at RES retained a significant amount of moisture throughout the summer, yet still had statistically lower θ ($p < 0.001$) than the same probe depth at NAT.

5. Discussion

The restored site (RES) of the BdB peatland has seen a distinct ecological improvement from its abandoned state. Since restoration, RES has developed many attributes that are common to the reference site (NAT) and other bog peatlands in the region (Poulin et al., 2012). Unlike UNR which lacks a *Sphagnum* moss cover, RES has developed a near complete *Sphagnum* moss carpet dominated by *Sphagnum* spp. (chiefly *S. rubellum*) and includes a variety of obligate vascular species characteristic of bogs (Poulin et al., 2012). However, other research at this site shows the community composition (i.e. a large abundance of herbaceous species) (Poulin et al., 2012) and carbon dynamics (Strack and Zuback, 2012) still vary from those at NAT, likely due to issues related to ecological succession (Poulin et al., 2012) and dissimilarity of key hydrological processes, which are explored below.

Although being a drier than normal spring and summer, rainfall and ET were not distinct from the first 3 years post-restoration (Table 1), which were also relatively dry. However, these data show that ET from RES (242 mm) is 87 mm lower than from NAT (329 mm) and 48 mm lower than from UNR (290 mm). The difference in ET between RES and NAT occurred despite both sites having a dominant vegetation cover of *S. rubellum*. The lower average θ in the upper 5 cm of *Sphagnum* at RES (0.12 ± 0.01) compared to NAT (0.23 ± 0.01) (Fig. 7) was probably limiting ET at RES. Given the relative close proximity of the sites (∼2 km) the incoming radiation, temperature and relative humidity were similar between sites (data not shown) thus differences in water availability would cause the differences in ET between sites (Kellner, 2001). The low moisture contents observed at RES decreased the water available for ET, thus lower ET was observed compared to NAT. The low ET and θ at RES signifies limited connectivity between the wetter cutover peat (0.74 ± 0.04) and *Sphagnum* capitula (evaporating surface). Given the lower bulk density of moss at RES compared to NAT (Fig. 2), the former likely had much poorer capillarity, hence limited ability to retain (i.e. a large abundance of large pores) and deliver water (i.e. low unsaturated hydraulic conductivity) to the surface (McCarter and Price, 2012).

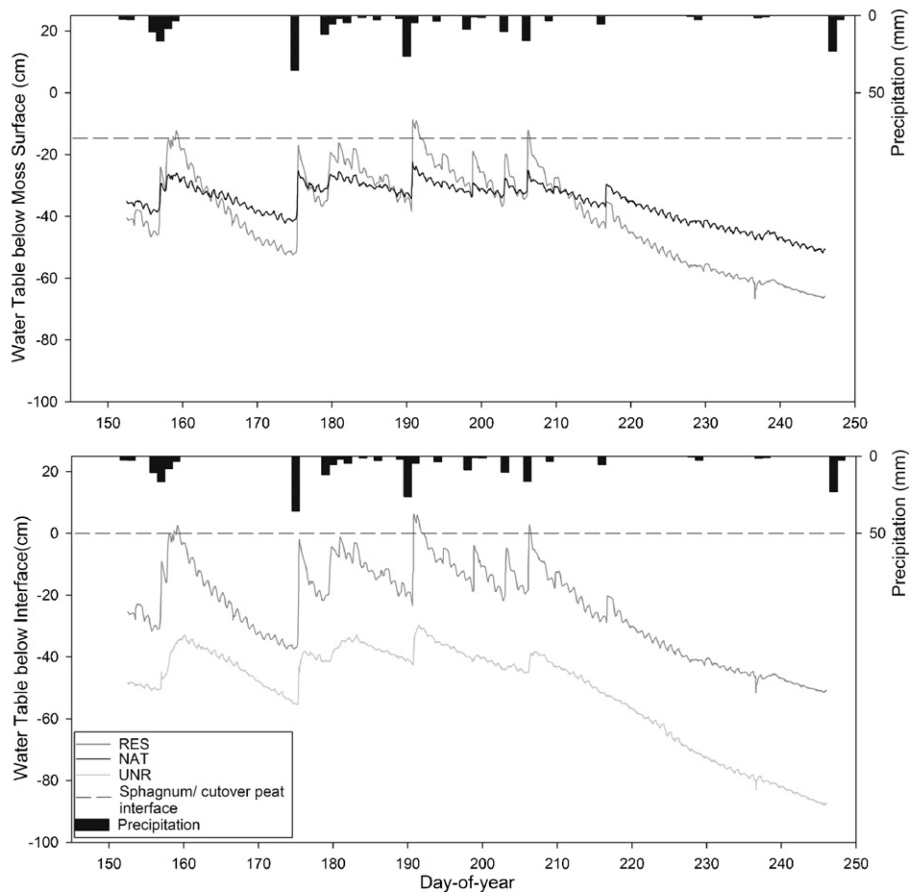

Fig. 5. Water tables over time (D 145–245) generated from the continuous water table data. RES and NAT's datum (water table = 0) are referenced to the top of the *Sphagnum* moss, which represents the current surface of RES and NAT. The bottom panel's datum (RES and UNR) is analogous to the datum used by Shantz and Price (2006a) and is currently the *Sphagnum*/cutover peat interface (dashed grey line), ~15 cm below the top of the regenerated *Sphagnum* moss at RES (as seen in the upper panel).

The flashy water table at RES (Fig. 5) indicates it responds to precipitation events more quickly and to a larger magnitude than both NAT and UNR, which is due to the wetter antecedent conditions of the cutover peat. The rapid response and the persistently drained state of the regenerated *Sphagnum* signify most of the precipitation was not retained in the loosely structured moss, but infiltrated and saturated the cutover peat or potentially flowed along the cutover peat/*Sphagnum* interface (i.e. at periods of high water table) to generate runoff (Fig. 3). The new moss had little water retention capacity (Fig. 7) and imparts a low hydraulic resistance, which explains the persistence of flashy runoff hydrographs for RES (Fig. 3) as was also noted by Shantz and Price (2006b). We note, however, that the ratio of runoff between RES and UNR in 2010 was 1:5.2, compared to 1:2.6 before the moss layer developed, signifying some water detention was caused by the moss layer. The water table at RES was statistically higher than at UNR; the water table at UNR was not statistically different from the initial assessments (Table 2). Since the initial assessments, the water table at RES increased by a further ~5–10 cm (Table 2). This may in part be explained by this detention of runoff. Despite the higher water table, there was no evidence that ET increased in 2010 compared to 2000–2002 (Table 1), as the wetter cutover peat still had limited connectivity with the regenerated *Sphagnum*.

At BdB, ET and precipitation (Table 1) are the dominant outputs and inputs of water, respectively. However, unlike RES and UNR, NAT was influenced by groundwater interaction due to the site's position within BdB peatland (i.e. lower in elevation than the dome of BdB), but does not represent a major source (or sink) of water within the study period (Table 1). The ΔS (Table 1) values appear similar between the sites; however, the largest portion of ΔS at RES was due to water lost from the cutover peat and not from the regenerated *Sphagnum* moss. This suggests it functions similarly to that of UNR. In contrast to the dominant influence of cutover peat on ΔS at RES, ΔS at NAT was greatest 15–22.5 cm below the surface within the dead yet undecomposed moss. The differences in the location of water storage changes at RES and NAT affect water availability for ET, and may be a limiting factor for carbon sequestration (McNeil and Waddington, 2003) at RES. These differences indicate that the progression of restoration towards conditions observed in the reference system is incomplete, with many of the processes still functioning similarly to UNR.

The inability of the regenerated *Sphagnum* moss at RES to retain water compared to that at NAT signifies that the water table and runoff dynamics are still controlled by the cutover peat rather than the regenerated *Sphagnum* moss layer. Until the regenerated moss layer develops greater water retention (i.e. through decay, collapse at the base, and lateral branch infilling (Waddington et al., 2011)), it is unlikely that the water table will behave similarly to a natural peat forming system. This includes its carbon sequestration function; although measurements for the dry 2010 season were inconclusive since both RES and NAT experienced a net carbon loss (Strack and Zuback, 2012). Lucchese et al. (2010) postulated that a 19 cm thick regenerated *Sphagnum* layer would be needed at BdB to provide sufficient water storage to maintain the water table above the old cutover peat, requiring 17 years based on their measured moss accumulation rates. However, the results of this

Table 2
Comparison of 2010 data to first 3 years post restoration. All measurements referenced to the interface between the new *Sphagnum* moss and cutover peat at the restored site, ~15 cm of moss growth has occurred on the cutover surface. Water table $n = 476$, 201, and 248 for RES, UNR, and NAT, respectively. Measurements were taken from D 147–245 (runoff D 181–245). RES $\Psi_{10\,\mathrm{cm}}$ $n = 65$, UNR $\Psi_{10\,\mathrm{cm}}$ $n = 68$, $\Psi_{20\,\mathrm{cm}}$ $n = 66$, UNR $\Psi_{20\,\mathrm{cm}}$ $n = 67$.

Year	2000[a]		2001[a]		2002[a]		2010		
Site	RES	UNR	RES	UNR	RES	UNR	RES	UNR	NAT
Average water table (cm)	−30.0 ± 9.5*	−45.5 ± 6.0***	−30.4 ± 10.5*	−40.4 ± 6.0***	−37.2 ± 14.3**	−44.3 ± 6.6***	−27.3 ± 14.9[b]	−42.3 ± 20.9**	−33.2 ± 9.0**
Average *Sphagnum* $\theta_{-5\,\mathrm{cm}}$	–	–	–	–	–	–	0.12 ± 0.01	–	0.23 ± 0.01
Average cutover peat $\theta_{-5\,\mathrm{cm}}$	0.80 ± 0.03	0.41 ± 0.02	0.72 ± 0.03	0.37 ± 0.02	0.69 ± 0.09	0.41 ± 0.04	0.74 ± 0.04	–	–
Average $\Psi_{-5\,\mathrm{cm}}$ (mb)	−6.8 ± 8.3	−41.8 ± 17.3	−8.7 ± 9.7	−29.8 ± 19.7	−24.8 ± 15.9	−39.9 ± 16.8	–	–	–
Average $\Psi_{-10\,\mathrm{cm}}$ (mb)	–	–	–	–	–	–	−43.0 ± 12.2	−44.1 ± 13.1	–
Average $\Psi_{-20\,\mathrm{cm}}$ (mb)	–	–	–	–	–	–	−41.4 ± 13.0	−40.6 ± 10.5	–

[a] Data from Shantz and Price (2006a,b).
[b] −42.3 cm from *Sphagnum* surface.
* Significantly different than RES at $p = 0.05$.
** Significantly different than RES at $p = 0.001$.
*** Significantly different than UNR 2010 at $p = 0.001$.

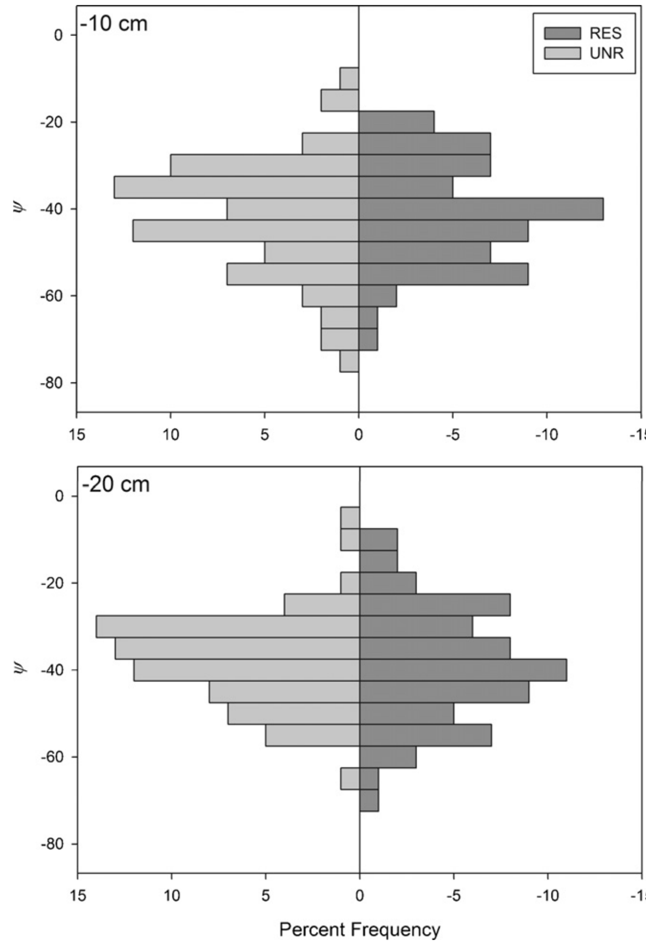

Fig. 6. Histograms of soil water pressures at 10 and 20 cm below the cutover peat surface (~30 and 40 cm below the regenerated *Sphagnum* surface). RES and UNR had similar average soil water pressures at both depths. The cutover peat/*Sphagnum* interface was at ~20 cm below the surface.

study indicate that the total thickness of the moss layer might not be as important as the moss' hydraulic properties (connectivity, retention, etc.) to the success of the restoration.

The vertical growth of the *S. rubellum* carpet (~15 cm) was greater than the rise in water table (~5–10 cm) since restoration, leading to the current low average water tables of −42.3 cm below the moss surface. Although *S. rubellum* is a hummock species it may not be as well suited to the low water tables observed at RES as other hummock *Sphagnum* species. For example, *S. fuscum* can thrive with average water tables similar to those observed at RES (−42.3 cm), due to its greater ability to transport water (Clymo, 1987; McCarter and Price, 2012; Rydin, 1985, 1993), while *S. rubellum* is most productive with higher water tables, typically between 10 and 20 cm below the capitula (Clymo, 1987). This indicates that the water table at RES still needs to rise by ~20 cm for the regenerated *S. rubellum* to be in its optimal growth habitat. However, this assumes that the moss structure (i.e. bulk density, water retention capacity, capillary conductivity, etc.) is similar to that of naturally occurring mosses. Over time, we anticipate that the base of the new moss layer will become partially decomposed and collapse to result in a medium with a smaller pore-size distribution and better water retention properties. Once the water table has risen further (i.e. primarily fluctuating within the regenerated *Sphagnum* moss), it seems likely that it should be able to retain enough moisture to promote a carbon accumulating system.

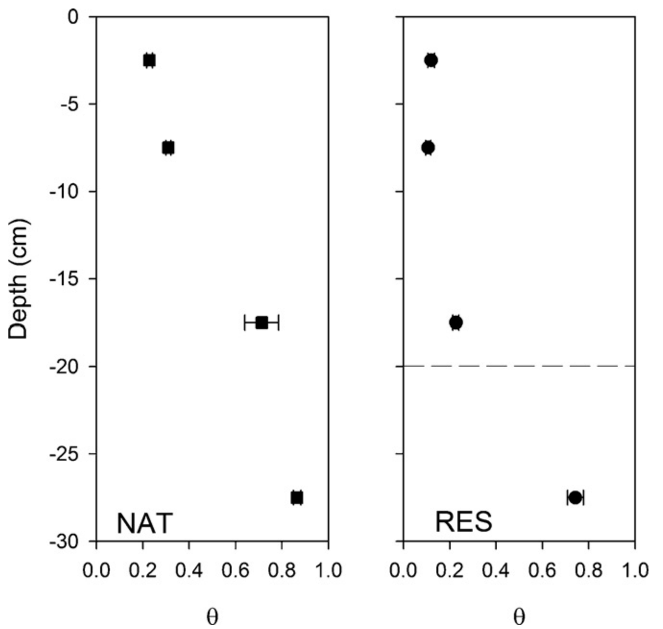

Fig. 7. Average volumetric soil moisture contents of the *Sphagnum* and cutover peat at RES and NAT. Measurements centred at 2.5, 7.5, 17.5, and 27.5 cm below the *Sphagnum* surface. The dashed grey line represents the approximate interface between the regenerated *Sphagnum* moss and the cutover peat. Error bars indicate 1 standard deviation. All NAT measurements are significantly different than RES at $p = 0.001$.

The water balance method allows for an assessment of the hydrological fluxes and stores between the three sites but is subject to measurement errors. The residual terms (1%, 38% and 27% of the precipitation at RES, UNR and NAT, respectively) (Table 1) represents the cumulative error from all water balance components. Through estimating ΔS for UNR using field ψ and a θ–ψ relationship derived by McCarter and Price (submitted for publication) to determine the field θ values at 10 and 20 cm, there was the potential for more error in this calculation compared to RES and NAT. This error could partly explain the high residual term associated with UNR. ET estimation probably accounts for most of the error within the water budget, given its large magnitude, chiefly error associated with the lysimeters used to calibrate the coefficient of evaporability (Van Seters and Price, 2001), but also combined errors in net radiation and soil heat flux (Price, 1996). An error in ET of ±15% represents ~36–50 mm of water. However, spatial variations, measurement errors and imperfect stage–discharge relationship (coefficient of determination > 0.90) also injected further uncertainty within the water budget (Van Seters and Price, 2001), although these fluxes were small. Error was introduced due to the unavailability of runoff measurements at UNR prior to D180; however, runoff prior to this was very limited because of a collapsed culvert draining UNR causing water to be retained on site. The very high flows on D180 reflect the rapid drainage of stored water after the culvert was repaired (Fig. 3). The visible flows prior to its repair were less than at RES and represent <6 mm of unaccounted outflow.

6. Conclusion

Although the restoration measures implemented in 1999 had a large and immediate effect on the site hydrology of BdB (Shantz and Price, 2006a), after 10 years of post-restoration development the system is still primarily controlled by water relations in the cutover peat beneath the regenerated *Sphagnum* moss. Although there is a 15–20 cm layer of regenerated *Sphagnum* moss at BdB, its properties are still distinct from a natural system and must evolve further for the hydrological variables to converge. The average water table depth is still outside the optimal range for *S. rubellum*, which covers the site. As the system evolved and the moss layer developed, the vertical growth outpaced the rise in water table, resulting in less favourable conditions for *S. rubellum*, and may result in a shift to *S. fuscum*. The low water tables and hydraulic properties of the moss has led to poor hydraulic connection with the (generally wetter) cutover peat, hence the regenerated *Sphagnum* being ~50% drier than the same species at NAT. The inability for the regenerated *Sphagnum* to transmit water from the wetter cutover peat to the top of the *Sphagnum* is potentially limiting the available moisture for the *Sphagnum* itself, thus possibly retarding the progress of the restoration (and net carbon sequestration). Assuming the mosses can adapt or tolerate this in the short term, more favourable conditions will develop in time as the water retention capacity of the mosses, particularly at the base of the profile, increases with decomposition and compaction or a shift in species from *S. rubellum* to *S. fuscum*. Only then will the water table fluctuate primarily within the regenerated *Sphagnum* moss layer and be more effectively transmitted up the profile to the capitula to facilitate net carbon sequestration.

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Glossary

Soil water pressure: The pressure of the soil water held within the soil.
Volumetric soil moisture content: The fraction of the total volume of soil that is occupied by the water contained in the soil.
Water table: The surface where the water pressure head is equal to the atmospheric pressure.
Evapotranspiration: The sum of evaporation (vaporization of liquid water) and transpiration (water loss vapor from plants).
Runoff: Water that is not retained in the soil matrix and flows overland or through ditches.
Lysimeter: A device used to measure actual evapotranspiration.