LETTER

Forestland-peatland hydrologic connectivity in water-limited environments: hydraulic gradients often oppose topography

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Abstract

It is common to conceptualize the water table as a subdued replica of surface topography, where groundwater recharges at, and flows from, topographic highs and flows to, and discharges at, topographic lows, in humid (i.e. wetter) environments. This concept is also regularly applied to peatland hydrology, where hydraulic gradients are shown to be towards the peatland. However, this may not be a realistic representation of hydrology for low-relief and sub-humid regions. While it is widely accepted that peatlands maintain internal water tables in drought conditions through a system of autogenic negative feedback loops, there is a general lack of knowledge concerning the controls on, and patterns of, forestland hydrologic process that drive the hydraulic gradients between wetlands and their adjacent forestlands in water-limited conditions in low-relief areas. This study identifies the hydrologic function (i.e. source or sink of water) of forested uplands and peatlands in the Boreal Plains region of Canada and demonstrates that during a mesic (non-drought) year most peatlands are, in fact, potential sources of groundwater to adjacent forestlands. Sixteen forestland-peatland pairs were selected to represent a spectrum of forested hummock and peatland morphometries, topographic positions, and geologic settings. Hydraulic gradients determined for each well pair during the ice-off season demonstrate that the dominant gradient under mesic climatic conditions is from peatlands to adjacent forestlands, opposite of the topographic gradient, and that the sink-source function of each land unit does not change seasonally. Water table depressions under each forested hummock indicate that boreal forestlands are not reliable sources of groundwater recharge, spatially or temporally, which supports previous research showing that peatlands are the primary water source for runoff; illustrating the need for alternative conceptualizations of catchment hydrology in water limited regions of the boreal. Social Media Summary. Forests are poor sources of water to boreal peatlands and landscapes due to water table depressions.

1. Introduction

A widely accepted approach in both conceptual and numerical models of groundwater flow is to assume that the water table is a subdued replica of topography (e.g. Hubbert 1940, Tóth 1963, Cardenas 2007). The topography-driven paradigms underpinning this water table configuration generally perform best in humid, high-relief regions or for large regional groundwater systems (Gleeson et al 2011); however, water table configurations are also controlled by climate (recharge) and geology (Freeze and Witherspoon 1967, Tóth 1970, Haitjema and Mitchell-Bruker 2005). Therefore, topography may not be a first-order control in water-limited regions or those with low relief (Winter 1999, Devito et al 2005, Hokanson et al 2019). These regions are globally prevalent (e.g. Southern Australia, Western Canada, Western Siberia, Central Europe, Northern China, The Great Hungarian Plain) and are considered to be hydrologically vulnerable to anthropogenic activity, including climate change. However, the intricate, highly non-linear interactions between climate, geology, and topography are difficult to predict (Jobbágy
and Jackson 2004, Jackson et al 2009, Condon and Maxwell 2015).

Tóth (1963) first analytically demonstrated the relationship between topography and groundwater flow systems (i.e. local, intermediate, regional) and groundwater fluxes (i.e. recharge and discharge). Furthermore, he demonstrated that with decreasing topographic relief the relative prominence of local flow systems (flow in which the recharge area is directly adjacent to its discharge area) also decreases. Despite this, local groundwater flow systems can be important components of the hydrological cycle, affecting surface or near surface processes such as solute transport, pond and wetland water and chemical budgets, and landform hydrologic connectivity (Tóth 2009). The spatiotemporal presence or absence of local flow systems (i.e. groundwater mounding under local topographic highs) is primarily controlled by net recharge (Haitjema and Mitchell-Bruker 2005), where regions with low recharge tend to have greater spatial variability in groundwater-surface water interactions (Schaller and Fan 2009).

The sink-source function (i.e. groundwater recharge or discharge) of a landscape unit and its proclivity to change through time is crucial to the regional water balance in complex water-limited, low-relief environments. The Boreal Plains ecozone, located in the Western Glaciated Plains of North America, is such an environment. It is characterized by thick, unconsolidated, heterogeneous substrates and a sub-humid climate, where potential evapotranspiration often equals or exceeds precipitation, manifesting as a regionally sub-humid climate with multi-year wet and dry cycles (Mwale et al 2009). Hydrogeology in the Boreal Plains is made even more complex by the presence of peatlands. While previous regional-scale studies have shown that runoff from large catchments is positively associated with peatland coverage (Van Der Velde et al 2013, Gracz et al 2015, Devito et al 2017), little is known about the spatiotemporal variability of or controls on hummock-scale processes or landform connectivity that control it. Nonetheless, identifying the spatiotemporal hydrologic behaviors of the smaller land units that make up larger runoff source areas is an important aspect of ‘scaling-up’ in order to predict landscape scale runoff responses (Jencso et al 2009).

Most previous studies concerning water table dynamics in undisturbed landscapes have focused on high relief, humid regions with shallow water tables and/or hydrogeologic settings that promote predictable and steady local-scale flow systems (Jencso et al 2009, Goodbrand et al 2019, Prancevic and Kirchner 2019). Consequently, there is a general lack of understanding regarding the spatiotemporal distribution of groundwater recharge and discharge zones in more complex and dynamic landscapes. Thick unconsolidated sediments, low relief, and a water-limited climate result in interdependent surface water and groundwater processes with varying spatiotemporal controls (Lissey 1971, Winter 1999, 2001). Traditional conceptualizations of water tables as subbed replicas of topography necessarily require that recharge and discharge zones are primarily fixed in space and dependent solely on topography. Alternatively, in heterogeneous low-relief regions, slight changes in the interannual climatic water balance or variations in vegetative cover can shift, or even switch, recharge and discharge zones through time. For example, a forested hummock may act as a source (i.e. groundwater recharge) during water surplus and subsequently become a water sink (i.e. subsurface discharge) during a water deficit when evapotranspiration exceeds precipitation (Heuperman 1999).

The Boreal Plains are experiencing unprecedented anthropogenic and natural disturbance, including climate change, oil and gas operations, and wildfire. As a consequence, boreal peatlands and forestlands are a primary focus of both reclamation and reconstruction efforts (Daly et al 2012, Wytrykush et al 2012). While the notion of topography-driven flow between forested uplands and peatlands is common and is often implied in conceptual site models (e.g. Holden 2006, Ireson et al 2015, Nwaishi et al 2015, Ketcheson et al 2017), it may not always be a realistic representation of boreal hydrology. It is well understood that peatlands maintain fairly stable internal water table depths, even in dry continental settings and under drought conditions, by limiting evaporation through a system of autogenic processes. For example, water table depth is involved in negative feedback loops with peat deformation (e.g. Morris et al 2011), moss surface resistance (e.g. Price et al 2009), and moss productivity (e.g. Thompson and Waddington 2008). We refer readers to the review paper by Waddington et al (2015) for more detailed descriptions. Despite this, there is a general lack of knowledge concerning the controls on, and spatiotemporal patterns of, external hydraulic gradients from forested hummocks to adjacent wetlands (Price et al 2005, Redding and Devito 2008, Dimitrov et al 2014). It is conventionally assumed, but not widely monitored, that in sub-humid boreal environments water moves from forests to wetlands during average, non-drought conditions (Ketcheson et al 2016). The intricate mosaic of forestlands and peatlands overlying thick heterogeneous glacial deposits typical of the Boreal Plains results in highly spatially variable evapotranspiration rates, subsurface hydraulic properties, and surface topographic gradients; all of which influence the hydrologic function of each land unit.

Through understanding these dynamic and complex environments we increase our ability as hydrologists to conceptualize groundwater and surface water movement and availability across a spectrum of geologies and climates by identifying primary controls in each landscape that may surpass those attributed to topography alone. To address this key knowledge gap and to test the common conceptualization of
topography driven flow and groundwater mounding under hummocks, the hydraulic gradients between peatlands and adjacent forested hummocks were analyzed at sixteen sites. Peatland-forestland pairs were purposefully selected to represent a spectrum of unconsolidated deposit types typical of those blanketting the boreal regions of the Western Glaciated Plains, forested hummock morphometries, and regional topographic position.

Previous work by Devito et al. (2005, 2012) has challenged the topographically defined catchment and the practice of assuming that the water table conforms to topography, and as a result introduced the idea of a ‘topography last’ hierarchical classification to identify the major controls over hydrological regions. Their work focused on concepts related to the dominant roles that climate (i.e. P and ET) and vertical fluxes have in regions with deep soils and large water storage potential. Following this, Hokanson et al. (2019) showed at the intermediate scale in the BP that the roles of climate and geology can have a greater effect than topography on water table position and variability. This study is a direct empirical test of these ideas at the hummock scale over a large and heterogeneous spatial extent.

2. Study site and methods

The Utikuma Region Study Area (URSA; 56°N, 115°W) is located 370 km north of Edmonton, Alberta, in the Boreal Plains ecozone of Canada. The region is characterized by low topographic relief and thick (45–240 m) heterogeneous glacial substrates overlying Cretaceous marine shale (Vogwill 1978). The climate is considered sub-humid, with long-term precipitation and potential evapotranspiration averaging 444 mm and 517 mm, respectively (Marshall et al. 1999, Hokanson et al. 2019). The primary sources of precipitation are short duration convective-cell storms, which occur during the summer months when evapotranspiration is highest (Devito et al. 2005, Brown et al. 2014).

The study region can be divided into three major hydrological response areas (HRAs): coarse outwash (CO), hummocky moraine (HM), and lacustrine clay till plain (CP), which were thoroughly characterized in Hokanson et al. (2019). The CO HRA contains areas of fine substrates with perched water tables overlying coarse sediments; perched over coarse (CO-P). These HRAs can be further discretized into hydrological units (HU): forestlands, peatlands, and open water. Forested hummocks are characterized by mixedwoods dominated by trembling aspen (Populus tremuloides), while the peatlands have a sparse canopy of black spruce (Picea mariana) and tamarack (Larix sp.). Peatlands are comprised of peatland mosses, with organic accumulations ranging from 2 to 5 meters with hydraulic conductivity values ranging from $10^{-4}$ to $10^{-6}$ m s$^{-1}$ in the top two meters (Lukenbach et al. 2017). For each HRA, considering the CO-P region independent of CO, four hummock–peatland pairs were chosen to represent a spectrum of hummock morphometries and topographic positions (peatland elevation). Over the 70 km long transect encompassed by this study, the peatland elevations have a range of 30 m, which is typical of the low relief of the Boreal Plains (Hokanson et al. 2019). Peatland areas range from 0.5 ha to greater than 100 ha. All hummocks have forest stands dominated by aspen (Populus tremuloides), except for CO-d, which is primarily jack pine (Pinus banksiana).

Precipitation data were collected throughout the 2018 hydrologic year (1 November, 2017 to 31 October, 2018) using two tipping bucket rain gauges in separate HRAs. The gauges were adapted for snowfall in winter months by using antifreeze reservoirs and data were validated with manual gauges. To place this study period in context of the long-term climate and to account for the strong effect of antecedent moisture conditions on hydrologic response in the Boreal Plains, the 3 year cumulative departure from the mean precipitation (3yrCDM) was calculated using the recent long-term mean precipitation (444 mm; 1987–2015) and preceding three annual precipitation values (Hokanson et al. 2019).

To characterize the hydrologic function of each HU and to determine the direction of the water table gradient between HUs, a single monitoring well (0.0381–0.051 m diameter polyvinyl chloride pipe) was located at each HU at each site (32 wells). Peatland wells were screened over the entirety of the well, while forestland wells were either screened over the entirety of the well or had solid casing extending from the top of the well to 1 m below the ground surface. In all cases the screened interval spanned the water table for the duration of the study. All wells were instrumented with pressure transducers (Solinst, Georgetown, Ontario, Canada; Northern Widget LLC, Minneapolis, Minnesota, USA), which recorded water levels at thirty-minute intervals during the ice-off period of 2018 (mid-May to mid-October) and were barometrically compensated using the closest barometric pressure transducer (Solinst). To validate the transducer readings, levels were also measured manually three times: Spring (mid-May), summer (mid-July), and fall (mid-October). Water table elevations were determined by coupling the water level data to survey data of the tops of the well casings collected using a theodolite or a digital water level (Smart Leveler, Smyrna, Tennessee, USA; ± 0.002 54 m). Pressure transducers were damaged at two sites (CO-P-d, CP-d); in which case only manual water levels are presented. The absolute difference in water table elevations ($\Delta h$) and gradient direction are presented in lieu of true gradients because variable, arbitrary distances between forestland–peatland wells would have an undue influence on the magnitude of calculated gradients.

The hydraulic conductivity ($K$) of the mineral substrate in each hummock was estimated using the
Hvorslev (1951) method, either at the primary hummock well or at a nearby, representative well. Values presented are geometric means of three tests, where both rising and falling head slug tests were used. Topographic profiles of the ground surface were obtained from LiDAR datasets collected in 2008 and were used to obtain metrics to characterize the morphometry of each hummock, specifically the height (H; elevation above adjacent peatland) and length (L; distance between peatlands).

### 3. Results

For the 2018 hydrologic year, precipitation totaled 498 mm and 467 mm in the CP and CO-P HRAs, respectively (figure 1), which are averaged to 483 mm to represent all URSA. Overall the 2018 hydrologic year was considered ‘mesic,’ or average, in terms of both annual precipitation and the 3yrCDM. In the context of the long-term climate at URSA (figure 1), 2018 was only 39 mm above the long-term average annual precipitation and the 3yrCDM from the mean was +38 mm.

Measured K values of the hummocks (table 1) are generally highest in the CO HRA ($3.7 \times 10^{-6}$ to $1.5 \times 10^{-4}$ m s$^{-1}$) and lowest in the HM HRA ($5.7 \times 10^{-10}$ to $1.3 \times 10^{-7}$ m s$^{-1}$). Conductivities of the CP and CO-P hummocks range from less than $1 \times 10^{-9}$ to $6.1 \times 10^{-7}$ m s$^{-1}$ and $1.8 \times 10^{-9}$ to $7.9 \times 10^{-9}$ m s$^{-1}$, respectively. Profiles through each site (table 1; figure 2) show the wide range of forested

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**Table 1. Site characteristics.**

| HRA | Site | Elevation (m asl) | $K$ ($\text{m} \text{s}^{-1}$) | Height $H$ (m) | Length $L$ (m) | $\frac{L}{H}$ (m/m) | Δ$h$ max (m) | Δ$h$ min (m) |
|-----|------|------------------|----------------|---------------|---------------|----------------|----------------|----------------|
| CO  | a    | 663              | $2 \times 10^{-8}$ | 4.2           | 190           | 45             | $-0.65$        | $-1.10$        |
| CO  | b    | 665              | $2 \times 10^{-8}$ | 10.1          | 190           | 19             | $-1.00$        | $-1.50$        |
| CO  | c    | 663              | $4 \times 10^{-8}$ | 2.1           | 102           | 49             | $-0.05$        | $-0.35$        |
| CO  | d    | 658              | $7 \times 10^{-8}$ | 9.7           | 145           | 15             | $-0.05$        | $-0.20$        |
| CO-P| a    | 673              | $3 \times 10^{-8}$ | 5.7           | 850           | 148            | $-1.20$        | $-2.75$        |
| CO-P| b    | 673              | $8 \times 10^{-9}$ | 2.1           | 115           | 55             | $-0.35$        | $-0.60$        |
| CO-P| c    | 675              | $2 \times 10^{-9}$ | 0.7           | 140           | 196            | $-1.40$        | $-1.90$        |
| CO-P| d    | 675              | $6 \times 10^{-9}$ | 0.4           | 125           | 313            | $-0.15$        | $-1.15$        |
| HM  | a    | 677              | $1 \times 10^{-7}$ | 2.2           | 130           | 58             | $-1.85$        | $-2.75$        |
| HM  | b    | 671              | $8 \times 10^{-9}$ | 5.5           | 380           | 69             | 3.15           | 1.30           |
| HM  | c    | 672              | $6 \times 10^{-10}$ | 2.4               | 228           | 94             | $-1.90$        | $-2.45$        |
| HM  | d    | 664              | $7 \times 10^{-9}$ | 1.4           | 180           | 128            | $-1.80$        | $-3.05$        |
| CP  | a    | 655              | $6 \times 10^{-7}$ | 1.2           | 135           | 110            | 1.00           | $-0.05$        |
| CP  | b    | 657              | $<1 \times 10^{-9}$ | 1.1          | 130           | 114            | $-0.15$        | $-0.45$        |
| CP  | c    | 644              | $1 \times 10^{-7}$ | 1.2           | 145           | 116            | 1.00           | $-0.40$        |
| CP  | d    | 659              | $<1 \times 10^{-9}$ | 0.9           | 45            | 49             | $0.00$         | $-0.30$        |

Note: HRA = Hydrologic response area; CO = coarse outwash; CO-P = perched over coarse; HM = hummocky moraine; CP = clay-till plain. Δ$h$ values are rounded to the nearest 5 cm.
hummock morphometries sampled. The length/height ratio \( L/H \) for the hummocks ranges from 15 to 195 m/m, where a small \( L/H \) indicates a tall narrow hummock (e.g. CO-d) and a large \( L/H \) indicates a short broad hummock (e.g. HM-c). Overall, the \( L/H \) values are reflective of the texture of each HRA (e.g. clay-rich sediments limit the height of hummocks at the time of glacial deposition), where CO and CP have the lowest and highest \( L/H \) values, respectively.

Seasonal water table fluctuations within each HU are included in figure 3. Peatlands showed little variability in water table position over the study period, both within (temporal variation over the study period at one well) and between sites, regardless of peatland topographic position (table 1). Forested hummocks, however, exhibited much more variability. Water tables in the CP HRA were the shallowest and had high variability within sites, but the least variability between sites. The CO HRA sites had the least variability within and the most variability between sites, with water table depths ranging from \( \sim 2.9 \) to \( \sim 7.7 \) m below ground surface. Water tables in the HM HRA were at intermediate depths \( \sim 4 \) m with high seasonal variability.

Hydraulic gradients were opposite to the topographic gradient, directed from the peatland towards the adjacent forested hummock, at 14 of the 16 sites.
(figures 2 and 4) indicating the presence of a groundwater depression beneath the hummock. Maximum and minimum water table elevation differences ($\Delta h$) are shown in table 1. A negative $\Delta h$ indicates that the peatland water table was above that of the forested hummock. At three hummock sites (CO-P-b, CO-P-c, HM-c) the water table was below the screened interval of the well for the duration of the study; however, the wells were drilled to a sufficient depth to imply that the water table was below that of the peatland and therefore to infer the direction of the gradient. Only two sites (CP-a, HM-b) had gradients towards the peatland for the majority of the study period. At Site CP-c, the gradient was towards the peatland for only 50 d ($\sim$30% of the study period). The CO sites had the lowest magnitude difference in water table elevations while the HM had the highest. The only forested hummock dominated by pine (CO-d), which was also one of the sandiest, had an essentially flat water table. We attribute the small difference in water table elevations at CO-d to isolated mounding within the peatland.

4. Discussion

We show that traditional topography-driven approaches to groundwater flow do not function in our complex water-limited environment, even in mesic, non-drought years. In peatland and forest hydrology there is a silent but prevalent assumption that water flows from highs to lows, even in sub-humid, low-relief areas. This paradigm presents itself in conceptual site models (e.g. Nwaishi et al 2015), assumptions for subsurface water flow between boreal forests and peatlands in numerical models (e.g. Dimitrov et al 2014), and in new approaches for peatland construction following large-scale disturbances (e.g. Price et al 2010). We demonstrate that the development of the groundwater mounding required to drive flow from topographic highs is both spatially and temporally infrequent in low-recharge settings like the Boreal Plains. Under mesic climate conditions, the typical water table configuration between peatlands was depressed, rather than mounded. These observed conditions necessarily require ‘negative recharge’ (i.e. upflux) which clearly exceeds ‘positive recharge’ from precipitation in these sub-humid environments, even in non-drought years. The spatial pervasiveness of groundwater depressions illustrate that negative net recharge is more of a rule rather than an exception in the Boreal Plains.

Where traditional hydrogeological paradigms would predict that groundwater mounding would be greatest (and ubiquitous) in areas of low permeability and undulating topography (Haitjema and Mitchell-Bruker (2005)), we find those areas (HM HRA) are most prone to deep groundwater depressions. In these cases, the low K and specific yield values found in fine-textured HRAs (i.e. CP, HM, CO-P; Thompson et al 2015), exaggerates the negative (however slight) net recharge required to form these depressions, which further limits the generation of lateral flow. Previous work by Hokanson et al (2019) supports this lack of lateral groundwater flow, where isotopic and hydrogeologic data showed that flow was primarily vertical with little to no lateral hydrologic connectivity and bulk water movement. In cases where there was a noticeable elevation difference between peatlands (HM-a,d and CO-P-c,d), the groundwater within the hummock was controlled by the relative topographic positions of the peatlands. The water table behavior was independent of the hummock morphometry and therefore did not rise with the surface topography between the peatlands. It instead was dependent on
the position of each peatland, further demonstrating the hydrogeologic influence peatlands have on the larger environment. In the singular pine sand hummock (CO-d), the water table was, in effect, flat. Additionally, it is high hydraulic conductivity, short length, and highly sandy texture means there is little capability for groundwater mounding to occur, regardless of recharge rate (Haitjema 1995). Previous work by Smerdon et al (2008) demonstrated that in high K settings, height above the water table was a primary control on groundwater recharge rates, where deeper water tables experienced higher overall recharge rates. These characteristics, coupled with the low transpirative demands of pine, likely make CO-d, and similar sites, key sources of groundwater recharge in the Boreal Plains.

In this study, hydraulic potentials, which drive groundwater flow, are not primarily controlled by topography or gravity, but by plant uptake. In the Boreal Plains, forestlands have higher ET rates and deeper rooting depths (up to 3 m; DeBye and Winokur (1985)) than peatland ET rates and peatland black spruce rooting depths (<0.5 m; Lieffers and Rothwell 1987). This disparity of evapotranspiration rates between boreal forestlands and peatlands has been shown through regional-scale studies (Prepas

Figure 4. Peatland and forested hummock water table elevations for each site. The dashed line shows the 1:1 relationship, where points to the left of the line show a gradient towards the forested hummock and points to the right of the line show gradients towards the peatland. For sites where the hummock well was dry, a time series of the peatland water table is presented and the bottom of the hummock well is shown for reference. All elevations are relative to 600 m asl. All elevation axes have equivalent scales.
et al 2006, Devito et al 2017, Hwang et al 2018), catchment-scale studies (Devito et al 2005), and stand-scale studies (Petrone et al 2007, Barker et al 2009, Brown et al 2010, Barr et al 2012, Brown et al 2014). These ET patterns coupled with the internal water-conserving mechanisms characteristic of boreal peatlands are the primary processes governing the hydraulic gradients, which are typically away from peatlands. Our results demonstrate these features in almost all scenarios (hummock morphometry, substrate texture, topographic position), even in a non-drought year. This study was conducted during mesic climate conditions, meaning the annual precipitation was close to the long-term average and the 3yrCDM was close to zero (i.e. no multi-year water deficit or surplus). Additional work is being conducted to determine the climatic conditions required to induce groundwater mounding under various hydrogeological conditions.

Water table depressions are well studied in the fields of dryland agriculture and afforestation (Jobbágy and Jackson 2004, Tóth et al 2014) and groundwater overexploitation (e.g. Changming et al 2001); however, study of the controls and thresholds governing naturally occurring depressions has largely focused on near-shore or riparian vegetation (e.g. Winter and Rosenberry 1998, Meyboom 1966). While traditional approaches from regions where P is greater than PET may correctly presume mounding, to adequately represent reality in water-limited environments, more emphasis needs to be placed on the roles that soil storage and evapotranspiration play in the water budget (Redding and Devito 2008). We show that even between two peatlands with stable water tables, vertical fluxes due to ET from the forested hummock are strong enough to create water table depressions. Research in arid environments or those with salinization problems (e.g. afforested grasslands) already emphasize vertical fluxes due to vegetation as the principal component of water budgets in low-relief areas (Allison et al 1994, Jobbágy and Jackson 2004); however, research and applications in climate transitional zones like the Boreal Plains have not yet adopted this as a primary approach and topography is usually considered as the first-order control on saturated sub-surface water flow (Dimitrov et al 2014).

Work by Devito et al (2017), Gibson et al (2002), Prepas et al (2006), which are all large-scale catchment studies, showed that long-term boreal catchment runoff was positively related to peatland cover and negatively related to deciduous forest cover. This study demonstrates the water table elevations and hummock-scale storage patterns and processes responsible for these trends, which has not been shown previously. Hummock-scale processes have large implications for catchment-scale runoff generation (Jencso et al 2009), and local flow generation in both natural and reconstructed landscapes (Lukenbach et al 2019). This work represents a crucial advance in the research needed to understand these multi-scale processes and their distribution in space and time.

Currently there are unprecedented efforts being put towards total landscape reconstruction following megaprojects (e.g. open-pit mining) in water-limited boreal environments, where regulatory requirements mandate that landscapes be reconstructed and returned to a self-sustaining, pre-disturbance capability (Government of Alberta 2018). Understanding hummock-scale processes and water table dynamics in natural systems is a necessary step in the planning and evaluating constructed and reclaimed landscapes (Devito et al 2012). Consequently, there is an urgent need for hydrologic frameworks and models that accurately identify the major controls on water movement. This study serves to demonstrate that in most scenarios forested hummocks are not reliable sources of groundwater to adjacent peatlands, and should not be constructed with the intent of acting as such.

The Boreal Plains ecozone of Canada is a water-limited environment, where potential evapotranspiration often equals or exceeds precipitation. Due to this delicate balance, the Boreal Plains and other similar landscapes have been identified as regions of high hydroecologic sensitivity to anthropogenic disturbances, such as agriculture, forestry, and climate change (Berggren et al 2011, Ireson et al 2015), which can easily tip this balance. Thompson et al (2017) used numerical simulations of a Boreal Plains catchment to show that water levels in aspen-forested hillslopes may be reduced by 0.5 to 1 m due to the effects of climate change. Additionally, it is predicted that temperature-driven increases in evapotranspiration will exceed any small increases in precipitation due to climate change (Wang et al 2014), which may serve to increase the temporal and spatial persistence of the hydraulic gradients or groundwater depressions presented here.

5. Conclusions

This is the first study to demonstrate the spatial pervasiveness of water table depressions between boreal peatlands. Traditional topography-driven approaches assume hummocks are sources of water (i.e. groundwater mounding) for local flow systems (Ketcheson et al 2016); however, we show that even in non-drought conditions, local flow from hummocks to adjacent wetlands is spatially infrequent. Realistic conceptualizations of hydraulic fluxes are necessary to predict landscape hydrologic responses, especially in areas susceptible to climate change or other anthropogenic disturbances. Additionally, in the expanding field of landscape reconstruction after large-scale disturbances (Cooke and Johnson 2002), immature wetlands and landscapes constructed with the intent that they be maintained by recharge from hummocks (Wytrykush et al 2012) may not succeed in the most
prevailing conditions of this climate (dry to mesic), unless located in a stable larger-scale groundwater discharge zone.

The sink-source function of forested hummocks in water-limited environments is not as simplistic as traditional topography-driven approaches would indicate. Forested hummocks do not steadily provide water to adjacent peatlands, and are not stable sources of recharge to the larger landscape. Regardless of how accurate, or indeed conservative, recharge or hydrophysical property estimates are, predictions of water table position will fail in these landscapes if conceptual and numerical models continue to be developed around the anticipation of water table mounding (Haitjema and Mitchell-Bruker (2005)). There is a clear need to shift away from ‘topography-first’ approaches in large parts of the boreal and vitally all sub-humid and low-relief regions.

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