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The hydrological functioning of a constructed fen wetland watershed

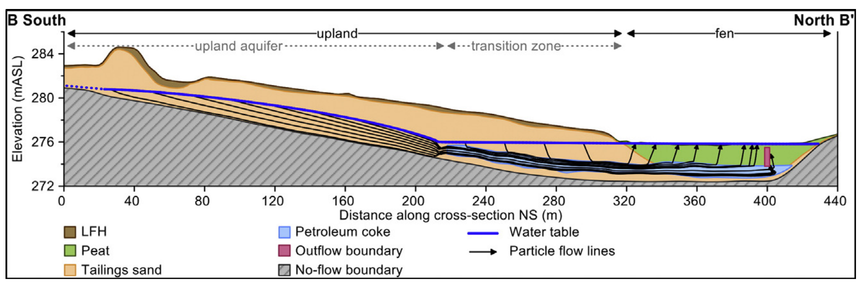
Scott J. Ketcheson *, Jonathan S. Price, Owen Sutton, George Sutherland, Eric Kessel, Richard M. Petrone

Department of Geography and Environmental Management, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

HIGHLIGHTS

- An upland aquifer and lowland wetland were constructed after oil sands extraction.
- Largest flux from constructed system was *AET* (75% and 111% of *P*).
- A subsurface layer of petroleum coke transmitted majority of groundwater.
- Ground frost in fen delayed groundwater water delivery.
- Modelling verified in-situ measurements of properties of construction material

GRAPHICAL ABSTRACT



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ABSTRACT

Mine reclamation requires the reconstruction of entire landforms and drainage systems. The hydrological regime of reclaimed landscapes will be a manifestation of the processes operating within the individual landforms that comprise it. Hydrology is the most important process regulating wetland function and development, via strong controls on chemical and biotic processes. Accordingly, this research addresses the growing and immediate need to understand the hydrological processes that operate within reconstructed landscapes following resource extraction. In this study, the function of a constructed fen watershed (the Nikanotee Fen watershed) is evaluated for the first two years following construction (2013–2014) and is assessed and discussed within the context of the construction-level design. The system design was capable of sustaining wet conditions within the Nikanotee Fen during the snow-free period in 2013 and 2014, with persistent ponded water in some areas. Evapotranspiration dominated the water fluxes from the system. These losses were partially offset by groundwater discharge from the upland aquifer, which demonstrated strong hydrologic connectivity with the fen in spite of most construction materials having lower than targeted saturated hydraulic conductivities. However, the variable surface infiltration rates and thick placement of a soil-capping layer constrained recharge to the upland aquifer, which remained below designed water contents in much of the upland. These findings indicate that it is possible to engineer the landscape to accommodate the hydrological functions of a fen peatland following surface oil sands extraction. Future research priorities should include understanding the storage and release of water within coarse-grained reclaimed landforms as well as evaluating the relative importance of external water sources and internal water conservation mechanisms for the viability of fen ecosystems over the longer-term.

1. Introduction

Approximately 4800 km^2 of the Athabasca oil sands region (AOSR) in Northern Alberta, Canada, has been deemed suitable for surface mining, which involve the large-scale removal of the surficial landscape (Government of Alberta, 2015). For example, by 2014, open-pit mining

* Corresponding author at: School of Geography and Earth Sciences, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L8, Canada.

E-mail addresses: ketchesj@mcmaster.ca (S.J. Ketcheson), jsprice@uwaterloo.ca (J.S. Price), ofsutton@uwaterloo.ca (O. Sutton), gsutherl@uwaterloo.ca (G. Sutherland), e2kessel@uwaterloo.ca (E. Kessel), rpetrone@uwaterloo.ca (R.M. Petrone).

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activities in the AOSR had disturbed an area in excess of 800 km^2 (Government of Alberta, 2015). Wetlands comprise approximately half of the pre-disturbance landscape in the AOSR, the majority of which (~90%) are fen peatlands (Vitt et al., 1996). Consequently, oil sands extraction activities are removing large quantities of peatlands from the landscape (Daly et al., 2012; Rooney et al., 2012).

Mine closure and reclamation designs aim to return landscapes to functioning ecosystems following surface mining of oil sands deposits. In 2007, the concept of peatland creation was adopted into the regulatory framework (AEPEA approval 94-02-00). Oil sands companies were required to test reclamation techniques that examined the feasibility of incorporating constructed bog and/or fen peatlands into a portion of the final reclaimed landscape. Emerging research is providing insight into how recently constructed peatlands are functioning (e.g., Biagi, 2015; Khadka et al., 2016; Murray et al., 2017; Nicholls et al., 2016; Nwaishi et al., 2016; Nwaishi et al., 2015; Scarlett et al., 2017; Vitt et al., 2016). Prior to this, however, the concept of peatland creation was largely untested. Due to the lack of prior experience, the development and refinement of the conceptual approaches suitable for peatland creation relied upon application of the current understanding of peatland and hydrological processes within natural and disturbed ecosystems into a mine reclamation context (Ketcheson et al., 2016). Although hydrologically isolated fen peatlands are common in the Western Boreal Plain (WBP) (Riddell, 2008; Thompson et al., 2015), fen peatlands situated in low-lying topographic positions in the reconstructed landscape may receive a combination of atmospheric, groundwater and surface water inputs. The surface and groundwater inputs will help to supplement limited atmospheric water availability during the summer months when potential evapotranspiration (*PET*) can exceed precipitation (*P*) in the WBP region (Bothe and Abraham, 1993; Marshall et al., 1999). Numerical modelling of an upland-fen watershed ecosystem constructed in a post-mining landscape in the AOSR indicates that the system should be capable of enduring periods of climatic stress (Price et al., 2010). The concept was incorporated into a design (Daly et al., 2012; Pollard et al., 2012), and is the subject of ongoing field-based research to evaluate its function.

Constructed catchments present new opportunities as field-scale research facilities to characterize ecohydrological processes in a relatively controlled setting (Gerwin et al., 2009; Hopp et al., 2009). In addition to satisfying regulatory requirements, the design, construction and evaluation of one of the first constructed fen watersheds provides information to improve soil cover systems and landform designs for mine reclamation projects worldwide. However, since integrating fen peatlands into reclamation and closure landscape designs is a relatively new concept, the current understanding of important hydrological processes in constructed fen peatlands and their associated watersheds is inadequate due to insufficient experimental and field data. Thus, the goal of this study is to characterize the distribution, storage and movement of water within a constructed upland aquifer – fen peatland system over the range of conditions encountered in the field. The specific study objectives are to: 1) Identify the dominant water fluxes within the designed upland – fen system; 2) Quantify the connectivity between the upland aquifer and lowland fen; and 3) Evaluate the hydrological performance of the constructed fen watershed.

2. Study site and methods

The Nikanotee Fen watershed is a constructed catchment located within an oil sands mining operations lease approximately 40 km north of Fort McMurray, Alberta (56°55.944′N 111°25.035′W; average watershed elevation ~288 masl). The site selection process for the location of the Nikanotee Fen watershed is outlined in detail in Daly et al. (2012). The stratigraphic profile underlying the watershed includes Middle and Lower McMurray formations that overlay a thin layer (~5 m) of fluvial sands situated atop Devonian limestone. This profile was capped with a mixture of lean oil sand, glacial material, clay, shale and loamy sand (Daly et al., 2012). The first phase of the construction included placing a geosynthetic reinforcement material (geogrid), a 1 m thick engineered compacted clay underlay and a geosynthetic clay liner (GCL) beneath the base of the constructed watershed. This was done in response to anticipated settling of the backfilled overburden materials as well as to hydrologically isolate the constructed watershed from the underlying backfilled overburden materials.

In the constructed system, fen peat from newly developed lease areas was placed at the toe of an upland aquifer (~3% basal grade towards the fen) designed to supply the requisite groundwater flow to sustain fen processes and functions. The upland aquifer was constructed using tailings sand (placed directly over the basal GCL) and capped with a thin (30–50 cm thick) LFH reclamation soil-capping layer (Fig. 1). This LFH soil-capping reclamation material comprises overstripped organic soil horizons L, F, and H salvaged with varying amounts of upper horizon mineral soils (Naeth et al., 2013) and thus differs from LFH soils in natural ecosystems as defined by the Canadian System of Soil Classification (Soil Classification Working Group, 1998). A more detailed description of the LFH material, and the soil hydrophysical properties, is presented in Ketcheson et al. (submitted). Approximately 5000 m^3 (~65 mm) of water was applied to the tailings sand material in the upland during the construction phase (summer 2012) to aid in material compaction. This water consequently contributed to the water stored in the upland aquifer (in addition to precipitation inputs).

At the base of the fen, a 50 cm layer of tailings sand is overlain by a 50 cm layer of petroleum coke followed by a 2 m thick organic peat layer (Fig. 1). The purpose of the petroleum coke layer, termed the 'underdrain' layer, was to more evenly distribute hydraulic head beneath the fen. This underdrain layer was also extended part way up the slope (beneath the zone of the upland termed the 'transition zone'; Fig. 1) to reduce the potential for groundwater (and salt) discharge at the surface of the upland-fen interface. The fen (2.9 ha) and upland (7.7 ha) system is situated within a larger watershed (total watershed area = 32.1 ha) that includes three previously reclaimed overburden slopes of varying age and a natural remnant slope (Fig. 1). The GCL was beveled to the surface of the natural slope in a way that precluded potential groundwater input. Further, surface infiltration capacity measurements made on the natural slope (data not shown) suggest that it did not contribute water to the system via surface flow. The east slope (8.1 ha; herein referred to as the 2007 slope) was reclaimed in 2007 and has a well-established vegetation cover relative to the south-east (8.2 ha) and west (2.4 ha) slopes, which were both reclaimed in 2011 (referred to collectively as the 2011 slopes). The hydrological role of these reclaimed slopes within the Nikanotee Fen watershed is evaluated by Ketcheson and Price (2016a, 2016b).

Several mesoscale landforms were incorporated into the design of the upland area. These included four hummocks, which are small (~400 to ~1500 m^2) landforms raised ~1 m above the surrounding area, as well as an experimental basin lined with a thin (0.5 m) layer of peat/mineral mix reclamation material (herein referred to as the 'peat-lined basin'). The peat-lined basin is a 0.2 ha depression situated ~0.5 m below the surrounding upland surface and directly adjacent to an upland hummock (Fig. 1). The stratigraphy in this basin is a 50 cm layer of peat/mineral mix soil situated atop the tailings sand aquifer material. A berm was constructed around the perimeter of the Nikanotee Fen watershed to isolate it from any surface water interactions from the adjacent landscapes and mine operations.

Several modifications were completed within the upland following the initial field campaign in 2013 in an effort to increase recharge to the upland aquifer. Shallow furrows (approximately 24 cm wide and 10 cm deep) were added to the surface of the LFH soil-capping layer, which doubled the surface infiltration rate (Ketcheson et al., submitted). At the same time, the LFH soil-capping layer was removed from a small area directly behind each of the upland hummock landforms (except for the hummock adjacent to the peat-lined basin), with the objective of creating enhanced recharge zones.