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# Hydrology of a wetland-dominated headwater basin in the Boreal Plain, Alberta, Canada

Corey Wells *, Scott Ketcheson [1], Jonathan Price

[a] Wetland Hydrology Laboratory, Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario N2L-3G1, Canada

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ABSTRACT

This study provides an in-depth analysis of the runoff generation dynamics and hydrological connectivity across upland-wetland transitions within a wetland-dominated headwater basin in the Western Boreal Plain (WBP), Canada. Basin runoff response between and among years was driven largely by differences in the timing and magnitude of precipitation relative to potential evapotranspiration, hence antecedent moisture conditions, which varied markedly over the four-year study (April–Sept). Runoff coefficients for individual precipitation events ranged from <1 to >90% depending on storm dynamics and antecedent conditions. Owing to its higher elevation, the basin received 55% more precipitation per month on average compared to 30-year climate normals and an average of 86 mm more precipitation per season than the nearby regional weather station. The wetland and adjacent forestlands became coupled during intermittent wet periods which generated substantial runoff. The findings of the current study suggest that, in contrast to conventional conceptual models, headwater catchments within the subhumid WBP have the capacity to generate significant runoff throughout the snow-free period. This has important implications for wetland maintenance and represents an important water delivery mechanism for downstream ecosystems where excess water is scarce.



## 1. Introduction

The Western Boreal Plain (WBP) comprises a mosaic of wetlands, lakes and forested uplands overlying generally deep and heterogeneous glacial deposits (Vogwill, 1978; Andriashek, 2003; Devito et al., 2012). The high intensity of resource extractive activities in the WBP demands a clear understanding of ecosystem functions and values, since these affect operational activities, landscape management and reclamation. In particular, the hydrological connectivity between these landform types is a key component of ecosystem health (Devito et al., 2012), and requires more study to better inform the regulatory framework.

The configuration of landform types and their hydrologic role in the landscape is governed largely by their hydrogeologic setting (Tóth, 1963; Winter, 1999) placed within the context of a subhumid climate, which in turn influences water storage and conveyance and hence water quality (Devito et al., 2000, 2005a; Ferone and Devito, 2004; Smerdon et al., 2005). In the subhumid WBP, wetlands facilitate the transmission of water across the landscape, whereas forestlands tend to have large storage capacities with generally high evapotranspiration (ET) and function as water sinks (Devito et al., 2012; Brown et al., 2014; Thompson et al., 2015). Along wetland-forestland interfaces, ground and surface water interactions are dynamic (Ferone and Devito, 2004; Devito et al., 2005b; Smerdon et al., 2005) and can lead to the development of biogeochemical 'hotspots' (Burt and Pinay, 2005). Thus, hydrologic coupling between landform types can have a strong influence on the volume and chemistry of runoff from wetlands supplying downstream basins (Gibson et al., 2002; Spence et al., 2011). In a region affected by large-scale industrial development (Webster et al., 2015), effective landscape management requires a better understanding of the function of catchments and their interactions with downstream ecosystems. It is particularly important to capture seasonal and inter-year climate variability over the long-term in this setting where catchment functioning is influenced by antecedent moisture conditions.

In the WBP, the hydrologic function of wetlands is constrained by a set of dominant controls, namely, climate and geology (Devito et al., 2005a). Excess water is generally minimal due to the synchronization of peak rainfall with maximum potential evapotranspiration (PET) (Marshall et al., 1999; Petrone et al., 2007; Brown et al., 2014), which exacerbates seasonal water deficits and limits the opportunity for runoff throughout the catchment (Devito

* Corresponding author.
*E-mail address:* corey.m.wells@gmail.com (C. Wells).
[1] Current address: School of Geography and Earth Sciences, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L8, Canada.

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et al., 2005b; Redding and Devito, 2008). Exceptionally wet periods typically occur every 10–15 years and help to regulate long-term moisture deficits (Devito et al., 2012). Unlike the Precambrian shield, where thin surficial deposits overlie impermeable crystalline bedrock, the deep, heterogeneous and generally low relief topography of the WBP generates a range of complex flow systems that influence storage, recharge/discharge functions and wetland permanence (Bachu et al., 1993; Devito et al., 2012; Wells and Price, 2015a). From the perspective of regional groundwater flow, wetlands located along topographically high positions exhibit seasonally dynamic hydrologic conditions and function primarily as groundwater recharge features (Tóth, 1963; LaBaugh et al., 1997; Winter, 2001). Often disconnected from regional-scale groundwater flow systems, recharge wetlands form within isolated basins and are influenced hydrologically by adjacent uplands (Ferone and Devito, 2004; Devito et al., 2012). Surficial topography often dominates groundwater flow in low-lying fine-textured regions of the WBP, where expansive wetland complexes form connected drainage networks that in some cases also function as zones of regional groundwater discharge (Devito et al., 2012; Wells and Price, 2015b).

Runoff dynamics at the basin scale are controlled largely by the runoff generation potential of the individual landscape hydrologic units within the catchment (i.e., wetlands and forestlands), as well as the spatiotemporal degree of hydrologic connectivity between those units (Roulet, 1990; Metcalfe and Buttle, 2001; Devito et al., 2005a; Bracken et al., 2013). In the WBP, the interface between wetlands and forested uplands is complex, and elevation differences among landscape units do not necessarily describe hydrologic interactions (Devito et al., 2005a). Water tables often slope against topography (Mills and Zwarich, 1986; Hayashi et al., 1998; Ferone and Devito, 2004; Smerdon et al., 2005; Thompson et al., 2015), while runoff contributions to wetlands are often negligible due to the dominance of vertical flow caused by deep unsaturated zone storage and strong evapotranspiration rates (Ferone and Devito, 2004; Redding and Devito, 2008, 2010). However, the magnitude of runoff in subhumid regions, including the WBP, can be highly dependent on soil water storage, which differs among landform types as well as within and between years (Wainwright and Parsons, 2002; Devito et al., 2005b; Smith et al., 2009). During long-term wetting cycles or seasonally wet periods (e.g., spring freshet), high water levels can increase the occurrence of surface saturation on upland areas or riparian margins, which can produce overland or shallow subsurface flow (Roulet, 1990; Devito et al., 2005a; Todd et al., 2006). While ongoing research in the glaciated regions of Alberta's Boreal Plain has described the hydrologic connectivity and response of wetland-upland catchments in detail (e.g., the Utikima Research Study Area), there is a need to expand the geographical range of our observations to provide insight into whether similar processes describe wetland-upland interaction throughout the regional WBP setting. This is particularly true for the Athabasca Oil Sands Region (AOSR) of northeastern Alberta, where resource development is transforming the natural hydrologic regime (Elshorbagy et al., 2005; Ketcheson and Price, 2016).

The purpose of this study was to examine the hydrology of a wetland-dominated headwater basin in northeastern Alberta, Canada, with a particular focus on runoff generation dynamics and hydrological connectivity across upland-wetland transitions. The study was conducted over four years (April–September; 2011–2014) to capture the dynamic connectivity of landscape units under a range of hydroclimatic conditions. Specific objectives included: (1) investigate spatiotemporal trends in basin runoff and connectivity; (2) explore the drivers behind this variability in hydrologic function; and (3) develop an improved understanding of the influence of uplands on wetland maintenance in the WBP.

## 2. Study site

The study was conducted at Pauciflora Basin (56°22′30.36″N, 111°14′3.29″W), a 0.42 km$^2$ headwater basin located approximately 40 km south-east of Fort McMurray, Alberta, Canada (Fig. 1). The basin is situated within the Central Mixedwood Subregion of the Boreal Plains Ecozone (Natural Regions Committee, 2006), with a mean annual air temperature of 1 °C and monthly means ranging from −17 °C to 17 °C between January and July, respectively (Environment Canada, 2015). The climate in the WBP is sub-humid (Bothe and Abraham, 1993; Marshall et al., 1999), with annual PET typically exceeding precipitation (an annual dryness index (PET:P ratio) of ~1.1 (Devito et al., 2012)). However, controls on evapotranspiration in many landscape units result in actual ET that is typically less than PET (Devito et al., 2005b; Petrone et al., 2007).

Pauciflora Basin is situated within the Stony Mountain Uplands, one of the four major uplands in northeast Alberta that roughly encircle the wetland dominated Dover Plains (Hackbarth and Nastasa, 1979; Andriashek, 2003). Elevations range from approximately 600–850 m above sea level (masl) along the Stony Mountain Uplands, with the Pauciflora Basin positioned at ~750 masl. Water drains radially from Stony Mountain into numerous tributaries of the Athabasca and Clearwater Rivers (Fig. 1). In the study area, marine shale of the LaBiche Formation underlies approximately 150 m of Tertiary and Quaternary drift, with the unsorted glacial tills of the Grand Centre Formation (25–50 m thick) forming the present land surface of the uplands (Andriashek, 2003). Enriched with an abundance of Precambrian shield rock fragments, the Grand Centre Formation was deposited during the Late Wisconsin of the last glaciation (Andriashek and Fenton, 1989).

A poor fen peatland (the "Pauciflora Fen") comprises 26% (0.11 km$^2$) of the basin, forming an elongated hourglass-shaped configuration bordered by forested uplands on all sides. A densely treed (predominantly *Picea mariana*) poor fen is located at the head (south-end) of the peatland system (herein referred to as the south treed fen, STF), which transitions northward into an open poor fen peatland composed of *Sphagnum* mosses and ericaceae shrubs (mid fen, MF) (Fig. 1). Sparse stands of *Larix laricina* and *P. mariana* occur sporadically throughout the entire peatland but are most concentrated at the 'neck' of the complex where the adjacent uplands pinch in (Fig. 1). Upland margins are dominated primarily by dense stands of *P. mariana*, which transition into *Picea banksiana* and *Populus tremuloides* at higher elevations. Feather mosses and shrubs comprise much of the slope understory, which overlay a dense silt and clay rich glacial till. The uplands along the western edge of the peatland have an average slope of ~13% and are much taller and more gradually sloping than the eastern uplands, which vary from convex shallow mounds to low but steeply sloped ridges (~34% slope) (Fig. 1d). North of the MF, the fen opens into a *Sphagnum* lawn bordered by sparse *P. mariana* to the east and west (north fen, NF). The basin drains northward where a gravel service road intersects the peatland and impedes water flow. This impoundment produced elevated water table levels in the NF, which caused tree dieback in that area (Bocking et al. unpublished results). At the time of road construction, a drainage culvert was installed at the northwest side of the service road, which functions as the basin outflow point (Fig. 1).

## 3. Methods

### 3.1. Hydrology

A network of four transects (T1 through T4), comprising 33 well and piezometer nests, were installed across the peatland and into