Water budget analysis of small forested boreal watersheds: comparison of *Sphagnum* bog, patterned fen and lake dominated downstream areas in the La Grande River region, Québec

Simon Tardif, André St-Hilaire, René Roy, Monique Bernier and Serge Payette

ABSTRACT

A water budget analysis (precipitation (*P*), surface runoff (*Q*), evapotranspiration (ET) and storage variations (ΔS)) was completed over a 3-year span for two *Sphagnum* bogs, three patterned fens and two shallow lakes all located in the La Grande River watershed in central Québec. The high variability of *P* from 2005 to 2007 during summer and fall (July to October) allowed us to produce water budgets over a large spectrum of wetness conditions at seasonal and event timescales. Bogs and fens (not lakes) have the intrinsic ability to keep the water table near the surface most of the time, which affects *Q*. Fens and lakes showed a similar hydrological behavior when compared to bogs, in spite of differences in *Q* and ΔS variability due to the typical vegetation structure of fens. This structure also tends to produce sharper rises of *Q* when compared to lakes that have overall smoother hydrograms. The dominant water budget term for bogs, fens and lakes was ΔS, *Q* and ET, respectively. Finally, an adaptation of the Penman–Monteith equation was successfully used to estimate potential ET. This revised method is based on peatland vegetation identification that provides a simple weighing factor for stomatal resistance.

Key words | aqualysis, bogs, evapotranspiration, fens, lakes, water budget

Simon Tardif
André St-Hilaire (corresponding author)
Monique Bernier
INRS-ETE,
490 De la Couronne,
Québec,
Québec G1K 9A9,
Canada
E-mail: *andre.st-hilaire@ete.inrs.ca*

René Roy
Hydro-Québec/Ouranos,
550 Sherbrooke ouest,
19ième étage tour ouest,
Montréal,
Québec H3A 1B9,
Canada

Serge Payette
Département de Biologie et Centre d'Études Nordiques,
Université Laval, Québec,
Québec,
Canada

INTRODUCTION

Peatlands are common ecosystems across Canada, covering about 15% of the total land surface (Tarnocai *et al*. 2000). Peatlands are the dominant wetland type of the boreal forest biome (Glaser & Janssens 1986) and they are one of the main water reservoirs of the northern hemisphere (National Wetlands Working Group 1988). In the province of Québec, at least 12% of the land surface is covered by peatlands (Payette & Rochefort 2001) which are largely distributed in a belt between the southern boreal forest and the southern limit of the arctic tundra, i.e., from 49°N to 58°N. The study area, the La Grande River watershed (97,600 km^2), is located in the middle of this belt and hosts a major hydroelectric complex that is producing close to 50% of Québec's electricity needs. Despite the large distribution of peatlands in the boreal biome, hydrological processes controlling their development and functioning are still ill-defined in rainfall–runoff models used to forecast and simulate water inflows to reservoirs. The poorly known processes generating surface runoff and hydrological connectivity within the drainage basin explains the absence of peatland water-routing in most models. Hydrological forecasts are important for water management upstream of existing hydraulic structures and also for the design of future facilities. Given current concerns on climate change issues, wetlands are also of great interest since hydrological fluctuations influence methane (CH_4) emission and/or carbon dioxide (CO_2) sequestration (Blodau 2002; Bubier *et al*. 2003; Belyea & Malmer 2004), two key

doi: 10.2166/nh.2014.219

greenhouse gases. For those reasons, a better understanding of bogs and fens hydrology is therefore necessary as a first step towards improving forecast models for different uses.

From an ecological point of view, bogs and fens are often two evolution phases of the same ecosystem. Fens are minerotrophic peatlands, meaning that the water (and nutrients) inputs include runoff/groundwater from the upslope area of the drainage basin, while bogs are ombrotrophic, which mean that they are (almost) exclusively rain-fed peatlands. In North America, the natural developmental pattern of peatlands consists of a young phase (fen) that evolves towards a mature phase (bog) through continuous peat accumulation (Gorham & Janssens 1992; Kuhry *et al.* 1993). Recent research on both bogs and fens hydrology focused on atmospheric, surface and groundwater fluxes, as well as carbon cycling (Price *et al.* 2005). As a result, our understanding of the hydrological processes in peatland ecosystems has improved in recent years. Most of these studies used a water budget approach and focused on some or all terms of the budget (Kane & Yang 2004; Déry *et al.* 2005).

Bogs are known to lack, or to have strongly reduced surface runoff most of the time, with subsurface flow being the dominant lateral flowpath (Quinton & Marsh 1999). The lack of surface hydrological connection at the local scale leads to underestimated runoff at the larger scale of the watershed. Quinton *et al.* (2003) indeed showed that, at the watershed scale, runoff was negatively (positively) correlated with the importance of bogs (fens) areal coverage. On the other hand, patterned fens, with their typical surface structure composed of an alternation of ponds and vegetated strings, seldom lack surface runoff. The fen microtopography influences water storage capacity (Price & Maloney 1994) whereas the total pond area regulates surface runoff (Glenn & Woo 1997). To add more complexity, it seems that for a given area of open water, the geometric distribution of the ponds influence runoff regimes at both mid-size scale ($\approx 100\ \mathrm{km}^2$) (Spence 2006) and local scale ($<1\ \mathrm{km}^2$) (Tardif *et al.* 2009). Hydrological similarities exist between bogs and fens, with the buffer effect being inversely proportional to water table level (Quinton & Roulet 1998; Price & Waddington 2000). The buffer effect is related to hydraulic conductivity, which is dependent on the structure of the peat, the latter being dependent on depth (Holden & Burt 2003) but also on the compressive–expansive nature of peat in relation to saturation conditions. This phenomenon known as 'mire breathing' (Kellner & Halldin 2002) allows the peat surface to follow the frequent water table rises and drawdowns during summer and fall (Roulet 1991).

In northern Québec, wetter conditions prevailed during the twentieth century, when compared to previous decades or centuries. Increased wetness had an impact both on lakes (Payette & Delwaide 1991, 2004; Bégin 2001) and subarctic rivers (Payette & Delwaide 2000). These wet conditions associated with a high water table over a long period also impacted peatland development. In fens, several vegetated strings are degraded and submerged, causing increased impoundment and pond coalescence. The degradation of the vegetation structure and the correlative increase of the pond surface caused by high water table conditions have been termed 'aqualysis'. In that perspective, the transformation of a fen to a shallow lake represents the ultimate phase of aqualysis. Will aqualysis continue to expand in the next decades? Recent updates in climate change studies anticipate for the next century a probable increase in mean annual precipitations combined with warmer temperatures (Christensen *et al.* 2007). Hydrological effects of a warmer and wetter climate are now relatively well documented for mid-latitude Québec and, to our knowledge, all results show a consistent pattern, i.e., an increase in annual runoff is anticipated (Clair *et al.* 1998; Slivitsky *et al.* 2004; Dibike & Coulibaly 2005; Frigon *et al.* 2007). These projected climatic conditions could contribute in maintaining and/or even intensifying aqualysis process in the area; further investigations on the hydrological budget of aqualysed peatlands and shallow lakes (i.e., as examples of fully aqualysed fens) are therefore required.

The first objective of this study is to compare water budgets of bogs, fens and small shallow lakes at both seasonal and event timescales. To achieve this, it is hypothesized that upslope influences from the forested area is similar between sites, a condition that was imposed a priori for site selection. The second goal of this study is to evaluate the field methods used for water budget terms calculations. The final goal is to present an original adaptation of potential evapotranspiration (PET) estimation method developed from field observations. By comparing sites showing a relatively large spectrum of aqualysis conditions, a better understanding of current peatland hydrology as well as some insights into their responses to the future climatic conditions will be gained.

METHODOLOGY

Study sites

Seven sites, all located in the La Grande River watershed in mid-latitude Québec were selected for this study: two bogs (sites 1 and 2), three fens (sites 3, 4 and 5) and two headwater lakes (sites 6 and 7). Sites 1, 2 and 3 are located in the western (54°N, 77°W), low-altitude (100 m above sea level – a.s.l.) and drier part of the La Grande River watershed whereas sites 4, 5, 6 and 7 are located in the eastern (54°N, 75°W), upper (400 m a.s.l.) and wetter part of the watershed (Figure 1). For the western sector (not available for eastern sector), long-term climate normals of the reference period (1971–2000) are the following: −3.1 °C for mean annual temperature and 680 mm for mean annual precipitation (Environment Canada 2008). Both bogs have almost no open water (0 and 1% of total area, respectively). The studied fens at sites 3, 4 and 5 have

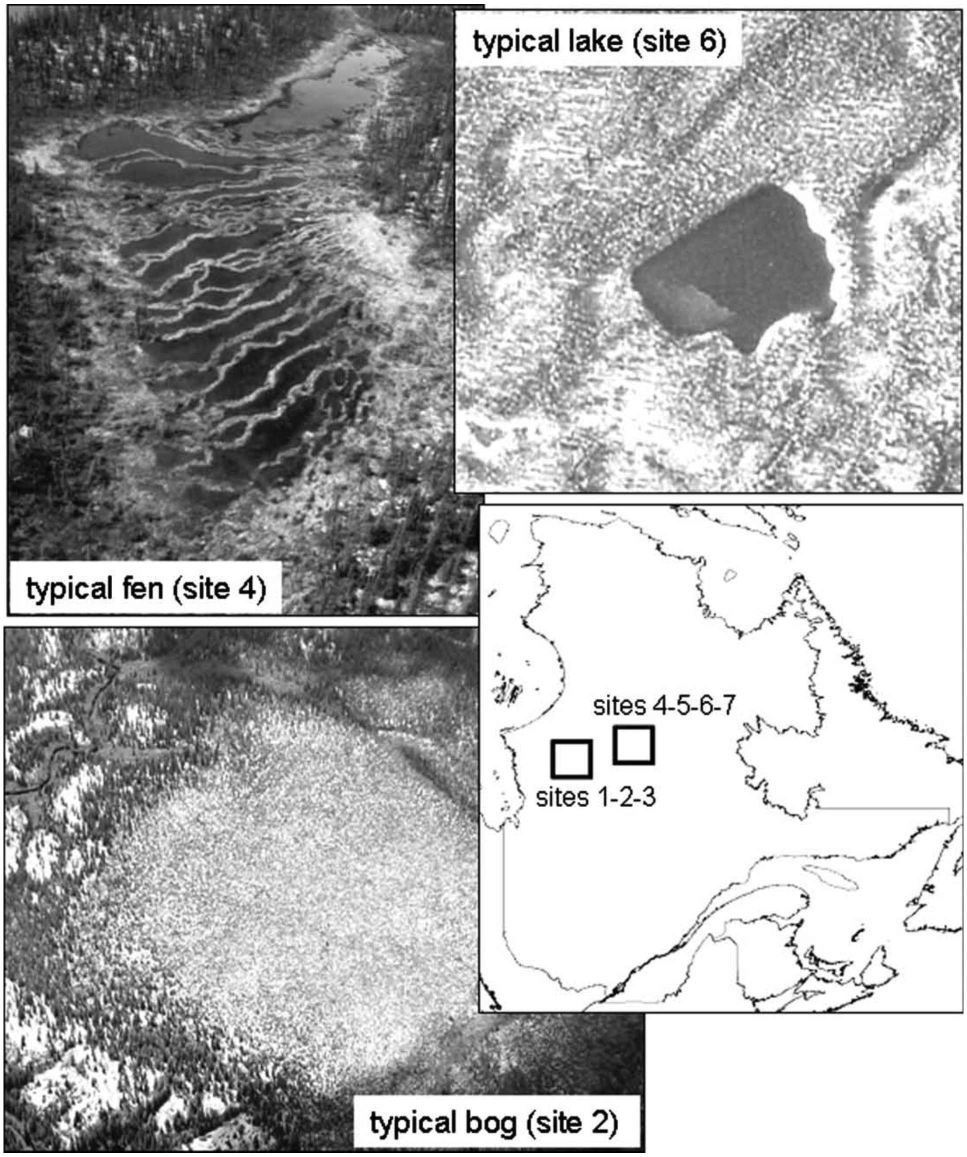

Figure 1 | Pictures of study sites. For sites 3, 4 and 5, outlet is visible at the upper part of the pictures.

open water ratios of 4, 35 and 35%, respectively. Small shallow lakes were considered to be representative of mature, fully aqualysed systems, i.e., 100% cover of open water.

Physiographic data characterizing each site were extracted from a database constructed in a Geographical Information System and using georeferenced aerial pictures. Watershed delineation was performed using digital elevation data and pictures, and the boundaries were confirmed by visual inspection of slopes in the field. All sites except both bogs have only one apparent outlet and all have drainage areas with the same order of magnitude (Table 1). The vegetation surrounding all sites is composed of a mixture of mature black spruce (*Picea mariana*) and lichens woodlands in the forested parts of the watersheds (Figure 1 and Table 1). Bogs hummocks are covered by small trees (*Picea mariana* and *Larix laricina*), shrubs (*Kalmia polifolia*, *Chamaedaphne calyculata* and *Vaccinium oxycoccos*), mosses (*Sphagnum fuscum* and *S. rubellum*) and lichens whereas hollows are generally covered by sedges and aquatic *Sphagnum* species. Both bogs have the same vegetation cover, except that in site 1 trees are more abundant and larger than in site 2. Fen vegetation is composed of small trees (*Picea mariana* and *Larix laricina*), shrubs (*Kalmia polifolia* and *Chamaedaphne calyculata*), sedges and a dense moss carpet with a dominance of brown mosses in hollows and around pools, and several *Sphagnum* species on the strings.

Hydrometeorological data and water budget terms

Data from three summers and falls are presented in this paper. Concomitant daily data were gathered between July 11 and October 31 for the years 2005, 2006 and 2007. The period covered in this study corresponds to the time when sites were cleared from the influence of spring melting until shortly prior to winter freezing. Data were collected during those periods at all sites except for site 7 which did not record data required for water budget calculations between July 11 and August 25, 2005 and had missing runoff data for 2007.

Meteorological data were obtained using sensors connected to CR10 and CR10x dataloggers (Campbell Scientific) installed in towers powered by a 12 V battery and 20 W solar panel. Data were sampled every 30 s, integrated into an hourly time step and then converted into daily data.

The water budget is calculated using Equation (1):

$$P - \mathrm{ET} - Q + / - \Delta S = \eta \qquad (1)$$

where P is the precipitation, ET is the evapotranspiration, Q is the specific surface runoff, ΔS is the storage variation of the water level and η is the residual term of error that is positive when there is water excess and negative when there is a water deficit (all units being in mm/day).

Precipitations

Rainfall was measured *in situ* (except for site 7) with a tipping bucket rain gauge (CS700 or TE525 combined with a CS705 glycol–methanol reservoir for winter precipitation, Campbell Scientific). Precipitations were corrected for sampling error according to Ducharme & Nadeau (2005), i.e., an increase of 9% for each liquid precipitation event.

Table 1 | Physiographic characteristics of study sites

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Ecosystem	Bog	Bog	Fen	Fen	Fen	Lake	Lake
Watershed area (m^2)	21,300	154,600	217,100	40,500	64,500	77,700	89,300
Bog/fen/lake area (m^2)	6,100	117,100	76,200	14,200	27,600	36,900	28,600
Fraction of watershed occupied by uplands (%)	71	24	65	65	57	53	68
Open water area (m^2)	0	150	2,900	4,900	9,600	36,900	28,600
Fraction of bog/fen/lake occupied by open water (%)	0	1	4	35	35	100	100
Vascular vegetation (%)	50	49.5	57.6	45.5	45.5	0	0
Non-vascular vegetation (%)	50	49.5	38.4	19.5	19.5	0	0

For site 7, the same precipitation data as site 6 were used, because of the small distance between the two sites (less than 2 km) and the close physical similarity of their watershed.

Runoff

Surface runoff was calculated via stage-discharge curves established at each site except for sites 1 and 2 (bogs) where there was no surface runoff. Instantaneous discharge was measured at each site visit with an integration of water velocities measured using a flowmeter (Marsh-McBirney flowmate 2000) at a wetted cross-section of the outlet, near the stilling well. There was only one outlet at each of the fen and lake sites. Outlets were trapezoidal in shape and flows had relatively low turbulence, with stable cross-sectional area throughout the study period. Given that the study period excluded the spring, water levels used in the present study were limited to those inferior to the bankfull level of each outlet. Water levels at each outlet were measured continuously with a hydrostatic pressure gauge (Levelogger model 3001, Solinst) located in a stilling well installed on the bank of each outlet. The recorded levels were corrected for barometric fluctuations using a linear regression between data from a Barologger (Solinst) and another barometric pressure gauge located in the nearby meteorological tower (61205V, R.M. Young). The uses of regressions were required at each site because of risk of error from the sole use of the Barologger that were affected by frost during winter months of 2005–2006. Regression equations of data collected over a 2-month period in the summer of 2005 (values ranged from 935 to 1,015 hPa) have an R^2 of at least 0.97. In order to be comparable with precipitation, evapotranspiration and water level data, discharge data (L/d) were finally converted into specific runoff (mm/d) by dividing them by watershed area.

Evapotranspiration

Daily PET was estimated with an adaptation of the Penman–Monteith (PM) model (Equation (2)) from Allen *et al.* (1998):

$$\lambda \mathrm{ET} = \frac{\Delta(R_\mathrm{n} - G) + \rho_\mathrm{a} c_p((e_\mathrm{s} - e_\mathrm{a})/r_\mathrm{a})}{\Delta + \gamma(1 + (r_\mathrm{s}/r_\mathrm{a}))} \qquad (2)$$

where ET is the potential evapotranspiration (mm/day), λ is the specific latent heat of vaporization (MJ/kg), Δ is the slope of the saturated vapor pressure–temperature curve (kPa/°C), R_n is the net radiation (MJ/m^2/day), ρ_a is the mean air density at constant pressure (kg/m^3), C_p is the specific isobaric heat capacity of the air (J/kg/°K), e_s–e_a is the vapor pressure deficit between saturation (s) and actual conditions (a) (kPa), r_a is the aerodynamic resistance (s/m), γ is the psychrometric constant (kPa/°C) and r_s is the stomatal resistance (s/m) of vegetation. Data required for computation are air temperature, incoming radiation, surface albedo, latitude, barometric pressure, relative humidity, wind speed and height of vegetation. The calculation procedure of the required variables for PM model is following Ward & Trimble (2004) and Allen *et al.* (1998) protocols.

The heat flux density to the ground (G) was computed with Equation (3) (Ward & Trimble 2004) where T_{t+1} and T_{t-1} are mean daily temperatures during the following and previous days and Δt is duration (in days) between T_{t+1} and T_{t-1}.

$$G = 4.2 * \frac{(T_{t+1} - T_{t-1})}{\Delta t} \qquad (3)$$

Aerodynamical resistances over water ($r_{\text{a-water}}$) and vegetation ($r_{\text{a-vegetation}}$) were computed with Equations (4) and (5) from Shuttleworth (1996) where w is wind speed (m/s at 2 m), d is the zero plane displacement height (m), zov is the roughness length governing momentum transfer (m), zoh is the roughness length governing transfer of heat and vapor (m), $zhum$ is the height of humidity measurements (m) and k is the von Karman's constant (–0.41):

$$r_{\mathrm{a-water}} = \frac{4.72 * \log(2/0.00137)^2}{(1 + 0.536 * \mathrm{w})} \qquad (4)$$

$$r_{\mathrm{a-vegetation}} = \frac{[\log((2-d)/zov) * \log((zhum - d)/zoh)]}{k^2 w} \qquad (5)$$

Some criticisms have been made on the use of stomatal resistance (r_s) in peatlands (Lafleur & Roulet 1992) because an important part of their surface is composed of a cryptogam canopy (non-vascular), and accordingly, direct application of the PM model may be considered inadequate. To solve this problem, Lafleur *et al.* (2005) used a correction factor based on the slope of a linear regression between calculated PET using PM with a null stomatal resistance ($r_s = 0$) and spot measurements of actual ET (AET) using eddy covariance technique. Since AET measurements were not available for this study, a different approach was used based on knowledge of watershed vegetation, here defined as the field structure method. The first step was to define values of r_s in the same general way as Martin *et al.* (1997), i.e., as a function of vapor pressure deficit. As shown by Summer & Jacobs (2005), the maximum conductance ($c = 1/r$) of a surface can be related to reduction of net radiation according to vapor pressure deficit. Instead of fixing maximum conductance with radiation, we empirically adjusted the logarithmic function (Equation (6)) to fit the range of r_s values proposed by Kellner (2001) for Swedish boreal bogs with vegetation cover similar to our study sites (from 0 to 400 s/m):

$$r_s = \frac{1}{(-0.2 * \ln(e_s - e_a) + 0.25) * (1/70)} \tag{6}$$

where r_s is the stomatal resistance (s/m) and e_s and e_a are respectively vapor pressure at saturation and current condition. The second step was to calculate site ET (Equation (7)), i.e., the sum of each surface ET multiplied by their respective fraction of site area (obtained from Table 1):

$$\mathrm{ET} = \mathrm{ET}_w * A_w + \mathrm{ET}_v * A_v \tag{7}$$

where A is the fraction of surface area and w and v refer to the two compartment types, i.e., open water ($r_{\text{a-water}}$ but no r_s) and vegetation (both $r_{\text{a-vegetation}}$ and r_s).

Storage variation

Water level (WL) was first measured in bogs and fens with a network of wells equipped with hydrostatic pressure gauges (Levelogger, Solinst) and corrected for barometric fluctuations (see the section Runoff). Wells were made of a long perforated PVC pipe inserted in the peat matrix until they reach the mineral substrate (between 1 and 2.5 m for sites 1, 3, 4 and 5, and up to 4 m for site 2). Wells were inserted in nylon stockings to prevent peat particles from filling up the pipes. The pressure gauges were suspended near the bottom of the pipes using a tin wire attached to the well's cap. Lakes WL were monitored using the same pressure gauges but anchored on a concrete block at the bottom of the lake rather than in a well. WL was used subsequently to define the dry and wet conditions in analysis of water budget at event timescale.

The next step was to convert WL data into storage variations (ΔS) using Equation (8), which is a variation of the method proposed by Proulx-McInnis *et al.* (2013):

$$\Delta S = \Delta WL * p_w * A_w + \Delta WL * p_v * A_v \tag{8}$$

where ΔWL is the water level variation, p is the porosities and A is the fraction of surface area of the two compartment types (v for vegetation and w for open water). For open water and peat, we used porosity values of 1 and 0.97 as measured by Levrel & Rousseau (2010) in a nearby peatland with very similar vegetation.

RESULTS

Data used in water budget terms

Before analysing results from water budget at both seasonal and event timescales, it is necessary to control the quality of the observations, in order to identify some of the potential caveats of the proposed methods. Concerning P, the quality of data was verified by comparing observations of site 3 with those from the Environment Canada station at LG-2 airport located 10–20 km away from sites 1, 2 and 3 as well as those from the Hydro-Québec station on the Necopastic River which is slightly closer, i.e., 1 to 10 km away from the same sites. Globally, over a season, measurements were coherent with those obtained at other stations. On the other hand, when shorter timescales are considered, data from sites 1, 2 and 3 sometimes show important differences in precipitation measured from various storm events in summer (Figure 2).

Concerning Q, rating curves were difficult to establish. Remoteness of sites, resulting in only few points available for the curve fitting ($\leq$10 at each site) and low water velocity

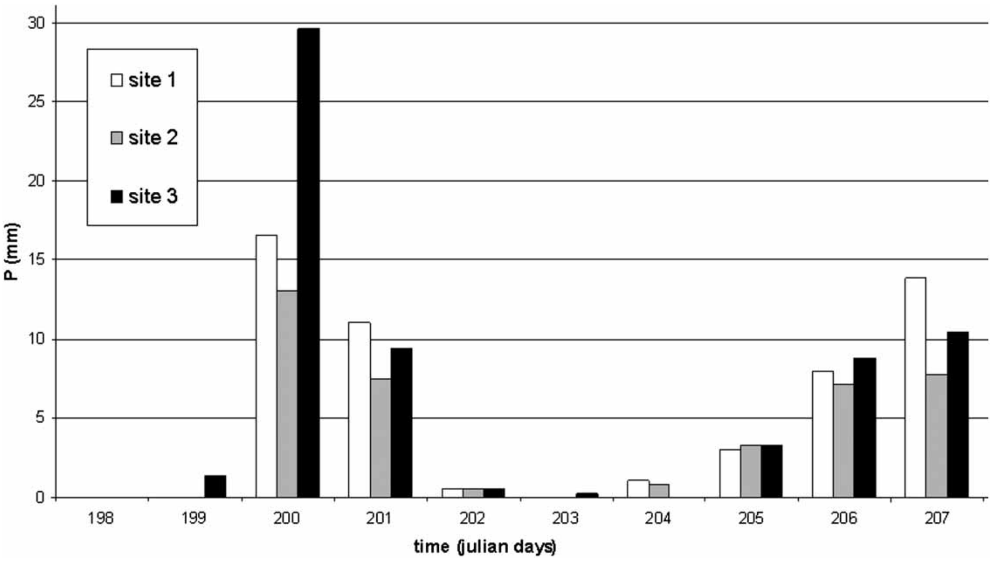

Figure 2 | Histograms of precipitation for sites 1, 2 and 3 over a randomly selected 10-day period in 2005.

(<10 cm/s) that were sometimes near the flowmeter detection limit (1 cm/s) were identified as the main sources of error. Flow data for dry and normal conditions, i.e., in the lower to middle portion of the rating curves are more accurate. On the other hand, the lack of points in wet conditions (especially for sites 3, 5 and 7) led to a potential overestimation of *Q* during wet spells. This is reflected in results of the water budget presented, especially at the seasonal timescale where the runoff overestimation was accumulated over a longer period. This is indeed less problematic at shorter timescale, especially when events occurred during dry or normal conditions (section Specific events water budget). For those reasons, only seasonal water budget of sites 4 and 6 are presented in the next section.

Concerning ET, the original field structure based method developed appears to provide adequate results. Results were compared to those obtained by Lafleur *et al.* (2005) using the average ratio of AET/PET over a 5-year period (Figures 3(a) and 3(b)), where AET and PET were respectively obtained from eddy covariance and the PM equation. *X*-axis shows results obtained in the present study from field structure method (section Evapotranspiration) whereas *Y*-axis values were calculated with Lafleur's PM equation but with our own meteorological dataset. Because we wanted to consider the impact of mire breathing, we used the AET/PET ratio of 0.617 related to high WL conditions, i.e., when WL is located in the top 25 cm layer under the surface. Visual observations over years confirm that despite important variations in WL position, it is almost always located in the upper layer (even in drought conditions), with the surface moving with WL. Daily data for bogs fit well with data from AET/PET method, with only a small overestimation of daily values (Figure 3(a)). This is true for normal conditions that prevailed in about 80% of summer and fall days. The overestimation is greater for fens and lakes (Figure 3(b)) but the comparison cannot be directly made because AET/PET ratios of fens and lakes at similar latitudes were unavailable in the literature, so ratios calculated on bogs were used.

WL data from replicate wells (not shown here) located in fens and bogs indicated that, although small differences exist in water table movements related to the location of the well in a pond or in a vegetated string, recorded levels generally move in a synchronous way. Data from a single well (the most representative of the mean conditions of all wells) were therefore used in the water budget calculations.

Seasonal water budget

Seasonal water budgets were computed for a concomitant period from mid-July to the end of October of years 2005, 2006 and 2007. Interestingly, those 3 years had highly variable wetness conditions (Table 2): 2006 was the driest year

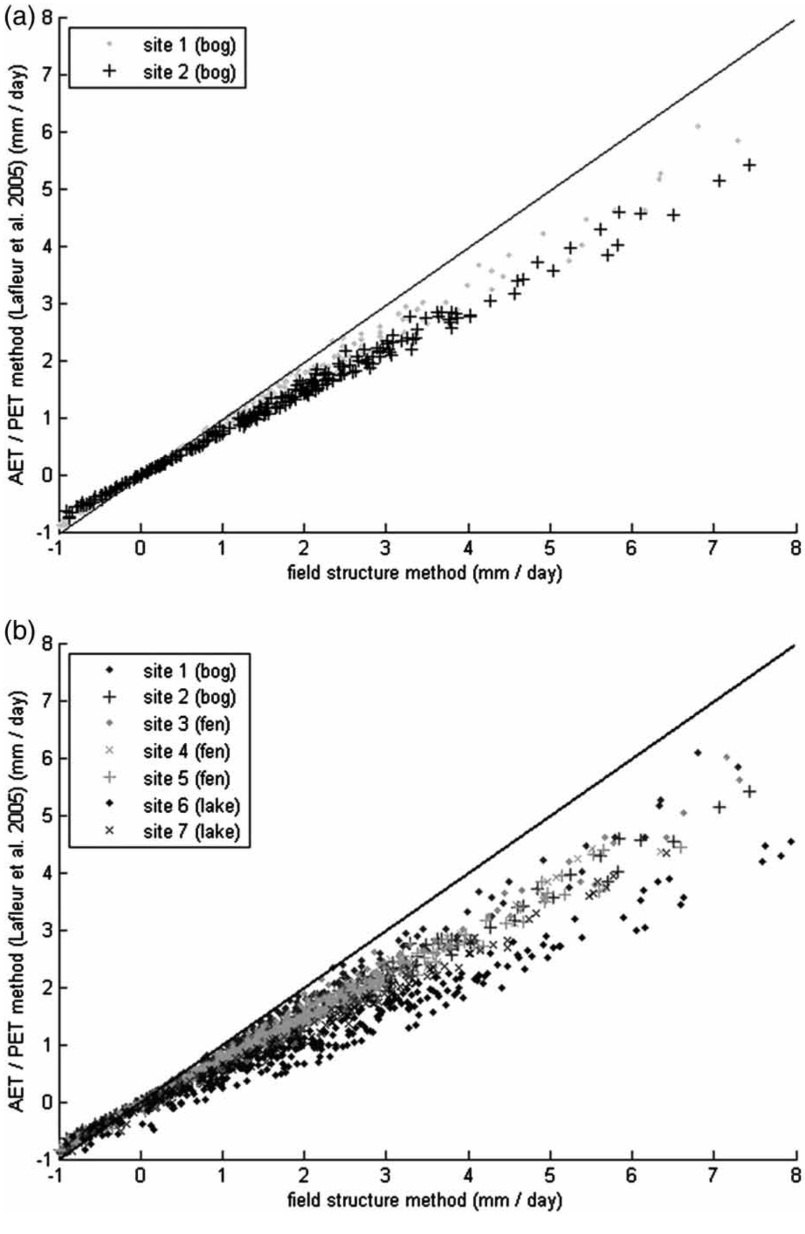

Figure 3 | (a) Comparison of methods using daily PET data of summer and fall for bogs. (b) Comparison of methods using daily ET data of summer and fall for bogs, fens and lakes.

with total precipitation of 239 to 434 mm during the study period, while 2007 was much wetter with totals of 485–649 mm and 2005 had intermediate (normal) conditions with totals of 309–589 mm. During all years, sites 4, 5, 6 and 7 located in the eastern and upper part of the watershed received systematically more precipitations than sites 1, 2 and 3 located in the western part.

Meanwhile, ET values remain relatively stable between years (Table 2). Table 3 contains a summary of main atmospheric data involved in the evapotranspiration process. The wetter year (2007) was the one with the lowest total ET, ranging from 98 mm (site 1) to 155 mm (site 6). Both 2005 and 2006 had similar values of respectively 116–207 mm and 122–195 mm. ET accounts for between 24 and 45% of total precipitation during a more typical year (2005). This percentage rose to 34–51% in a dry year (2006) but dropped to 17–24% in a wet year (2007). Because of their important fraction of open water and for all years,

Table 2 | Precipitations (mm), ET losses (mm) and ET/P ratios for all sites and years during the study period (from July 11 to October 31)

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
P (2005)	375	309	408	472	589	559	334*
P (2006)	239	278	252	290	394	434	434
P (2007)	485	551	621	581	649	649	649
ET (2005)	116	140	132	138	141	207	61*
ET (2006)	122	141	133	129	133	195	154
ET (2007)	98	112	109	106	108	155	126
ET/P (2005)	31%	45%	32%	29%	24%	37%	31%*
ET/P (2006)	51%	51%	53%	44%	34%	45%	36%
ET/P (2007)	20%	20%	18%	18%	17%	24%	19%

Asterisks beside values of site 7 refer to a slightly shorter study period in 2005.

lakes tend to have higher total ET than bogs and fens, which were more similar. All three fens had very similar ET for all years. This can be explained by their similarity in key factors driving ET (solar radiation, wind speed, open water and watershed configuration). On the other hand, both bogs showed differences in ET, site 2 (a large circular dome shape) being much more exposed to wind than site 1 (a very small triangular bog with denser tree coverage). Both lakes also showed differences in ET due to their areal importance in the watershed, site 6 covers 47% of the watershed while site 7 only covers 32% (Table 1).

Depending on the year, runoff is by far the most variable term. Unfortunately, because of the aforementioned errors associated with stage-discharge curves, only data from sites 4 and 6 are presented here (Table 4). Year 2006 was the driest one with total runoff values of respectively 221 and 159 mm while 2005 (intermediate) and 2007 (wet) had respectively values of 298 and 208 mm and 351 and 287 mm.

The last term of the hydrological budget, ΔS, was defined as the difference in storage between the end of the study (October 31) and the beginning (July 11) (Table 4). For 2005, data from both sites showed a similar recharge during the season (61 mm for site 4 and 65 mm for site 6). On the other hand, 2006 showed storage decrease during the season (−22 mm for site 4 and −63 mm for site 6, which received much more P during the same period) while 2007 showed marginal storage fluctuations during the season (11 mm for site 4 and −6 mm for site 6).

Finally, Table 4 contains complete water budgets for sites 4 and 6 for all years. Depending on the years, budgets 'closed' in different ways, as shown by η values in both absolute and relative errors. For 2005, site 4 and site 6 showed a 97 mm (21% of total P over the period) and 208 mm (37%) excess, respectively. The error term was smaller for 2006 (dry year) with −82 mm (28%) and 18 mm (4%), as expected because runoff was restricted in the more reliable part of the stage-discharge curves most of the season. On the other hand, 2007 (wet year) showed greater error values of 134 mm (23%) and 200 mm (31%). Figure 4 shows the cumulative curves of daily data for all terms for years 2006 and 2007. At coarse resolution, we can see that for similar P curves, both sites produce similar responses in PET and Q; the response in ΔS

Table 3 | Summary of mean atmospheric data for all sites and years during the study period (from July 11 to October 31)

		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Air temperature (±0.1 °C)	2005	10.7	11.1	10.4	9.6	9.3	9.5	9.5*
	2006	9.3	9.6	9.0	8.2	7.8	8.0	8.0
	2007	9.8	10.0	9.5	8.0	8.8	7.7	7.7
Relative humidity (±3%)	2005	83.5	81.2	80.7	81.2	82.6	79.7	79.7*
	2006	81.0	79.2	78.4	81.5	82.2	78.3	78.3
	2007	84.0	82.0	81.1	84.3	84.4	84.8	84.8
Wind speed (±0.3 m/s)	2005	1.0	2.1	1.9	1.7	1.8	1.2	1.2*
	2006	1.1	2.2	2.0	1.8	1.9	1.3	1.3
	2007	1.2	2.5	2.2	1.9	2.0	1.9	1.9
Solar radiation (±0.85 MJ/h/m^2)	2005	471	497	499	476	473	473	473*
	2006	541	545	545	494	502	494	494
	2007	476	471	484	411	447	410	410

Units and sensors precisions are provided in parentheses.

Asterisks beside values of site 7 refer to a slightly shorter study period in 2005.

Table 4 | Seasonal water budget of sites 4 (fen) and 6 (lake) for years 2005 to 2007

	2005		2006		2007	
	Site 4	**Site 6**	**Site 4**	**Site 6**	**Site 4**	**Site 6**
P (mm)	472	559	290	433	581	649
Q (mm)	298	208	222	159	351	287
PET (mm)	154	182	151	179	122	140
ΔS (mm)	61	65	−22	−63	11	−6
η (mm)	97 (21%)	208 (37%)	−82 (28%)	18 (4%)	134 (23%)	200 (31%)

See Equation (1) for the definition of each term.

also had similar variations, but the lake seems to produce a smoother curve than the fen with high WL variability, but of smaller amplitude than site 4.

Specific events water budget

At the event scale, our analyses were focused on a few sequences of concomitant rainfall happening under known soil wetness conditions, thus generating singular hydrological events at each site. Using Q time series, we defined a hydrological event from a trough to a peak back to a trough and only kept those with roughly the same duration of about 10 days. We also selected them to have a variety of hydrological conditions from dry to wet. Water budget results of the three specific studied events are presented in Table 5, which contains all terms for all sites, complementary information related to their date and duration as well as the mean standardized WL at the beginning of each event. The last statistic is used to qualify the general wetness state of sites when the rainfall happened.

Event 1 happened in late September 2005, lasted 11 days and the rainfall (28–67 mm) occurred when the mean standardized WL was 0.79, which means that *in situ* WLs were relatively high. This event is therefore defined as 'high precipitation on wetter than normal conditions'. Event 2 occurred in mid-September of 2006, lasted 8 days and rain (12–34 mm) fell when the mean standardized WL was

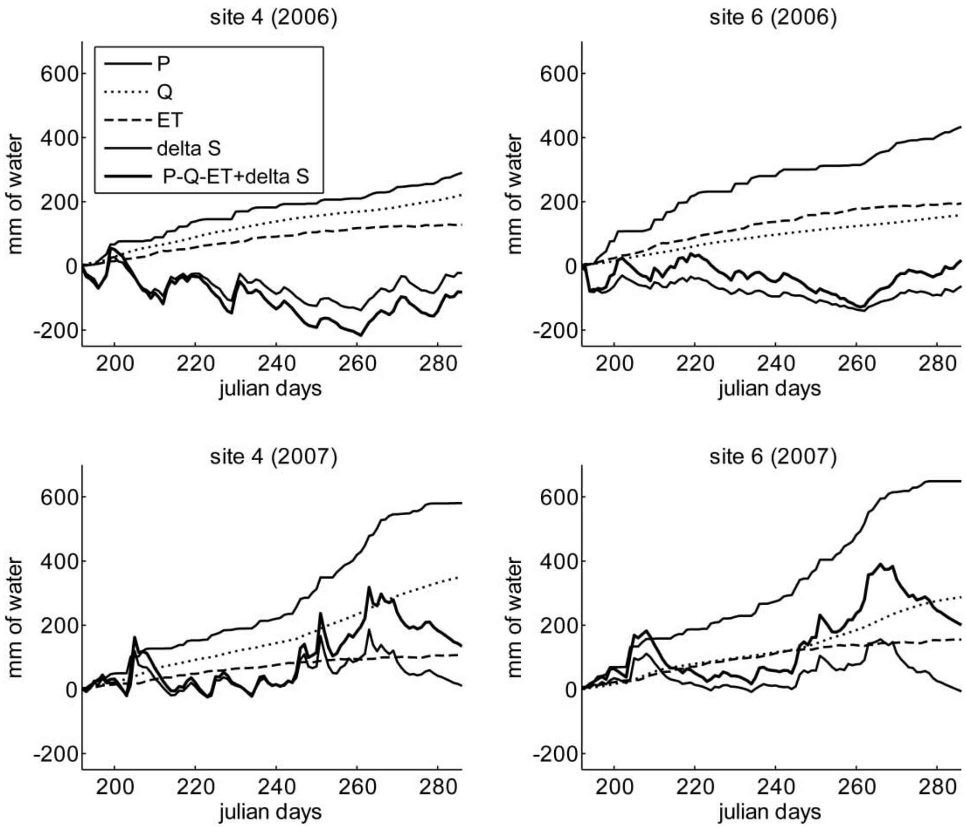

Figure 4 | Seasonal water budget of 2006 (dry) and 2007 (wet) for sites 4 and 6.

Table 5 | Water budgets for all sites for three events caused by concomitant rainfalls

		Site 1 (bog)	**Site 2 (bog)**	**Site 3 (fen)**	**Site 4 (fen)**	**Site 5 (fen)**	**Site 6 (lake)**	**Site 7 (lake)**
Event 1: Date: 09/17/05–09/27/05; Duration: 11 days; Mean standardized WL at the beginning: 0.79	P	30.7	28.0	34.1	47.1	66.4	66.7	66.7
	PET	7.9	9.4	8.7	9.3	9.1	12.6	10.3
	Q	0.0	0.0	144.7	44.4	95.4	31.6	77.5
	ΔS	−17.5	−14.3	−0.4	−8.5	2.7	−6.7	−5.5
	H	5.4	4.3	−119.8	−15.2	−35.3	15.7	−26.5
Event 2: Date: 09/07/06–09/14/06; Duration: 8 days; Mean standardized WL at the beginning: −1.58	P	27.4	33.8	24.1	14.1	14.4	11.9	11.9
	PET	6.7	8.0	7.8	6.4	7.0	10.7	8.2
	Q	0.0	0.0	18.6	11.1	0.4	10.3	7.7
	ΔS	46.6	18.0	14.8	−3.0	−1.4	−9.7	6.3
	η	67.3	43.7	12.6	−6.4	5.7	−18.7	2.4
Event 3: Date: 07/31/06–08/06/06; Duration: 7 days; Mean standardized WL at the beginning: −1.22	P	46.8	66.2	32.9	34.1	59.0	53.7	54.3
	PET	10.6	12.4	11.3	8.3	9.0	14.4	11.0
	Q	0.0	0.0	19.3	18.5	65.8	15.6	15.8
	ΔS	135.3	106.1	29.2	59.1	8.9	16.9	−1.5
	η	171.4	159.9	31.5	66.4	−6.9	40.6	25.9

All values are in millimetres (mm).
See Equation (1) for the definition of each term.

−1.58, which means that *in situ* WLs were quite low. This event is therefore defined as 'low precipitation on drier than normal conditions'. Finally, event 3 occurred in early August 2006, lasted 7 days and the rainfall (33–62 mm) happened when the mean standardized WL was −1.22, which means that *in situ* WLs were also relatively low. This event is therefore defined as 'high precipitation on drier than normal conditions'.

Rainfall of event 1 (high P on high WL) occurred when WLs were already high due to another important rain spell in the previous week. Spatially, total P were registered from a single storm in the western part of the basin (sites 1, 2 and 3) while the eastern received another one, but smaller near the end of the event. This spatial variability explains differences in total P. Meanwhile, ET data were more homogeneous and ranged from 7.9 to 12.6 mm while ΔS showed a general drawdown (on six sites of seven) during the 11-day period with variations of +2.7 to −17.5 mm. Runoff values were highly variable with 0 mm for both bogs to 144.7 mm. Sites 3, 5 and 7 had very high Q values (144.7, 95.4 and 77.5 mm, respectively) and are likely good examples of the overestimation of Q in the wetter parts of stage-discharge curves as mentioned in the section Data used in water budget terms. On the other hand, sites 4 and 6 showed realistic Q values (44.4 and 31.6 mm), thus the residual terms are smaller (−15.2 and −15.7 mm) by opposition to higher values for sites 3, 5 and 7 (−119.8, −35.3 and −26.5 mm). Despite the absence of Q for the bogs, they show very small η terms of 5.4 and 4.3 mm. Since ΔS decline is more important than ET losses, we do consider that bogs somehow regulate their *WL* with subsurface runoff while they are in discharge phase, i.e., when the water table is high and their water storage capacity is therefore limited.

Event 2 (low P on low WL) was a low to moderate rain storm that happened after a dry spell of 10 days. The storm was stronger in the western part of the watershed (24.1 to 33.8 mm) than in the eastern part (11.9–14.4 mm). As in event 1, ET values were still quite similar (6.4–10.7 mm). Because of the dryer conditions, flows estimated using the stage-discharge curves can be used with greater confidence. Q values were more homogeneous and small (0.4–18.6 mm). On the other hand, the ΔS were highly variable for this event (−9.7 to +46.6 mm). Western sites (1, 2 and 3) that received more P also had higher ΔS. Eastern sites showed smaller and less variable ΔS values (−9.7 to +6.3 mm). Bogs seem to be in recharge phase with high ΔS rises (even higher than P total for site 1) and, hypothetically, no subsurface runoff is suspected for this period. Despite low Q values, both fens and lakes kept their runoff production abilities.

Event 3 happened also during dry conditions but the context is slightly different for eastern and western sites. Precipitation came in a single storm for the western part and in two storms in 4 days for the eastern part. Prior to P, the western sub-basin had a 10-day-long drought. The Eastern part had a 7-day dry spell, followed with a storm 3 days before the beginning but their initial WLs were still low despite this earlier storm. Once again ET values were still quite similar (8.3–14.4 mm). Q values were in the same range for sites 3, 4, 6 and 7, inexistent for bogs and rather important for site 5 where we observed the highest standardized WL before the event due to the highest P total in the pre-event storm. All ΔS values except for site 7 (near 0) were positive (8.9–135.3 mm) during the period, indicating that storage was higher at the end of the event compared to the beginning. This is especially true for both bogs that experienced a strong ΔS rise (higher than total P) during the event. This is the opposite of event 1 and similar to event 2; bogs here seem to be in a very effective recharge phase.

Isolating synchronous hydrological events in seven sites smaller than 1 km^2 in a natural and remote watershed is not an easy task. Water budget at this timescale seldom 'close' very well, since various hydrological processes generating runoff operate at different speeds from fast (rain storm) to slow (storage drawdown in bogs). For example, an event water budget can be positive (water excess) only because a second rain event happened before storage returned to its initial condition. Fortunately, an important residual term does not mean that useful information cannot be extracted from data.

DISCUSSION

This water budget study of *Sphagnum* bogs, patterned fens and shallow lakes aimed at better understanding of hydrological behavior of mid-latitude Québec wetlands over a 3-year summer and fall span. It allowed us to appreciate the variability of water budget terms during dry, average and wet years. Budget calculations were assessed in the context of peatland hydrology and/or small lake dominated watersheds (<1 km^2). From this assessment, we learned the following facts that will be useful for further similar studies.

(1) In summer and fall, when local storms prevailed, the spatial heterogeneity of precipitation (Table 2 and Figure 2) confirms that when working with small spatial and/or timescale hydrological issues, a dense network of stations is important to maintain a good areal coverage (St-Hilaire *et al.* 2003). As shown from results of this study, with watersheds smaller than 1 km^2, the installation of an *in situ* precipitation gauge is strongly recommended.

(2) The ET method based on the field structure seems to provide a good estimate for about 80% of the distribution over our study period with an overestimation of the extreme values during warm and dry summer days (Figure 3). Data were in the same range of AET values than most studies related to subarctic wetlands (Lafleur *et al.* 2005). This comparison is only possible for bogs because of a lack of reference data for fens and lakes but, nonetheless, the method was also applied to fens and lake watersheds. The overall results of the new field structure method provide an interesting way to provide a good estimation of AET (via PET), but would need a validation using spot or continuous AET measurements in a future study.

(3) The method used to measure flow, i.e., a stilling well located at the outlet associated with the production of stage-discharge curves was found to be sub-optimal. Remoteness of study sites, low flow velocities (few cm/s) and instability of the outlet's cross-section in fens due to sediment transportation are the main error sources that seem to lead to important overestimation of runoff in higher than mean wetness conditions. The method gives acceptable results in drier than average conditions when runoff data are estimated using the lower portion of stage-discharge curves. Overall, we do not recommend this method for similar watershed settings. Parshal flumes or trapezoidal canals (Jutras *et al.* 2007) may represent a better option, provided they have suitable dimensions to capture both low flow and flood events.

(4) Drainage basin boundaries may be difficult to identify in peatlands, which generally have low slopes. However, given their location at the downstream end of the drainage basin, the task of finding the water divide was not insurmountable. However, as with most wetlands, there could be discrepancies between the hydrogeological and surface drainage basin boundaries. The challenge associated with groundwater studies in

wetlands has been recognized for a long time (Carter 1986) and can be partially addressed by an increased monitoring effort using a denser network of wells and piezometers than the one used in the present study.

(5) Patterned fens with a moderate degree of aqualysis regulate themselves with occasional bursts of runoff that last longer and with greater amplitude than lakes (representing a high degree of aqualysis). This behaviour is probably due to their typical structure of succeeding ponds and vegetal strings. This variability in runoff conditions could be related to runoff generation processes proper to high and low water tables as exposed by Kvaerner & Klove (2008), i.e., a release from peat storage during low water table spells that is added to overland flow during high water table spells. Between those extreme states, ponds configuration play a complex but crucial and rather misunderstood role in runoff generation. Runoff rise anticipated from climate change in the region could be counterbalanced by a less variable behavior when open water fraction from fens will approach those of lakes.

CONCLUSION

Our study aimed at comparing drainage basins with different downstream configurations, bogs, fens and lakes, which represent a gradient of aqualysis. In spite of the uncertainty associated with error from instrumentation and field logistic constraints, the present study allowed the following conclusions to be drawn.

- The relation between ΔS and Q seems different between aqualized fens and lakes. Our results tend to show that, for humid ecosystems of this region such as bogs, fens and lakes where water availability is seldom restricted, ET is more constant between years than precipitation and runoff, representing approximately 20% of P in wet years and 40% in dry years. Variability is much more important at daily timescale, with higher values during warm, dry and sunny summer days. For both bogs and fens, water table was almost always near the surface, despite important precipitation events or dry spells that lasted several days.
- The non-aqualized bogs regulate themselves mainly with slow and regular storage drawdown caused by ET and probably by subsurface runoff (not measured). Dramatic rises in WL can occur with heavy rainfall over dry conditions. The processes generating these important WL rises remain unclear at this point but could be hypothetically linked to a strong capillarity pressure of the dry and typical bog vegetation when water becomes available.
- Fens ET values were generally very similar to those of bogs while those of lakes were systematically higher (nearly twice as much as bogs) due to the absence of stomatal resistances in the calculation procedures, which correspond to the absence of vegetation in the equation. Considering that all sites have a similar type of upslope land use (roughly the same forested coverage), differences in ET total lie in the respective importance of the two structural entities (open water and vegetation) as well as their watershed configuration that influence exposition to wind and radiation.
- Finally, lacking this typical vegetation structure, shallow lakes tend to have a much simpler hydrology. ET is more important over open water than on peatlands and runoff is not directly related to lake level. They often produce short, quick and small runoff rises. If aqualysis expansion in the next decades due to the anticipated rises in both precipitation and runoff for the La Grande region associated with warmer and wetter air is confirmed, we should anticipate more ‘lake type’ runoff behaviour in highly aqualized peatlands, that could become therefore simpler to model than bogs or even fens with low open water ratios.

ACKNOWLEDGEMENTS

The authors would like to thank all the Aqualysis research team including professionals, graduate and undergraduate students (field helpers) from Institut National de la Recherche Scientifique (INRS-ETE), Université Laval and Université du Québec à Montréal (UQAM), you know who you are. Sincere thanks also to co-founders who allowed this research programme to be completed: FQRNT, NSERC and Hydro-Québec in association with the Ouranos Consortium.

REFERENCES

Allen, R. G., Peireira, L. S., Raes, D. & Smith, M. 1998 Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, 1998. 05/25/09.

Bégin, Y. 2001 Tree-ring dating of extreme lake levels at the subarctic-boreal interface. *Quat. Res.* **55**, 133–139.

Belyea, L. R. & Malmer, N. 2004 Carbon sequestration in peatland: patterns and mechanisms of response to climate change. *Glob. Change Biol.* **10**, 1043–1052.

Blodau, C. 2002 Carbon cycling in peatlands – A review of processes and controls. *Environ. Rev.* **10**, 111–134, NRC Canada 2002.

Bubier, J., Crill, P., Mosedale, A., Frolking, S. & Linder, E. 2003 Peatland responses to varying interannual moisture conditions as measured by automatic CO_2 chambers. *Glob. Biogeochem. Cycles* **17** (2), 1066.

Carter, V. 1986 An overview of the hydrologic concerns related to wetlands in the United States. *Can. J. Bot.* **64**, 364–374.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., Sarr, A. & Whetton, P. 2007 Regional climate projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Clair, T. A., Ehrman, J. & Higuchi, K. 1998 Changes to the runoff of Canadian ecozones under a doubled CO_2 atmosphere. *Can. J. Fish. Aquat. Sci.* **55**, 2464–2477.

Déry, S. J., Stieglitz, M., Rennermalm, A. K. & Wood, E. F. 2005 The water budget of the Kuparuk River Basin, Alaska. *J. Hydrometeor.* **6**, 633–655.

Dibike, Y. B. & Coulibaly, P. 2005 Hydrologic impact of climate change in the Saguenay watershed: Comparison of downscaling methods and hydrologic models. *J. Hydrol.* **307**, 145–163.

Ducharme, P. & Nadeau, M. 2005 Performance des précipitomètres. Rapport pour diffusion interne à Hydro-Québec de l'Institut de Recherche en Électricité du Québec (IREQ). IREQ-2005-087, June 2005, 29. [Comparison of performance of rain gauges. Report for internal distribution, Hydro-Québec and Québec's Institute of Research on Electricity, IREQ.]

Environment Canada 2008 Canadian Climate Normals or Averages 1971–2000. Available at: http//www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html. 05/25/09.

Frigon, A., Slivitzky, M., Caya, D. & Roy, R. 2007 Construction of hydro-climatic projections and first-order estimation of their associated uncertainties form Regional Climate Model simulations: Application to water management of hydropower reservoirs in Québec. *La Houille Blanche* **6**, 97–103.

Glaser, P. H. & Janssens, J. A. 1986 Raised bogs in eastern North America: Transitions in landforms and gross stratigraphy. *Can. J. Botany* **64**, 395–415.

Glenn, M. S. & Woo, M. K. 1997 Spring and summer hydrology of a valley-bottom wetland, Ellesmere Island, Northwest Territories, Canada. *Wetlands* **17**, 321–329.

Gorham, E. & Janssens, J. A. 1992 Concepts of fen and bog re-examined in relation to bryophyte cover and the acidity of surface waters. *Acta Soc. Botanicorum Pol.* **61**, 7–20.

Holden, J. & Burt, T. P. 2003 Hydraulic conductivity in upland blanket peat: measurement and variability. *Hydrol. Process.* **17**, 1227–1237.

Jutras, S., Clerc, C. & Rousseau, A. N. 2007 Rapport d'installation d'un canal trapézoïdal à l'exutoire une tourbière nordique. Rapport interne I-237. INRS-ETE, Québec, p. 24. [Report on the installation of a trapezoidal canal at the outlet of a northern peatland.]

Kane, D. L. & Yang, D. 2004 *Overview of Water Balance Determinations for High Latitude Watersheds*. Northern Research Basins Water Balance. IAHS Press, Oxfordshire, UK, pp. 1–12.

Kellner, E. 2001 Surface energy fluxes and control of evapotranspiration from a Swedish *Sphagnum* mire. *Agr. Forest Meteor.* **110**, 101–123.

Kellner, E. & Halldin, S. 2002 Water budget and surface-layer water storage in a *Sphagnum* bog in central Sweden. *Hydrol. Process.* **16**, 87–103.

Kuhry, P., Nicholson, B., Gignac, L. D., Vitt, D. H. & Bailey, S. E. 1993 Development of *Sphagnum*-dominated peatlands in boreal continental Canada. *Can. J. Botany* **71**, 10–22.

Kvaerner, J. & Klove, B. 2008 Generation and regulation of summer runoff in a boreal flat fen. *J. Hydrol.* **360**, 15–30.

Lafleur, P. M. & Roulet, N. T. 1992 A comparison of evaporation rates from two fens of the Hudson Bay Lowlands. *Aquat. Bot.* **44**, 59–69.

Lafleur, P. M., Hember, R. A., Admiral, S. W. & Roulet, N. T. 2005 Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. *Hydrolog. Process.* **19** (18), 3533–3550.

Levrel, G. & Rousseau, A. N. 2010 Étalonnage de sondes FDR (Frequency Domain Reflectometry) sur les cinq premiers centimètres des sols et de couverts de bryophytes de deux tourbières minérotrophes du milieu boréal Québécois (Canada). *J. Can. Télédétect.* **36** (4), 313–331. [Calibration of FDR (Frequency Domain Reflectometry) sensors within the top five centimetres of soils covered with mosses in two fens located in Québec's boreal forests.]

Martin, T. A., Brown, K. J., Cermak, J., Ceulemans, R., Kucera, J., Meinzer, F. C., Rombold, J. S., Sprugel, D. G. & Hinckley, T. M. 1997 Crown conductance and tree stand transpiration in a second growth *Abies amabilis* forest. *Can. J. Forest Resour.* **27**, 797–808.

National Wetlands Working Group 1988 *Wetlands of Canada. Ecological Land Classification Series, No. 24*. Sustainable Development Branch, Environment Canada, Ottawa, Ontario & Polyscience Publications Inc., Montreal, Quebec, p. 452.

Payette, S. & Delwaide, A. 1991 Variations séculaires du niveau d'eau dans le bassin de la rivière Boniface (Québec nordique): une analyse dendrochronologique. *Géographie Phys. Quaternaire* **45**, 59–67. [Century scale variations of water levels in the Boniface River drainage basin (Northern Québec): a dendrochronological analysis.]

Payette, S. & Delwaide, A. 2000 Recent permafrost dynamics in a subarctic floodplain associated with changing water levels (Quebec, Canada). *Arct. Antarct. Alp. Res.* **32**, 316–323.

Payette, S. & Rochefort, L. 2001 *Écologie des tourbières du Québec-Labrador*. Les Presses de l'Université Laval, Québec, Canada, p. 621. [Ecology of peatlands in Québec-Labrador.]

Payette, S. & Delwaide, A. 2004 Dynamics of subarctic wetland forests over the past 1500 years. *Ecol. Monogr.* **74** (3), 373–391.

Price, J. S. & Maloney, D. A. 1994 Hydrology of a patterned bog-fen complex in southeastern Labrador, Canada. *Nord. Hydrol.* **25**, 313–330.

Price, J. S. & Waddington, J. M. 2000 Advances in Canadian wetland hydrology and biogeochemistry. *Hydrol. Process.* **14**, 1579–1589.

Price, J. S., Branfireun, B. A., Waddington, J. M. & Devito, K. J. 2005 Advances in Canadian wetland hydrology, 1999–2003. *Hydrolog. Process.* **19**, 201–214.

Proulx-McInnis, S., St-Hilaire, A., Rousseau, A. N., Jutras, S., Carrer, G. & Levrel, G. 2013 Seasonal and monthly hydrological budgets of a fen-dominated forested watershed, James Bay region, Quebec. *Hydrol. Process.* **27**, 1365–1378.

Quinton, W. L. & Roulet, N. T. 1998 Spring and summer runoff hydrology of a subarctic patterned wetland. *Arct. Alp. Res.* **30**, 285–294.

Quinton, W. L. & Marsh, P. 1999 A conceptual framework for runoff generation in a permafrost environment. *Hydrol. Process.* **13**, 2563–2581.

Quinton, W. L., Hayashi, M. & Pietroniro, A. 2003 Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydrol. Process.* **17**, 3665–3684.

Roulet, N. 1991 Surface level and water level fluctuations in a subarctic fen. *Arct. Alp. Res.* **23** (3), 303–310.

Shuttleworth, W. J. 1996 Evaporation. In: *Water Resources Handbook* (L. W. Mays, ed.). McGraw-Hill, New York.

Slivitsky, M., Frigon, A. & Caya, D. 2004 Impact de changement climatique sur le régime hydrologique des rivières du Nord du Québec et du Labrador. 57e congrès annuel de l'Association Canadienne des Ressources Hydriques, 16–18 juin 2004, Montréal, Québec, Canada. [Impact of climate change on the hydrological regime of Northern Québec and Labrador rivers.]

Spence, C. 2006 Hydrological processes and streamflow in a lake dominated watercourse. *Hydrol. Proc.* **20**, 3665–3681.

St-Hilaire, A., Ouarda, T. B., Lachance, M., Bobée, B., Gaudet, J. & Gignac, C. 2003 Assessment of the impact of meteorological network density on the estimation of basin precipitation and runoff: a case study. *Hydrol. Process.* **17**, 3561–3580.

Summer, D. M. & Jacobs, J. M. 2005 Utility of Penman-Monteith, Priestley-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. *J. Hydrol.* **308**, 81–104.

Tardif, S., St-Hilaire, A., Roy, R., Bernier, M. & Payette, S. 2009 Statistical properties of hydrographs in minerotrophic fens and small lakes in mid-latitude Québec, Canada. *Can. Water Resour. J.* **34** (4), 365–380.

Tarnocai, C., Kettles, I. M. & Lacelle, B. 2000 *Peatlands of Canada*. Geological Survey of Canada, Open File 3484, scale 1:6500000.

Ward, A. A. & Trimble, S. W. 2004 *Environmental Hydrology*, 2nd edn. CRC Press, Boca Raton, FL, p. 475.

First received 6 December 2012; accepted in revised form 24 November 2013. Available online 3 January 2014