Hydrological budgets of a watershed including a highly aqualysed fen, James Bay, Quebec, Canada

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Abstract

Minerotrophic fens occupy a large percentage of north boreal Quebec. During the last decade, some of them have been subjected to an increase of their water surface, a sign that they may be evolving towards an aquatic ecosystem. For a better understanding of their hydrological behaviour, a study was conducted on a small watershed, including a fen, in the James Bay region (54 06'52"N, 72 30'01"W).The objective of this study was to calculate the hydrological budgets of the summer 2009 at different time steps. Measurements of precipitation (*P*), runoff (*Q*) and groundwater levels (*WL*) were taken during the ice-free season. Three semi-empirical equations (Thornthwaite, Priestley-Taylor and Penman-Monteith) were used and compared for potential evapotranspiration (*PET*). The first two equations, having fewer parameters, overestimate the *PET* when compared to the third equation. The use of pressure level gauges installed in wells, for the calculation of peatland water storage, is inconclusive. Swelling, peat decomposition and plant composition could be responsible for a non-negligible amount absorbed water, which is not accounted for by well levels. The estimation of peat matrix water storage is potentially the largest source of error and the limiting factor to calculate hydrological budgets in this environment. The results show that the groundwater level and the water storage vary depending on the season and especially after a heavy rainfall. Finally, the results illustrate the complexity of the migration of water through the site and, thus, raise several questions to be resolved in the future.

Introduction

Peatlands occupy 12 to 17% of the Canadian landscape (Payette and Rochefort, 2001; Lafleur *et al.,* 2005, Letts *et al.,* 2008). In the province of Quebec (Canada), the majority of this type of wetland is located in the James Bay area, where the major hydroelectrical reservoirs are located. North American peatlands are poorly documented in the literature and hydrological processes are very inadequately understood (Lafleur *et al.,* 2005). For several years, it has been hypothesized that many peatlands have evolve towards aquatic ecosystems, through the expansion and coalescence of their ponds to the detriment of vegetation strips that collapse and degrade (Dissanska *et al.,* 2009; Payette, 2008). This phenomenon, called aqualysis, leads to questions about the future of northern boreal peatlands of Quebec and the consequences of a dynamic process such as aqualysis on the water retention capacity of peatland.

Objectives

(1) Calculate seasonal and monthly potential evapotranspiration values using semi-empirical equations such as Thornthwaite, Penman-Monteith and Priestley-Taylor and to compare the results;
(2) Estimate the variations of the peat matrix water storage and illustrate the link with changes in groundwater levels;
(3) Present the seasonal and monthly hydrological budgets of the watershed.

Study site

- Small 12.5-ha watershed located in the James bay region;
- Slope of 1.45% (-135° relative to north);
- Includes a 3.5-ha minerotrophic peatland;
- Average temperature -3.2°C;
- Annual precipitation 782 mm (32% of snow);

Peatland:
- Two sections with a succession of ponds and strips;
- A larger pond near the outlet;
- High proportion of water surface (31% of peatland area);

Figure 1. Location of the study site (54°06'868'' N; 72°30'083'' W)

Methodology

- Wind speed (m/s)
- Wind direction
- Precipitation (mm)
- Atmospheric pressure (kPa)
- Temperature at ground level (°C)
- Air temperature (°C)
- Relative humidity (%)
- Vapour pressure (kPa)
- Solar radiation (MJ·m²·J⁻¹)

Figure 2. Meteorological station

***P* = Precipitation (mm)**
***PET* = Potential evapotranspiration (mm)**

PET was calculated from the meteorological station parameter with these equations:
(1) Thornthwaite (Th);
(2) Priestley-Taylor (P-T);
(3) Penman-Monteith (P-M);

For example (P-M equation*):

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)}$$

*Only one that the three tested equations that takes into account the albedo and the percentage of each land cover

Hydrological budget :

$$P - PET - Q = \Delta WL + \eta = \Delta s$$

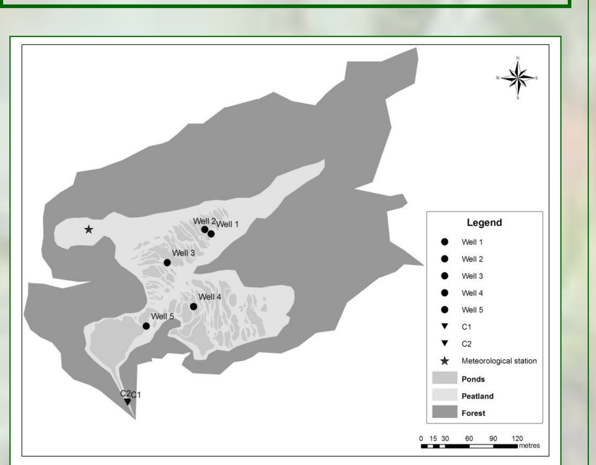

Figure 3. The position of the meteorological station, the wells and the trapezoidal channels on the study site

***Δs* = water storage variation (mm)**

Water storage was calculated with this equation:

$$S_{t+1} = S_t + ((P - PET - Q)\cdot \Delta t \cdot A)$$

where S_t is the initial water storage calculated with the porosity results, S_{t+1} is the storage at day *t+1*, Δt is the daily time step and *A* the watershed area (m³).

Figure 4. (a) Trapezoidal channels at the outlet of the watershed and (b) the camera, that automatically take one picture every hour, installed in front of the channels

***Q* = Runoff (mm)**
***ΔWL* = Water level variation (mm)**
***η* = Error term (mm)**

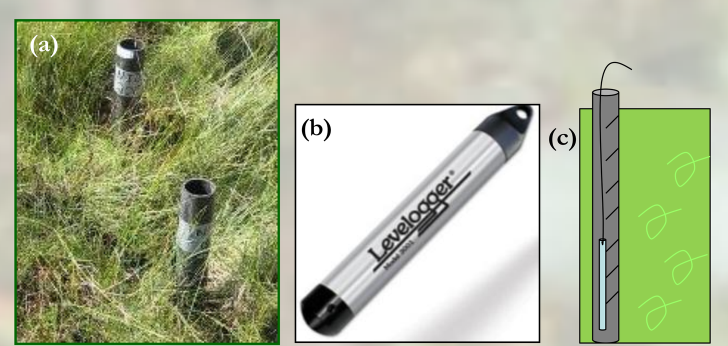

Figure 5. (a) Wells formed by a PVC pipe installed *in situ* ; (b) a picture of a levelogger inserted into well and (c) a schematic representation of a complete well

Results

Objective (1) : Calculate seasonal and monthly potential evapotranspiration values using semi-empirical equations such as Thornthwaite, Penman-Monteith and Priestley-Taylor and to compare the results

- Cumulative *PET* :
  (a) Thornthwaite (Th) : 208,5 mm; (b) Priestley-Taylor (P-T) : 205,4 mm;
  (c) Penman-Monteith (P-M) : 162,2 mm
- Results of a one-way ANOVA test between mean *PET*:
  -P-M averages were significantly different (p-value=0.001 and 0.004, α=0.05);
  -Th and P-T were not significantly different (p-value=0.925, α=0.05);
- Hydrological budgets were calculated in two ways:
  (1) with an average Th and P-T *PET* results;
  (2) with P-M *PET* results.

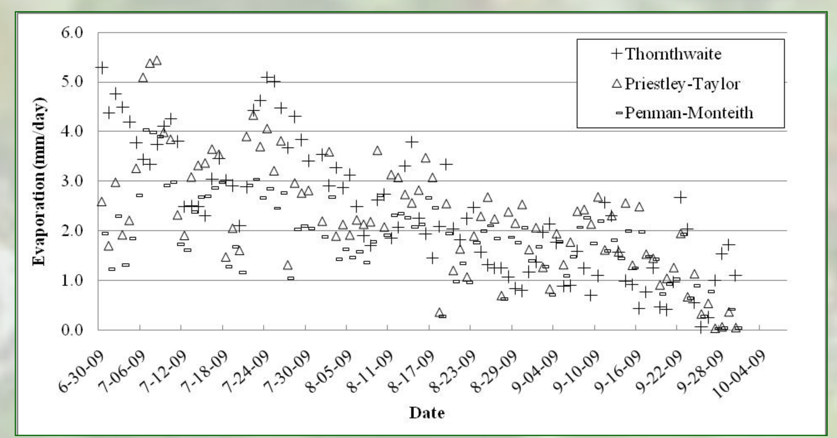

Figure 6. Potential evapotranspiration from 1 July to 23 September 2009, resulting from (a)Thornthwaite, (b) Priestley-Taylor and (c) Penman-Monteith equations

Objective (2) : Estimate the variations of the peat matrix water storage and illustrate the link with changes in groundwater levels

- Storage variation (*Δs*) :
  -Negative in dry periods with low runoff;
  -Increased after rainfall events;
  -Greater when calculated with P-M *PET* values;
- Link between *Δs* and *ΔWL* :
  - with averaged Th-P-T (R^2=0.36);
  - with P-M (R^2=0.32);
- Hydraulic gauge recorded gravitational water and did not account for all of the variation of stored water in the capillarity fringe and unsaturated zone of the peat matrix;
- Water level change does not correspond to a soil water variation, the peat volume change by compaction and expansion.

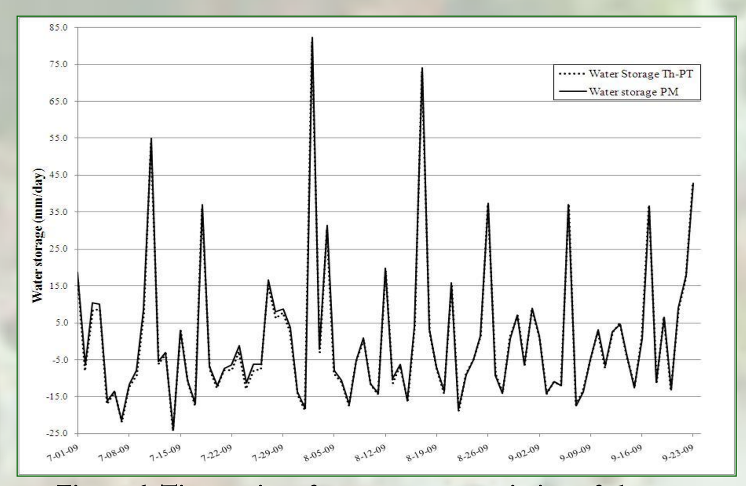

Figure 6. Time series of water storage variation of the two peatland hydrological budgets calculated from 1 July to 23 September 2009

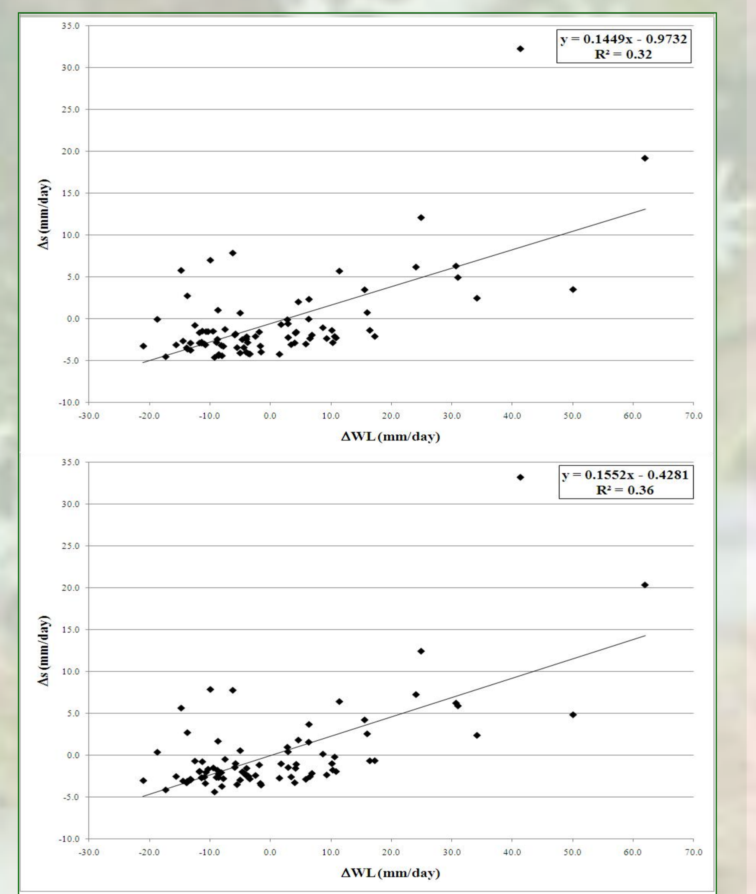

Figure 7. Regression between WL and the water storage variation in the peat matrix calculated from hydrological budget using (a) the average of Th and P-T *PET* equations (R^2=0.32) and (b) the P-M *PET* equation (R^2=0.36)

Objective (3) : Present the seasonal and monthly hydrological budgets of the watershed

Seasonal budget :
- *P* was about one third;
- *PET* represented almost one third;
- *Q* and *Δs* comprised the other third.
- *PET* was the major loss of water;
- *Q* was twice as low as *PET*;

Monthly budgets :
- August = the month with the largest *P* and *Q* (nearly ten times more than those of July);
- August and September = *P*>83%;
- July = *PET* rates ≈ 2/3 of the monthly water budget (nearly two times more than those of September);
- *Δs* rates varied widely depending on the month, greatly fluctuated in late August and increased in September.

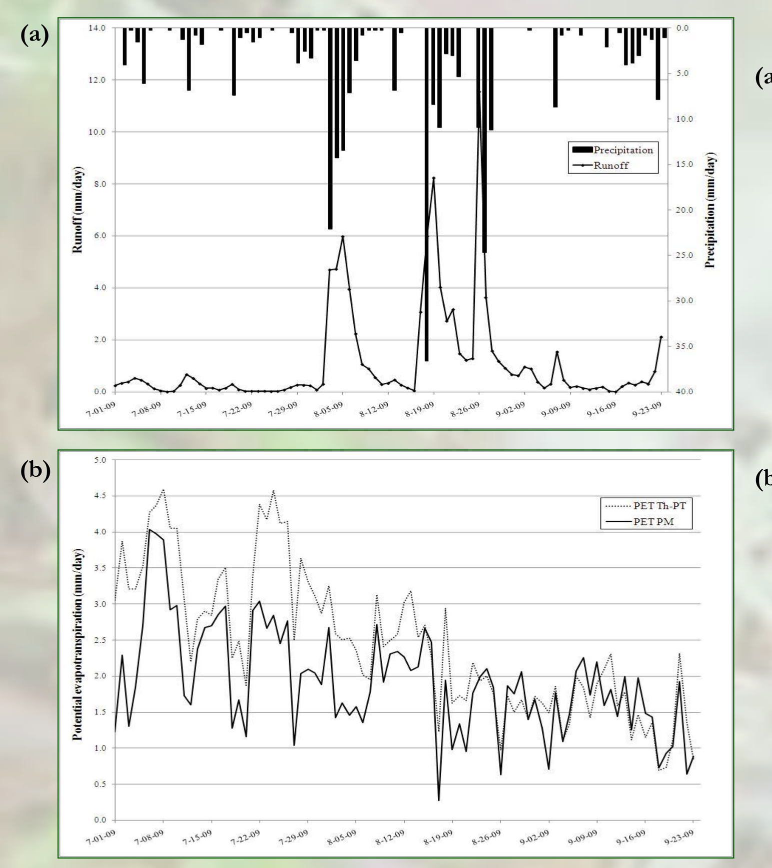

Figure 8. Time series of (a) precipitation and runoff and (b) potential evapotranspiration of the two peatland hydrological budgets calculated from 1 July to 23 September 2009

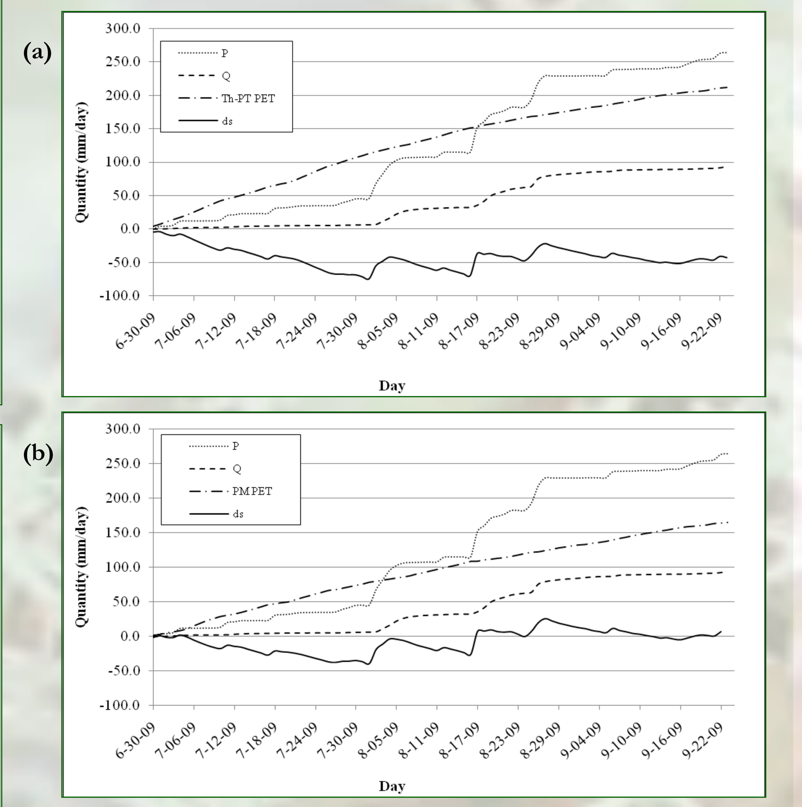

Figure 9. Cumulative terms of hydrological budgets from 1 July to 23 September 2009, calculated from the peat matrix water storage, the average of the wells and (a) the average of the Thornthwaite and Priestley-Taylor (Th-PT) *PET* and (b) the Penman-Monteith (P-M) *PET*

Conclusion

Understanding the present and future behaviours of this type of watershed is useful in the context of James Bay, where an important percentage of the electricity production capacity of the province of Quebec is located. Several points deserve additional investigations. As the water storage capacity seems to be a limiting factor in the calculation of a hydrological budget, laboratory and field studies of the water retention in a column of peat could be proposed using lysimeters adapted to different microenvironments characterizing this type of watershed. A quantification of the swelling magnitude of non-vascular plants and bryophytes may provide useful information as well.

References

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