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Application of hydropedology to predictive mapping of wetland soils in the Canadian Prairie Pothole Region

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ABSTRACT

Digital soil mapping of wetland soils has met with limited success in part because terrain attributes based on hillslope hydrology are inappropriate for predicting the pedological consequences of wetland hydrology. Our objective is to synthesize recent developments in the hydrology and hydrochemistry of wetlands in the northern Prairie Pothole Region (PPR) and apply this enhanced understanding to the predictive mapping of wetland soils. The landscape-scale distribution of freshwater vs. brackish/saline soils is controlled by salt transport by episodic surface fill-and-spill events and (more rarely) by groundwater–surface interactions. Both sets of hydrological processes lead to ponds in lower-elevation spillways having more saline conditions. At nine freshwater ponds studied at three study areas (Swift Current, St. Denis, and Melfort, Saskatchewan) the elevation threshold between wetland-recharge (i.e., gleyed soils with deep (2- to 5-m) zones of carbonate depletion) and wetland-discharge (i.e., carbonated soils with no B horizon formation) soils corresponds to the maximum water level recorded at the nine ponds over approximately 40 years of water level measurements. The band of discharge soils surrounding the wetland extends for approximately 1 m elevation above of this water level elevation. The spatial distribution of wetland-recharge and wetland-discharge soils in freshwater ponds provides an enduring record of pond hydrological conditions and can be readily adapted to predictive soil mapping in this region.
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1. Introduction

The past decade has seen a substantial increase in our knowledge of landscape-scale hydrology in the Prairie Pothole region (PPR) of North America. A fundamental tenet of hydropedology is that we should be able to apply this improved knowledge of hydrology to understand the controls on the distribution of wetland soils in these landscapes; in turn, this enhanced understanding on the controls of soil distribution should lead to improved prediction of soil distribution using the tools of digital soil mapping (Thompson et al., 2012).

Our goal in this paper is to review recent literature on the hydrology and hydrochemistry of northern PPR landscapes and then use this information to refine a hydropedological model for wetland soils; this model is then used to develop a predictive spatial model for the distribution of wetland soils in this region. Specifically we draw upon data from nine sites in the northern PPR to a) predict the spatial pattern of freshwater vs. brackish/saline ponds at the landscape scale and b) determine the hydrological controls on the distribution of recharge and discharge soils at the scale of individual ponds. The research draws heavily on research for the St. Denis National Wildlife Area (SDNWA), where research on interactions between hydrology and other ecosystem attributes has been conducted by Environment Canada and other partners since 1968.

Clear relationships occur between the distribution of soil properties and taxa and terrain attributes based on hillslope hydrology (e.g. specific catchment area, wetness index) and profile curvature (Florinsky et al., 2002; King et al., 1983; Manning et al., 2001; Pennock, 2003; Pennock et al., 1987) for upland soils of the PPR and these have been widely used in digital soil mapping in this region (MacMillan et al., 2005) and elsewhere (Thompson et al., 2012). Most of these studies in the PPR and elsewhere have, however, excluded areas of the landscape with any significant extent of wetland soils and digital soil mapping has, overall, been less successful at predicting the distribution of wetland soils (Murphy et al., 2007, 2009). Murphy et al. (2009) suggest that this lack of success is due to an overdependence on convergent flow accumulation and a failure to account for the effects of dispersive flow in low-lying landscape positions and the effects of local downslope topography.

Both Bedard-Haughn and Pennock (2002) and Murphy et al. (2007, 2009) suggest that distance to water is also a key attribute for predictive mapping of wetland soils, as had been earlier proposed by Thompson et al. (1997). In the work of Murphy et al. (2007, 2009) the depth-to-water value approximates the distance between the local water surface and the point in question; low values indicate closeness to water (and the higher probability of saturated soils). In both of their studies pre-

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existing hydrographic information was used to delineate surface water features. Existing hydrographic data has also played a key role in recent attempts (e.g. Dvorett et al., 2011; Martin et al., 2012) to classify wetlands in the U.S. using the hydrogeomorphic classification system of Brinson (1993) and Smith et al. (1995).

Bedard-Haughn and Pennock (2002) also, however, indicate the major limitation to using point-in-time hydrographic data for soil modeling in the PPR:

> "The ephemeral nature of open water bodies on the Canadian Prairies forms a limitation to the application of terrain predictors. Many wetlands have standing water only during the wettest years. It was fortunate that both of the sites used in this study had open water bodies that could be used as secondary indicators of solute cycling, but to successfully apply this combination of terrain-based predictors to other sites, some knowledge of the typical hydrologic regime could be required" p. 188.

The hydrological status of PPR wetlands at any point in time may not be representative of the hydrological conditions responsible for the spatial distribution of soils.

2. Synthesis of hydrological research

The hydrogeology of wetlands in the PPR is dominated by the properties of the glacial deposits that cover the region. These deposits consist for a large part of clay-rich till with detrital carbonates from Paleozoic limestone (Last and Last, 2012) and pyrite. In the weathered zone above the water table the pyrite is oxidized and reacts with the carbonates to form sulfate salts, mostly anhydrite ($CaSO_4 \cdot 5H_2O$) (van Steempvort et al., 1994). The till typically has low permeability at depth except where it is heavily jointed near the ground surface. Flow through deeper tills is very slow and aquifers of sand and gravel below such till "aquitards" receive only very slow recharge (van der Kamp and Hayashi, 2009).

The water balance of ponds in the PPR is complex. At the simplest level two types of ponds occur: fresh-water ponds and brackish/saline ponds. Water inputs to both types of ponds occur through direct precipitation, and, in wet conditions, near-surface flow through the upper part of the soil (Hayashi et al., 1998b; Heagle et al., 2007; Nachshon et al., 2013). Surface water is also added, in periods of sustained above-average precipitation, through episodic fill-and-spill events, where some normally isolated ponds spillover and form a connected channel that distributes water throughout the catchment (Cook and Hauer, 2007; Leibowitz and Vining, 2003; Shaw et al., 2012). Recent evidence indicates that the salinity levels in these fill-and-spill ponds increase from higher to lower elevations in the spillover sequence and are highest in terminal ponds in the spillover sequence (Cook and Hauer, 2007; Nachshon et al., 2014).

The two types of ponds can also differ in their interaction with groundwater. Brackish/saline ponds may receive water (and solutes) by discharge from deep aquifers as well as by the episodic surface flow from higher elevations through fill-and-spill events (Nachshon et al., 2013, 2014). Fresh-water ponds are zones of groundwater recharge, where water moves from the pond to underlying aquifers (if present) (van der Kamp and Hayashi, 2009).

For both types of ponds, the rate of water flow to and from the deep aquifers is very slow due to the very low permeability (typically 0.02–0.03 mm d^{-1}) of the underlying sediments (van der Kamp and Hayashi, 2009). These rates are too small for groundwater to play a significant role in the hydroperiod of ponds (van der Kamp and Hayashi, 2009).

Loss of water from ponds occurs due to a) evaporation and b) infiltration of water into the wetland sediments. The ratio of shoreline to pond area is a key determinant of the ratio of evaporation to infiltration–infiltration is enhanced for ponds with large shoreline:area ratios relative to small shoreline:area ratio ponds (Millar, 1971). For ponds with very large areas relative to their shoreline, evaporative losses are approximately 4–5 mm per day (Millar, 1971) corresponding to estimates of lake evaporation in the region.

Water is readily conducted through to the wetland fringe due to the higher hydraulic conductivity of the surficial glacio-lacustrine and lacustrine silts and oxidized tills, which creates an effective transmission zone that readily conducts water laterally (Hayashi et al., 1998b; Heagle et al., 2013; Knuteson et al., 1989; Parsons et al., 2004). The decrease in hydraulic conductivity with depth can be several orders of magnitude; for example, at the SDNWA Miller et al. (1985) and Hayashi et al. (1998a) measured saturated hydraulic conductivities on the order of 10^{-6} m s^{-1} for near-surface till and sand and gravel lenses, 10^{-8} m s^{-1} for underlying oxidized tills, and 10^{-10} m s^{-1} for the deepest unoxidized tills.

Capillary rise and uptake by plant roots cause water loss by evaporation and transpiration in the wetland fringe surrounding ponds. Loss of near-surface water also occurs by the same processes from exposed pond sediment when the pond area decreases.

3. Hydrogeochemistry review

The chemistry of water in freshwater ponds closely reflects that of the soil water of the surrounding uplands and is dominated by Ca^{2+} as the main cation and (HCO_3^-) as the main anion (Heagle et al., 2013). As the water from these ponds slowly percolates through the underlying glacial sediments they gain solutes through the dissolution of soluble salts below the surrounding uplands, and these solute-rich waters are slowly transferred through the deeper groundwater flow system (if laterally extensive aquifers are present) until they reach the surface in discharge depressions (Henry et al., 1985; Nachshon et al., 2013). Dissolved salts are also transported to lower-elevation depressions and streams by episodic streamflow during fill-and-spill events (Cook and Hauer, 2007; Nachshon et al., 2013). Extreme wet periods may cause the water table beneath the uplands to rise above the level of the fresh-water ponds and the resulting flow of shallow groundwater can bring dissolved salts from the surrounding saline soil back into the ponds (Nachshon et al., 2014).

The combined effects of solute-rich groundwater discharge (where it occurs) and transport through episodic fill-and-spill events cause the solute load in lower-lying wetlands to increase until precipitation of salts occurs, leading to the formation of major salt reservoirs beneath the pond sediments of brackish/saline ponds, especially those that are terminal ponds in a spillway (Arndt and Richardson, 1988; Heagle et al., 2013; Miller et al., 1985). Movement of salts from the reservoir to the pond water maintains the salt concentration of the pond water even after freshening of the water occurs (Heagle et al., 2013) by precipitation inputs.

Water loss due to evaporation from the pond or evapotranspiration from the soil pore water in wetland fringe causes an increase in the concentration of solutes in the water (Waiser, 2006), which can trigger a series of mineral precipitation reactions (Whittig and Janitzky, 1963).

Changes in water chemistry are initially controlled by calcite precipitation. In their study of North Dakota potholes, Arndt and Richardson (1988) found that the precipitation of calcite began at an electrical conductivity (EC) of 1000 μs cm^{-1}. The second stage is the precipitation of gypsum ($CaSO_4 2H_2O$), which is limited by the previous removal of Ca^{2+} by calcite precipitation. Arndt and Richardson (1988) and Steinwand and Richardson (1989) found that precipitation of gypsum occurs above EC levels of 3700 μs cm^{-1}. The preferential precipitation of calcite and gypsum causes an increase in the proportion of Mg^{2+} relative to Ca^{2+}. The removal of Ca^{2+} and bicarbonate from solution through precipitation leads to dominance of the water by Mg–Na–SO_4–Cl (Hardie and Eugster, 1970) and hence the amount of SO_4^{2-} increases as EC increases.

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