Advances in Canadian Peatland Hydrology, 2003-2007

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Abstract: Peatlands represent over 90% of Canadian wetlands and are the focus of considerable hydrological and biogeochemical research. Research on evapotranspiration (ET) has shown that it can exceed annual precipitation (P) where there are replenishing flood events. Evaporation from open water ponds in boreal peatlands exceeds ET from vegetated riparian zones by about two times, but surrounding forests can shelter small ponds by reducing turbulence. In an open bog, evaporation was modelled by separating the surface into vascular vegetation, hummock moss and hollow moss surfaces, and showed that vascular plants contribute 60-80% of ET, mosses making up the remainder with hummock mosses dominant over hollows. Runoff from peatlands is enhanced by features ranging from headwater swamps, ice-cored peat plateaus, patchy arctic wetlands and even sections of riverine peatlands. Groundwater fluxes can be quite erratic, and depend on transient properties of the peat that depend on moisture content (e.g., unsaturated hydraulic conductivity) to unsteady saturated hydraulic properties (e.g., hydraulic conductivity, specific yield) caused by peat compression and dilation associated with water storage changes. Surface elevation adjustments can result in a more stable depth to water table, increase evaporation losses, increase methane emission, and attenuate pore-water concentration of contaminants. Research on Canadian peatlands has also made significant methodological advances, including measurement of hydraulic properties of living mosses and peat pore-water and pore dimension characteristics. A considerable multi-annual effort has also been made in evaluating carbon dynamics from Canadian peatlands. Summer moisture availability is important to determining carbon fluxes with some peatlands experiencing enhanced productivity following drought (water table drawdown). Sudden changes in water table elevation promote DOC production and export. Methane bubbles confound hydraulic gradients and flows by creating local pockets of pressure, which are then released episodically when the entrapped gas reaches a threshold content. Canadian peatland hydrology continues to be actively researched in lab, field and modelling studies.

Résumé :

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Introduction

The objective of this paper is to highlight the milestones and advances made in Canadian peatland hydrology between 2003 and 2007. This paper follows two similar reports for the periods 1999 to 2003 (Price *et al.*, 2005a) and 1995 to 1999 (Price and Waddington, 2000). Canadian wetlands are categorized as bogs, fens, swamps, marshes and shallow open water (NWWG, 1988), and comprise 14% of Canada's land area (NWWG, 1988). Peatlands represent over 90% of Canadian wetlands (Tarnocai, 1998) and are the main focus of the research presented in this review. However, some discussion on the hydrology of non-peat accumulating wetlands is also included.

Wetlands are defined as areas with the water table at, near, or above the land surface for long enough to promote hydric soils, hydrophytic vegetation, and biological activities adapted to wet environments (NWWG, 1988). As such, wetland ecosystems exist in the landscape where there is an adequate water supply, such as in regions where on average, precipitation exceeds evaporation loss or where drainage is impeded, or sustained inflows from surface or subsurface sources alleviate the water deficit. Due to climatic or edaphic conditions, marsh, shallow water, and some swamps are wetland classes that produce little or no peat (Zoltai and Vitt, 1995), while peatlands are wetlands that have accumulated organic sediments exceeding 40 cm, and include bogs, fens, and some swamps (NWWG, 1988). Fens and (some) swamps are minerotrophic peatlands, receiving water and nutrients from atmospheric and telluric sources, whereas bogs are ombrotrophic, receiving water and nutrients dominantly from direct precipitation.

Over the period from 2003 to 2007 there have been major advances in Canadian peatland hydrology. We begin this review with a comprehensive discussion on research into the main fluxes of water: evapotranspiration, surface water and groundwater. We conclude with a discussion on peatland carbon cycling and ecohydrology because Canadian peatland hydrology research has revealed the importance of carbon cycling feedbacks on peatland hydrology through peat accumulation processes and subsequent changes in the hydro-physical properties of peat.

Evapotranspiration

A number of studies of evapotranspiration (ET – the combined process of direct evaporation and transpiration) have taken place on Canadian peatlands in recent years. Some research has been conducted in support of hydrologic budgets, while others have focused on the ET process itself. Peters *et al.* (2006) examined the hydrology of perched basins in the Peace-Athabasca Delta regions of northern Alberta. They showed that water loss by ET normally exceeded annual precipitation (P) resulting in constant drawdown of the water table between replenishing flood events. Petrone *et al.* (2007) studied ET from a boreal wetland complex in central Alberta. They found that evaporation from open water ponds exceeded ET from vegetated riparian zones by about two times. Nearby forests had a significant impact on pond evaporation through sheltering and turbulence influences and thus forest management can play an important role in wetland ET and its hydrology. Humphreys *et al.* (2006) compared peak growing season ET rates from six wetlands located in central and western Canada and found that maximum ET rates between sites varied from 0.21 to 0.34 mm hr^{-1}. They suggested that this small range was due to off-setting controls on ET across the various wetland types, in particular where increases in vascular plant leaf area decreased the importance of moss (or surface) evaporation and vice versa. These authors also investigated the link between water and carbon balances by computing water use efficiencies, which show much more variation by wetland type than ET rates.

The most concentrated research effort into peatland ET has taken place at the Mer Bleue bog located in eastern Ontario. Admiral *et al.* (2006) and Admiral and Lafleur (2007a) investigated seasonal and inter-annual partitioning of available energy into latent heat flux and the surface controls on this flux. Results from these studies supported the development of a three-component ET model that separates the bog into vascular vegetation, hummock moss and hollow moss surfaces (Admiral and Lafleur, 2007b). Model runs indicate that vascular plants contribute 60-80% of the total latent heat flux, while mosses make up the remainder with hummock mosses the dominant source. In addition, there was little variation in this partitioning during the growing season. Lafleur *et al.* (2005a) examined a five-year time series of ET measurements from the bog and showed that, although maximum summer ET was similar in most years, annual ET varied because of length of the warm season and, to a lesser extent, winter ET losses. Annual P:ET ratios varied between 1.5 and 1.9. In a novel approach to ET modelling, Hember *et al.* (2005) attempt to relate the long-term ET record from the Mer Bleue bog to large-scale patterns of atmospheric circulation. Although unsuccessful at modelling daily ET, the method showed promise at monthly and seasonal time scales. With further development, such modelling could be used to derive ET for water budget studies under future climate scenarios.

Surface Water and Hydrologic Flow Paths

Advances have also been made toward understanding the hydrological functioning of widely occurring peatland types. For example, Fitzgerald *et al.* (2003) demonstrated that headwater swamps can strongly affect the physical and chemical character of streamflow. During large storm events, the water table can rise quickly and swamps can expand to engulf marginal pools. Hayashi *et al.* (2004) and Quinton *et al.* (2003) sought to understand the hydrologic functions of unique peatland types in a region of discontinuous permafrost, including channel fens, flat bogs, and peat plateaus, using isotopic and chemical signatures of surface and subsurface water, as well as hydrometric measurements. They found that peat plateaus are important runoff producers, flat bogs store most of the water they receive, and channel fens convey water to the basin outlet. Van der Kamp *et al.* (2003) found that prairie wetlands became unsustainable in areas where cultivated lands were converted to undisturbed grassland, since the infiltration rate of the frozen soil in grasslands is high enough to absorb most or all snowmelt. Woo and Young (2003; 2006) found that patchy wetlands in the high arctic include snowbank-fed wetlands, groundwater-fed wetlands, riverine wetlands and lake-outlet wetlands. Their studies showed that the amount of seasonal snow, together with the timing and duration of snowmelt, are important factors in defining the amount of water available for ponds and wetlands at the start of the summer season, and indicating the time when runoff and vertical water losses, such as seepage and evaporation, start to dominate the local wetland flux and storage processes. Many of these patchy wetlands also depend on various water storages (e.g., late-lying snowbeds, near-surface ground ice) to sustain water levels during warm, dry summers. Depletion of these storages with climate warming may result in the disappearance of these wetlands (Woo and Young, 2006).

Groundwater and Peat Properties

Since 2003, several key milestones have been reached that have improved our understanding of the physical and hydraulic properties of peat. Price (2003) demonstrated that peat profiles can experience compression and expansion seasonally, which may alter the depth-permeability relation and are also an important water storage change mechanism (Hogan *et al.*, 2006). Whittington *et al.* (2007) showed seasonal volume changes related to peat type dictated by plant community structure, where woody roots or fleshy rhizomes reduced compressibility. Wet sedge peat underwent the greatest seasonal surface adjustment (Whittington *et al.*, 2007) and is also the most susceptible to subsidence following drainage (Whittington and Price, 2006), thus maintaining a shallower relative water table. Higher compressibility peat that can maintain saturation can attenuate variations in pore-water concentration of contaminants (Mouniemne and Price, 2007). The compressibility of peat diminishes with time, although expansion of pores by seasonal frost in the upper layer provides a significant degree of recovery (Kennedy and Price, 2005). Furthermore, re-activation of this property is important in restoring peatlands (Shantz and Price, 2006a). The process can be modelled, but requires difficult parameterization (Kennedy and Price, 2004).

Hydrogeological setting controls the groundwater regime and development of peatlands in the Hudson Bay Lowlands (Glaser *et al.*, 2004); in maritime blanket bogs (Lapen *et al.*, 2005); in hyper-maritime forested peatlands (Emili *et al.*, 2006; Emili and Price, 2006) and in a kettle-hole wetland (Dempster *et al.*, 2006). Changes to groundwater regimes have been noted in response to wet/dry cycles and human-induced disturbances. Ferone and Devito (2004) found peatland-to-pool flows were reversed during drought periods. Water table changes following drainage, as well as prescribed burning, can produce more favourable conditions for tree growth (Lavoie *et al.,* 2005). However, tree removal, and even pre-commercial thinning, can induce a rise in the water table of forested peatlands (Jutras *et al.*, 2006). Drained and cutover peatlands have an erratic water table regime caused by degraded peat hydraulic properties (Price and Whitehead, 2004). New peat extraction where the acrotelm is preserved shows great promise (Cagampan and Waddington, 2007; 2008) but nevertheless, degraded peat properties result in lower soil-water pressures that are detrimental to recolonization of peat-forming *Sphagnum* mosses (McNeil and Waddington, 2003). Where mosses have recolonized they modulate water table and soil-water pressures (Price and Whitehead, 2004). Full-scale restoration of these systems may still be possible with appropriate water and vegetation management (Campeau *et al.*, 2004; Cobbaert *et al.*, 2004; Montemayor *et al.*, 2008; Shantz and Price, 2006a; b).

Groundwater modelling studies have shown that lateral subsurface water redistribution is a necessary mechanism for simulating water table depth in peatland sites (Ju *et al.*, 2006). Lapen *et al.* (2005) used a model of blanket peatlands to show that lower hydraulic conductivity of lagg peats redistribute water to the surface.

Several new field diagnostics have recently been developed. Hogan *et al.* (2006) developed and tested new field techniques to evaluate peat storativity and hydraulic conductivity in boreal fens. Conly *et al.* (2004) described the depth-gauging method used in obtaining long-term water-level data for wetlands on the Canadian Prairies. Quinton *et al.* (2008) proposed a physically-based equation that calculates peat permeability from the pore-size distribution, as an alternative to estimating permeability as a function of depth. Hayashi and Quinton (2004) extended the applicability of the Guelph permeameter method to peat soils underlain by an impermeable boundary, such as bedrock or permafrost, with a new set of shape factors determined by numerical simulation. Other researchers have focussed on alternative means of in-situ measurement of peat permeability, including water tracing (Weiler and Naef, 2003; Quinton and Gray, 2003), and tension infiltrometer measurements at successive pressure heads (Bodhinayake *et al.*, 2004). Carey *et al.* (2007) measured the water conducting porosity of organic soils for different pore radii ranges using the method proposed by Bodhinayake *et al.* (2004) and compared these values to active pore size distributions from laboratory thin sections and pressure plate analysis. Total water conducting porosity was 1.1 × 10^{-4}, which accounted for only 0.01 % of the total soil volume. Price *et al.* (2008) developed a method for direct laboratory measurement of unsaturated hydraulic conductivity of moss. They found a four order of magnitude decrease in unsaturated hydraulic conductivity as soil-water pressure dropped from zero to -25 cm of water.

Petrone *et al.* (2004a) analyzed soil moisture distributions in the field to test scale effects and noted spacing of the samples in a grid was more important than just sampling density. Price *et al.* (2005b) found that peat bulk density and fibre content are poor indicators of peat compressibility.

Carbon Cycling and Ecohydrology

Natural peatlands are important elements of both the contemporary and Holocene global C cycle (Frolking and Roulet, 2007). A six-year carbon balance at Mer Bleue peatland near Ottawa was determined from continuous net ecosystem CO_2 exchange (NEE), regular instantaneous measurements of methane (CH_4) emissions, and export of dissolved organic C (DOC) from the peatland (Roulet *et al.,* 2007). The mean exchange of CO_2-C, CH_4-C, and DOC export were -40.2 ± 40.5 (± 1 SD), 3.7 ± 0.5, and 14.9 ± 3.1 g C m^{-2} yr^{-1}, which represents a mean carbon uptake of 21.5 ± 39.0 g m^{-2} yr^{-1}. This value was very similar to Gorham's (1991) estimates for northern peatlands. Moisture can affect both CO_2 fixation and ER, not necessarily in the same direction (Lafleur *et al.,* 2005b) and moisture availability in July, August and September was a critical factor in determining annual CO_2 exchange of the Mer Bleue peatland (Lafleur *et al.,* 2003).

Global warming is expected to impact northern wetlands by extending the growing season and lowering the water table position due to enhanced evapotranspiration (Roulet *et al.,* 1992; Moore *et al.*, 2006). Studies of timing of spring arrival and CO_2 exchange at the Mer Bleue bog over a five-year period showed little variation in the start of growing season from one year to the next, and suggested that the changes in arrival of spring may only be important for increasing carbon storage at more northern latitudes (> 60 °N). Strack and Waddington (2007) determined that in pools and hollows, reductions in CH_4 emissions following water table drawdown were limited, and fluxes may actually increase. Soil subsidence maintained water tables close to the surface and drier conditions may result in increased vegetation productivity (Strack *et al.*, 2004; Strack *et al.*, 2006a). Subsidence can result in greater water table fluctuations. Sudden decreases in water table position can increase DOC production (Blodau and Moore, 2003) and concentration (Blodau *et al.*, 2004; Strack *et al.*, 2008) demonstrating the strong coupling between peatland carbon cycling and hydrology.

Land-use change (drainage, extraction, flooding) can have a pronounced impact on vegetation and carbon fluxes and stores in peatlands (Waddington *et al.*, 2005). Asada *et al.* (2005) demonstrated that shallow flooding of a peatland caused an initial net decrease in carbon stores but the development of vegetation on floating peat mats offset this decrease in carbon storage. In cutover peatlands a stable moisture supply is most beneficial to *Sphagnum* growth (Petrone *et al.*, 2003; 2004b; Cagampan and Waddington, 2007) compared with repeated wetting and drying events (McNeil and Waddington, 2003). CO_2 exchange in these ecosystems has been correlated to DOC concentration (Glatzel *et al.*, 2003). DOC export did not decrease following the restoration of extracted peatlands (Waddington *et al.*, 2008) but CH_4 flux increased after restoration due to both the supply of labile carbon and the enhanced CH_4 transport from vascular plants (Marinier *et al.*, 2004; Waddington and Day, 2007).

Methane ebullition occurs when the buoyant forces of entrapped gas exceed the forces restraining it (Strack *et al.*, 2005; 2006b) allowing the gas to escape to the atmosphere. Evidence of this has been found in both laboratory (Baird *et al.*, 2004; Kellner *et al.*, 2006) and field (Strack *et al.*, 2005) experiments. Baird *et al.* (2004) found a threshold gas content limit of approximately 10-14% while Kellner *et al.* (2006) found threshold values of 12 and 15% provided very good results when modelling ebullition events. These gas bubbles also affect the hydrological properties of peat since as bubbles form, they block off voids, and have the potential to greatly reduce water and solute transfer from surrounding areas (Kellner *et al.*, 2005), creating a localized zone of over-pressuring (Kellner *et al.*, 2004).

Conclusions

This review has demonstrated that major advances have been made in Canadian peatland hydrology, particularly the study of surface and groundwater flow in peatlands and the hydrophysical properties of peat. However, evapotranspiration is still a relatively understudied part of the peatland hydrologic balance. Recent advances in ET research in Canada underscore the importance of wetland type in determining water losses by ET. Although ET rates may not vary greatly between wetlands, the underlying controls do. Consequently, modelling of wetland ET requires more deterministic approaches, especially in predicting impacts of climate warming on peatland ET.

Canadian peatland hydrology research has also demonstrated the strong coupling between ecological, biogeochemical and hydrological processes in wetlands and in particular peatlands. Moisture conditions not only determine, in part, the type of vegetation in a wetland but also have a strong control on the rate of photosynthesis and also the rate of decomposition. The carbon stored in a wetland becomes the matrix in which water flows and thereby feeds back to the carbon sequestration process and also the transport of solutes. A failure to couple hydrology, ecology and biogeochemistry would suggest that our current understanding of peatland hydrology is limited (Belyea and Baird, 2006) and truly coupling these disciplines represents a considerable challenge for wetland hydrology research in the years to come.

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