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Little-Devito, Mika; Mendoza, Carl; Chasmer, Laura; Kettridge, Nicholas; Devito, Kevin

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Opportunistic wetland formation on reconstructed landforms in a sub-humid climate: influence of site and landscape-scale factors

M. Little-Devito, C. A. Mendoza, L. Chasmer, N. Kettridge, K. J. Devito

Abstract

Initiation of wetland features is integral to sustaining landscape eco-hydrological function and meeting defined goals in surface mine reclamation. Within the sub humid climate of the Athabasca Oil Sands, Canada, the water generation mechanisms (external water sources, internal feedback mechanisms) that enable wetlands to form opportunistically on recently reconstructed landscapes are currently unknown, restricting the flexibility in mine closure planning. To address this knowledge gap, we interpret site and local physical characteristics of opportunistic wetlands within the Athabasca Oil Sands through a synoptic survey. Wetlands formed in ~ 8% of the random survey transect areas designed and planted for forestlands. Wetlands had vegetation structures characteristic of woody Salix spp. swamps and narrow-leaved Carex spp. marsh wetland types, with minor coverage of open water marshes. Wetlands formed opportunistically over a range of slopes, aspects and topographic positions, across contrasting fine and coarse-textured landforms. However, different wetland establishment and maintenance controls exist on fine and coarse-textured landforms. On coarse-textured landforms with large groundwater transmissivity, wetland formation was influenced by landscape-scale factors; wetlands were restricted to the toes of slopes and areas intersecting groundwater. On fine-textured constructed landforms, small and large wetlands occurred on lower landscape elevations with the potential for the external (cumulative) water sources, and in hydrologically isolated locations with little potential for runoff contribution from adjacent forestlands (saturation and wetland formation through internal feedback mechanisms). Regardless of landscape position, wetlands formed on flat areas and in shallow inward draining endorheic pans with clay rich soils where low water storage potential promotes frequent surface saturation. These findings have important implications in landscape reclamation design, suggesting that passive techniques that support internal feedback mechanisms may offer a more cost effective reclamation approach compared to more active, expensive techniques that aim to develop wetlands with external water sources.

Introduction

Surface mining in the Athabasca Oil Sands is a prominent disturbance in the Boreal Plains of western Canada (Audet et al. 2015) and has a profound impact on the pre-disturbance landscape (Doley and Audet 2013). The Boreal Plains support expansive mosaics of forest-wetland-pond complexes and although the climate is sub-humid, wetlands, primarily peatlands, represent 25 to 80% of the land cover (NRC 2006; Devito et al. 2017). A challenge in meeting the requirement of reclaiming all disturbed land to an equivalent land capability by mine closure will be the construction of commercially productive forest juxtaposed with the creation of a variety of wetland types whilst ensuring water yields for maintenance of downstream ecosystems to sustain the original landscape eco-hydrologic function and ecosystem services (Johnson and Miyanishi 2008; Devito et al. 2012; Ireson et al. 2015). To achieve these goals, reclamation design must move beyond local-scale control for specific forest (Rowland et al. 2009) or wetland creation (Price et al. 2010; Ketcheson et al. 2016) and consider the varying hydrologic roles of wetlands (e.g., receivers and transmitters vs. generators of water) in water movement at the landscape scale (Devito et al. 2012; Doley and Audet 2013).

Wetland formation is promoted by surface moisture saturation, soil anoxia, exclusion of upland vegetation and predominance of wetland vegetation (Winter 1988; Rodriguez-Iturbe et al. 2007), with external or allogenic physical processes leading to autogenic processes that feedback to influence plant and microbial activity and wetland succession (Payette 1988; Nwaishi et al. 2015). Conceptual models developed for the Boreal Plains (Halsey et al. 1998; Ireson et al. 2015; Devito et al. 2017) and approaches to reclaim radically disturbed areas (Tongway and Ludwig 2011; Audet et al. 2015) highlight the need to understand the interaction of topography within contrasting coarse-textured and fine-textured surficial glacial deposits which create differences in water storage and transmission that influence forest and wetland formation and their eco-hydrologic function. Although there has been considerable research and improved understanding of wetland (including peatland) development, most studies in the Boreal Plains generally presume an appropriate water level is present or maintained for primary succession of wetlands or peat initiation (Ruppel et al. 2013; Nwaishi et al. 2015). A thorough understanding of the site and landscape physical characteristics that provide a range of potential sources of water and the soil storage-atmosphere interactions that promote surface saturation and initiate wetland formation is limited, particularly in a sub-humid climate. Increased understanding of these controls within the Boreal Plains has implications for the management and assessment of cumulative effects on natural systems, as well as for the design, cost and ultimate success of reclaimed and constructed landscapes (Devito et al. 2012; Wytrykush et al. 2012; Audet et al. 2015).

Improvements in reclamation efforts have been facilitated by our advances in conceptualizing natural analogue systems, as materials used on oil-sand mining leases can mimic the function of natural regions on the Boreal Plains (Devito et al. 2012; Wytrykush et al. 2012). However, dictating post-disturbance topography, surficial geology, and soil media during landscape reconstruction on the Athabasca Oil Sands can provide an opportunity to further test our conceptual understanding of ecosystem development (Jackson et al. 2009; Doley and Audet 2013). This understanding can be used to expand the range of approaches available to support the recovery of radically disturbed sites (Audet et al. 2015) and optimize landscape design to facilitate development of natural, hybrid (reversibly different), or novel (irreversibly different) functioning ecosystems (Johnson and Miyanishi 2008; Doley and Audet 2013) under long-term climate cycles (Carrera-Hernandez et al. 2012) and in future climates (Rooney et al. 2015).

The current premise of wetland formation within the Boreal Plains and design for construction on the Athabasca Oil Sands (CEMA 2014) assumes that topographic relief supports sufficient external surface or groundwater contributions to the wetland water budget to accommodate the deficit between precipitation and evapotranspiration of a sub-humid climate and maintain soil saturated conditions (Price et al. 2010; Rooney et al. 2012; Ketcheson et al. 2016). However, regional runoff studies show limited runoff from forest ecosystems while peatland wetland land covers are water source areas on the Boreal Plains (Devito et al. 2017). Formation of isolated wetlands perched above regional water tables by confining layers of clay, calcrete, or bedrock and lacking ground water or surface runoff inputs, have been observed in water-limiting arid (Melly et al. 2017) and sub-humid Boreal Plains climates (Devito et al. 2005; Hokanson et al. 2016), highlighting the possibility of autogenic and internal soil-atmosphere interactions in initial wetland development (Waddington et al. 2015; Dixon et al. 2017).

If internal feedback mechanisms enable formation, wetlands may form on both topographic highs and lows, in extended flat areas or gentle depressions with limited runoff sources, and where low soil permeability and storage potential combine with poor drainage to enable frequent and rapid soil saturation after precipitation events (Atkinson and Cairns 1994; Schoeneberger and Wysocki 2005; Dixon et al. 2017). This can promote wetland soil development and vegetation types and structures with low evapotranspiration rates (Winter 1988; Rodriguez-Iturbe et al. 2007) while also impeding terrestrialization by forest species (Bates et al. 1998). Wetlands forming by internal soil-atmospheric interactions would tend to have a larger size and circular shape to conserve water loss from lateral drainage, and would be limited to landscape positions that facilitate protection from atmospheric exchange (Millar 1971; Ollis et al. 2015). In contrast, if external water sources are the dominant factor influencing wetland formation, wetlands should be limited to low lying areas at the toes of slopes where sufficient surface runoff collects or the water table intersects the land surface for groundwater contributions (van der Velde et al. 2013).

Despite the sub-humid climate, wetlands have formed opportunistically on areas of reclaimed landforms designed to develop into commercial forestlands in the Athabasca Oil Sands, and such 'opportunistic wetlands' likely outnumber all other reclaimed wetlands (CEMA 2014). Establishment of unplanned wetlands are not unique to the Athabasca Oil Sands, and have been recorded in previous studies where 'accidental' wetlands have been observed on flat, compacted areas post coal mining (Atkinson and Cairns 1994), and in abandoned urban areas with poor drainage (Palta et al. 2017). Examination of the site and landscape-scale characteristics where opportunistic wetlands form can provide a unique opportunity to obtain valuable insight into the potential mechanisms that support wetland establishment and maintenance. This can direct management policy (particularly in sub-humid climates; e.g., Jackson et al. 2009), landscape design and the potential for more passive cost effective reclamation techniques to reach targets of wetland coverage for constructed landscapes in the Athabasca Oil Sands (Rehounkova and Prach 2006; Doley and Audet 2013; Prach et al. 2013).

This study is the first of a larger project examining the controls of wetland formation and structure, and thus their role in the eco-hydrology of constructed landscapes in the Athabasca Oils Sands. Herein we present results from synoptic soil and vegetation surveys and the examination of site and local physical characteristics where wetlands form on constructed landforms newly reclaimed as forest to determine: (1) the frequency, distribution and initial types of opportunistic wetlands forming, and (2) the relationship of landscape position and soil layering to infer the potential role of external water sources, such as surface runoff and groundwater and, alternatively, internal feedback mechanisms such as low soil storage and site protection, on wetland formation in sub-humid landscapes.

Study area

The study area is located on Syncrude's Mildred Lake lease in the Athabasca Oil Sands region, approximately 40 km north of Fort McMurray, Alberta, Canada (Wytrykush et al. 2012), in the Central Mixedwood subregion of the Boreal Forest Natural Ecoregion of Alberta (NRC 2006) and the Boreal Plains ecoregion of Canada (see Devito et al. 2017). The region has a sub-humid, mid-boreal climate with cold winters and cool summers and a mean annual temperature (1981–2010) of 1 °C (Environment Canada 2013). Ecodistrict estimates of mean annual precipitation are 436 mm, with approximately 30% falling as snow, and mean annual potential evapotranspiration using Thornthwaite's and Penman's approaches are 517 mm and 536 mm, respectively (Marshall et al. 1999; NRC 2006). Precipitation at Mildred Lake for the 2016 and 2017 hydrologic year (1 Nov to 31 Oct) was about normal (442 mm) and below normal (309 mm), respectively (https://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp). The prevailing wind direction is from the east with a shift to the west from July through September; the strongest wind gusts arrive from the west (Environment Canada 2013).

The pre-disturbance landscape was typical of the Central Mixedwood, with subtle relief and flat to undulating plains with some hummocky uplands (NRC 2006). Sediment thickness over bedrock varied from 10 to 20 m (MacCormack et al. 2015), with little interaction between bedrock aquifers and surface waters. The local surficial geology was comprised mainly of fine-textured glacio-lacustrine deposits, with some hummocky clay-rich glacial till moraines, and coarse-textured glacio-fluvial and aeolian deposits (Fenton et al. 2013). In poorly drained sites, organic soils (predominantly peatlands) of 1 to over 4 m in depth formed, which represented significant cover (~ 60%) in the study area. A general description of organic and mineral soil, and vegetation type and distribution, relative to surficial geology, is presented in NRC (2006) and Devito et al. (2017).

The three reclaimed landforms were constructed on the pre-existing Central Mixedwood landscape in lifts and then recontoured at the landform scale with large flat tops, sloped sides with incised terraces, and flat bases, with variable frequency and size of terracing (Boese 2003) (Fig. 1). Fine1 and Fine2 landforms were largely constructed from overburden of fine-textured saline-sodic shale from the Cretaceous Clearwater formation. Coarse1 landform was constructed from coarser-textured processed tailings sand by hydraulically and mechanically forming exterior dykes and hydraulic infilling of the center (Fig. 1).

Constructed landforms and locations of survey transects for the three material storage areas: Southwest Sands Storage (A–A′) deposit composed of coarse-textured processed oil sands deposits (Coarse1), and South Bison Hills (C–C′) (Fine1) and W1 (B–B′) (Fine2) deposits constructed of fine-textured Clearwater shale overburden on the Syncrude Mildred Lake lease. Typical elevation profile illustrating landform top, slope and bottom for each landform is shown. The inset shows the location of Athabasca Oil Sands (star) and Boreal Plains (green) within Canada

The underlying overburden or tailings sand of each landform was capped generally with 1 m of reclamation material. The reclamation design used multilayer covers, usually with 20 cm of salvaged peat above 80 cm of secondary glacial mineral soil, with some variation across mine sites based on parent material and construction strategies (Boese 2003; Rowland et al. 2009). Newly reclaimed areas were often fertilized and seeded to agronomic barley in year zero and then planted one to two years after soil placement, usually at 2000 stems/ha with trembling aspen (Populus tremuloides) and white spruce (Picea glauca). Siberian larch (Larix sibirica) was also planted in selected areas on Fine1 and Coarse1. No wetlands were designed for Coarse1 or Fine2; two open-water depression ponds (< 1 m depth) were designed on Fine1, only one was intersected by the synoptic survey. For erosion control, vegetated swales oriented down the landform slope have been designed and planted on the fine landforms, typically with brush sills composed mainly of live cuttings of willow (Salix spp.) at variable distances within the swales (Raymond 2004). Progressive reclamation resulted in variable reclamation ages, and some areas on each landform were not included due to inaccessibility (Fig. 1).

Fine1 is approximately 218 ha, has an elevation range from 307 to 352 m asl. Reclamation commenced in 1992 and was completed in 2004 (Fig. 1). Fine2 is ~ 1316 ha, with ~ 673 ha reclaimed, and has an elevation range from 325 to 410 m asl. Reclamation on Fine2 commenced in 2003. This landform has a larger flat top and more terracing on the landform slope than Fine1. Coarse1 is 2911 ha, with ~ 292 ha of reclaimed area, and a current elevation range from 349 to 418 m asl. Reclamation commenced in 1998. Coarse1 is an operational tailings dam with active reclamation; this survey was limited to the external sides and base of the landform dyke. Material is actively being added to the top of Coarse1 dyke, as well as hydraulic placement of tailings in the center, and these areas were excluded from the survey (Fig. 1).

Methods

Field data collection

Three random transects in both east–west and north–south orientations (total of 6) were selected for each landform and surveyed in 45 to 60 m wide swaths, during the summers of 2016 and 2017 (Fig. 1). A Garmin Monterra GPS and an Apple iPad Air2 with a Bad Elf Pro external GPS and the Collector for ArcGIS application were used to navigate transects and map features to within 5 m accuracy. Wetlands intersected by transect swaths were identified, the boundaries of the entire wetland delineated (inside and outside the transect boundary) and the portion within the transect recorded (wetland polygon or sub-set).

A modified version of the Ontario Wetland Evaluation System (OMNR 2014) was used to identify, delineate and define wetland types, forms and boundaries. The complex and generally unknown nature of newly reclaimed landscapes makes distinguishing wetlands from a non-wetland (not yet a forest) challenging because of the short time for many wetland indicators to fully develop, particularly soil characteristics which are key in delineating wetlands. At least two of a combination of the three basic visual indicators for delineating wetlands and their boundaries (OMNR 2014; Government of Alberta 2015) were sought. The indicators were: (1) hydrology from site morphology, presence of ponded water or saturated soils, evidence of flooding or ponding with remaining aquatic vegetation; (2) soil anoxia by the presence of gleying or mottling, sulfide smells, iron concretions or oxidized rhizospheres, potential organic soil accumulation; and, (3) wetland vegetation with presence of indicator species, dominance of facultative wetland species, or indication of dying upland vegetation.

Wetlands encountered along transect swaths were assessed as being able to map according to the following wetland criteria and size restrictions (modified from OMNR 2014): wetlands less than 5 m in diameter were not recorded; wetlands 5 to 10 m in length were mapped by field measurements of width and length; wetlands 10 to 100 m in diameter were mapped using a combination of field sketches facilitated using the iPad, and soil-vegetation parameters were recorded; and, wetlands greater than 100 m in diameter were mapped using satellite imagery on the iPad, and soil parameters were recorded in the field for all vegetation community zones (described below) visible on the satellite image. Boundaries separated by less than 10 m were mapped as the same wetland (OMNR 2014).

For each wetland, distinct zones or communities were delineated and mapped based on vegetation form and dominant species as outlined in OMNR (2014). A soil profile and vegetation survey were collected for each zone. Soils were collected using a 2-inch hand auger within each zone of the wetland and, for most wetlands, in the adjacent non-wetland area. Soil texture was estimated by hand at approximately 5 cm resolution using Thien (1979). Soil texture profiles and depth to confining layer were defined using only secondary mineral soil capping material; mechanically placed ex situ peat, organic soils, or peat-mineral mixtures at ground surface were assumed equivalent to naturally occuring LFH organic horizons (CEMA 2014). Cores were terminated once the confining layer was encountered, or 1 m was reached, and thus ranged from 0.2 to 1 m depth. Detailed core logs were recorded, but only dominant soil texture and depth to confining layer were used in this study (see below). At each site within a distinct vegetation zone, a 10 × 10 m plot was surveyed for the occurrence (based on ≥ 25% coverage) of 16 wetland vegetation forms, the dominant vegetation form, and the dominant species in that vegetation form (OMNR 2014).

Parameter generation and data analysis

Point data and wetland polygon boundaries collected during field surveys were used to develop parameters to: (1) describe general wetland characteristics and location on the landforms, (2) compare site characteristics in wetlands to adjacent non-wetland areas, and (3) compare wetland to non-wetland regions of transects across landforms.

Wetland characteristics and distribution

To determine percent coverage and density, only areas of wetlands intersected by survey transect swaths (wetland polygon or sub-set) were summed and compared to the total transect swath area. Wetland sub-sets and total transect area were only counted once in areas where transects overlapped.

For examining general wetland characteristics, the entire wetland area and perimeter encountered by the transect swath were generated using field measurements and traces off satellite images in ESRI ArcGIS Desktop version 10.5. Wetland shape was calculated using Hutchinson's (1957) shoreline development equation where Shape is equal to wetland perimeter (P) divided by 2 times the square root of wetland area (A) times pi (π). A shape value equal to 1 is circular, while larger shape values indicate more elongated or convoluted shapes. To determine wetland location at the landform scale, each landform was categorized into flatter top, sloping middle, and flatter base and the wetland location within each noted. To determine the relative elevation for each wetland, each landform was further separated into fundamental hydrologic landscape units (FHLU) as described by Winter (2001), where a FHLU encompasses an upland (top) and lowland (base) separated by a steeper slope of the landform (Fig. 1). Mean wetland elevation relative to the elevation range for each FHLU was determined using a 1 × 1 m resolution digital elevation model (DEM) created from 2017 LiDAR imagery (see Fig. 1). To assess the potential influence of landform-scale protection from wind or solar radiation, the modal aspect ratio of each wetland was estimated using the aspect tool in ArcGIS 10.5 by resampling the DEM at a coarse resolution (100 × 100 m) with bilinear interpolation. The wetland modal aspect was compared with growing season cumulative wind direction and velocity observed at meteorological stations located at or near each landform (Carey 2013).

Site-scale comparison of wetland and adjacent non-wetland areas

At both wetland and non-wetland soil core sites the soil drainage class was estimated using the dominant soil texture class (Thien 1979) of the top 20 cm on the secondary mineral capping material relative to the soil textural classes in the USDA (2017) soil survey manual and expected hydraulic conductivity (Rawls et al. 1982). Sand and loamy sand were defined as high drainage; sandy loam, sandy clay loam, loam, silt loam, and silt were defined as moderate drainage; and silty clay loam, clay loam, sandy clay, silty clay, and clay were defined as low drainage. For each core site the confining layer in the secondary mineral soil layer was defined by the presence of at least 20 cm of continuous fine-textured soil classified as poor drainage; this was interpreted to constitute a confining layer that would impede vertical flow resulting in a hydraulic break with the layer below (Li et al. 2014). Depth to confining layer was measured from the surface of the primary organic capping layer. The aspect, slope, topographic position index, and solar radiation during summer solstice at each wetland and non-wetland core site were calculated using aspect, slope, and points solar radiation tools in ArcGIS 10.5 (spatial analyst surface and solar radiation toolset) using the DEM resampled to a 3 × 3 m pixel size using bilinear interpolation. This pixel size was selected to provide sufficient information for site location given the GPS accuracy. Topographic position index (categorized into valley, toe slope, flat, mid slope, upper slope, and ridge) was determined as described and developed by Jenness (2006). Relative elevation of each core site was determined relative to the range in elevation within each FHLU. Depth to confining layer and overall soil texture for wetland and non-wetland soil core sites were plotted and compared in R version 3.4.4. Landscape and site variables measured constitute both continuous and categorical parameters, thus binary logistic regression (BLR) in R version 3.4.4 was used to assess which combination of variables (soil drainage, depth to confining layer, relative elevation, site aspect, site percent slope, topographic position index, and solar radiation) best distinguish wetland versus non-wetland sites.

At two representative wetlands per landform, 2 inch diameter wells were installed to a depth of 1 m in forest (non-wetland), wetland-forest edge, swamp and open water communities and continuous water levels were recorded (Solinst model 3001 level logger edge) in selected open, swamp and forest locations from August 2016 to October 2017.

Comparison of wetland and non-wetland areas across landforms

Transect swath areas were separated into wetland and non-wetland polygons to determine wetland coverage and assess potential differences in site characteristics between wetland and non-wetland areas of each landform. All wetland polygons within and portions of larger wetland polygons (sub-sets) that were intersected by survey transect swaths were considered as individual samples, resulting in a total of n = 146 polygons (n = 36, 89 and 21 for Fine1, Fine2 and Coarse1, respectively) with a median area of 248 m^2 (range 8 m^2 to 8574 m^2). Non-wetland areas of transect swaths were randomly divided into polygons with areas approximating the range of wetland polygon areas, with a median area of 272 m^2 (range 10 to 2410 m^2). Topographic position index, percent slope, and solar radiation summary statistics for each non-wetland and wetland polygon were calculated using the DEM resampled to a 20 × 20 m pixel size and bilinear interpolation for each wetland and non-wetland polygon in ArcGIS 10.5. This pixel size was selected to provide sufficient information for the scale of analysis (i.e., median wetland size). Distribution of modes for topographic position index, and medians for percent slope and solar radiation, were generated for wetland and non-wetland polygon areas using a random selection with replacement for 1000 iterations using 1, 5, and 10 (for topographic position index) and 10, 20 and 50 (for percent slope, solar radiation) piece sample sizes in R version 3.4.4. Clear separation of wetland and non-wetland distribution of measures of central tendency is indicative of distinct populations.

Topographic catchments were delineated for a sub-set of wetlands (n = 66) where transect coverage provided an estimate of the forest and wetland coverage within the catchment. In initial attempts the ArcGIS Hydro toolset was not able to resolve topographic boundaries for many catchments due to the low relief and lack of defined wetland outflows. Therefore, catchment topographic boundaries were delineated manually using high-resolution DEM in combination with satellite imagery and field verification where possible.

Results

Wetland occurrence and type

Wetlands were observed across all landforms and represent ~ 8% of the overall landscape at a density of ~ 0.8 wetlands ha−1, based on cumulative area of wetland polygons that intersected the random transect survey swaths (Table 1). Wetland density and percent cover were similar on coarse-textured to fine-textured landforms; however, there was a large disparity in wetland density and percent cover on survey transects between Fine2 (0.9 ha−1, 10%), and Fine1 (0.50 ha−1, 4%). Of the total wetland area surveyed along the transect swath, swamps followed by marshes represented the greatest proportion of wetland types; open water wetlands accounted for less than 10% of the total wetland area (Table 1).

Total area covered by the survey transects; total wetland coverage (%) and density (# wetlands ha−1) of polygons in the transect swaths; percentage of the wetland cover designated for each wetland type for the landform overall of Fine1 and Fine2 (fine-textured overburden deposit) and Coarse1 (coarse-textured processed sand deposit) on the Syncrude Mildred Lake lease (see Fig. 1 for landform and transect locations)

The complete wetland complexes intersected by the survey transects ranged in sizes and shapes across all landforms (Table 2). On all landforms the majority of wetlands intersected by the survey transects were small (< 0.05 to 0.2 ha), but comprised less than 10% of the total wetland area (Fig. S1). The majority of the wetland area was derived from a few larger (0.5 to 5 ha) wetlands. All wetlands with water to sample, were classified as freshwater (< 5000 µS; Government of Alberta, 2015) and near neutral pH (see Table S2). Most wetlands were complexes of wetland types, varying in vegetation forms or communities (Table 2; Fig. 2). Open water communities were generally not vegetated (< 25% aquatic vegetation) but were surrounded by marsh vegetation forms. Marsh wetland types generally had only one dominant (≥ 25% cover) vegetation form, and were predominantly narrow-leaved emergent sedge (ne, Carex spp., ~ 60% total marsh area) followed by robust emergent cattail (re, Typha spp., ~ 30% total marsh area). Most swamps surveyed were comprised of short and tall woody shrubs of willow (Salix spp.) co-dominant with sedge. Brown mosses were co-dominant (≥ 25% cover) in a selection of all three wetland types (Table 2). The spatial orientation of an example set of communities, from small isolated to larger wetlands, is represented in Fig. 2. Wetland outer edges were predominantly composed of woody swamp and narrow-leaved emergent communities. Progressive zones of narrow-leaved emergent then robust emergent wetland communities were present moving from the margin to the wetland interior, with occasional open water communities near the center of the complexes.

Dominant vegetation form is defined as covering > 25% of the area. Vegetation forms from OMNR (2014): ds dead shrubs, ts tall shrubs (woody 1 to 6 m), ls low shrubs (woody < 1 m), re robust emergents, ne narrow leaved emergents, u unvegetated, gc groundcover (herbs), m moss

Example of configuration of dominant vegetation forms (OMNR 2014) and associated topographic catchment boundaries of wetland complexes that intersected transects on the flat top of Fine2 landform (see Fig. 1). Wetlands not intersected by survey transects and not included in wetland or vegetation form area covered calculations are shown in pale green. Underlay is grey scale for 1 m^2 resolution DEM. See Table 2 for labels for vegetation forms

Wetland distributions across landforms

Wetlands were found on all landform positions, with the greatest frequency and percent cover of wetlands observed on the tops and benches of slopes of the fine-textured landforms, and primarily observed near the toe slope and mid-slope benches or base on the coarse-textured landform (Fig. 3). No relationship was observed between wetland relative elevation and shape for each individual landform or for all landforms combined ($r < 0.236$, $p > 0.1$). The topographic position index provides a higher resolution estimate of localized slope within landform positions (Table 3). Most wetlands on Coarse1 were generally larger and elongated, forming at the toe-slope and on extended flat areas on the landform base and terraces within the landform slope. Large elongated wetlands oriented parallel to the landform slopes of Fine2 are notable. These wetlands, classified as valley, correspond to constructed erosion control sills on swales (Raymond 2004) (Table 3; Fig. 1). Larger elongated wetlands perpendicular to landform slope are associated with ditching near the lower mid-slope and base of the fine-textured landforms. Circular wetlands (shape index < 1.5) were generally observed on the flat landform top of Fine2, and large flat areas of lower terraces of the landform slope of Fine1 (Figs. 1, 3). Large circular wetlands were associated with constructed flat endorheic pans (shallow inward draining depression; see Ollis et al. 2015) designed to inhibit large depressions and ponded water and reduce runoff velocity and erosion when draining the tops of constructed landforms as shown in Fig. 2. These areas were planted with forest vegetation (Populus tremuliodes, Picea glauca) and not designed for wetlands.

Ratios of forest runoff contributing area to receiving wetland area range from greater than 100:1 to less than 1.5:1 for contributing catchments of both small and large wetlands (Fig. 4). Low relief and differential settling resulted in numerous isolated basins and limited effective runoff of non-wetland (forest) contributing areas adjacent to many wetlands, particularly on the very low slopes observed on landform tops and terraces (see Fig. 2). For ~ 25% of the wetland catchments that could be delineated, non-wetland contributing areas were less than the ratio 3.3 to 1 estimated to compensate for region moisture deficit (precipitation − potential evapotranspiration equals 100 mm), assuming runoff of ~ 30 mm (Huang et al. 2015; Devito et al. 2017).

At the landform scale wetlands appear to be preferentially situated on the leeward side of the prevailing wind direction for each landform (Fig. 5).

Site and local physical characteristics associated with wetland formation

The overall binary logistic regression model predictions were significant (Chi Square $p < 0.001$, 85 to 89% accuracy) using local and site characteristics to compare and discriminate non-wetland with wetland edge and again with wetland center locations (soil core site) for each wetland intersected by the survey transect (Table 4). The analyses indicate that as local slope of a site increases, the prevalence of a wetland decreases ($p < 0.001$). In addition, relative to flat areas, valley (wetland edge $p < 0.003$ and wetland center < 0.001) and toes of slope ($p = 0.002$ and < 0.001) topographic position indices are more likely to be associated with a wetland compared to non-wetland. Relative to secondary mineral soil with a poor drainage class, wetlands are also less likely than non-wetlands to have soils classed as moderate drainage ($p < 0.016$ and < 0.003). In contrast, binary logistic regression analyses indicate that wetlands sites occur in areas with greater depth to confining layer ($p < 0.098$ and 0.016).

Comparative analyses of the transect survey suggest both wetland polygons and representative non-wetland polygons were predominantly found on areas with a flat topographic position index, which is representative of the dominant landscape macro- and micro-topography (Fig. 6a). However, non-wetlands occurred at all topographic position indices defined on the landforms, while wetlands were limited to flat, toe of slopes and valleys, with only a small fraction (< 2%) found on mid-slope indices. These wetland polygons on mid-slopes were located on seepage faces. Further comparative analysis and higher resolution of the modal slope indicates the wetland polygons were found in flatter areas with shallower slopes (< 3%) compared to non-wetland polygons (3 to 6%) (Fig. 6b). Further comparison of transect polygons indicate little difference in solar radiation between wetland and non-wetland areas (Fig. 6c.).

The depth of confining layer in secondary mineral capping, as well as depth of primary capping material was variable, but generally shallow for non-wetland sites and the wetland edge or center sites (Table 5). Median depth to water level position did not mirror depth to confining layer and was much shallower (closer to the surface) at wetland centers and deepest (further below the ground) at non-wetlands sites. Although the water level positions relative to the ground surface were variable, reflecting seasonal differences in sampling and drying out of many sites, maximum height of water level positions show that wetland centers and edges flooded, whilst no saturation or flooding of adjacent non-wetland areas was observed across all landform positions (see also Supplementary Table S1).

Continuous water level measurements from selected sites further illustrate the degree of interaction between adjacent forest, wetland edge (swamp) and center (open, sedge) on the fine landforms during the study period (Fig. 7). Peak water elevations in the wetlands were associated with large rain events in late summer and late spring of 2016 and 2017, respectively, with a secondary peak during snow melt. Shallow wells were dry in forests and wetlands following drought conditions in 2015 and early 2016. Pond water level positions in and above the sediments responded rapidly (15 cm rise) and corresponded to 9.6 cm of rain that fell in late August and early September 2016. Ponded water remained, with responses to rain events, until mid-July 2017 and then water levels declined in response to below average summer rain for July and August 2017. Water level rises in the swamps lagged behind pond water levels during the late summer 2016 rain events. Swamp water levels responded rapidly (rise and decline) to further rain events in autumn 2016 (further 5.6 cm rainfall), and snowmelt and rain events in 2017. Water level positions in the swamps remained within 20 cm of the ground surface but did not accumulate greater than 5–10 cm of standing water during the wetter periods. Water levels declined in late summer 2017. In contrast, forest wells showed no near surface responses in water level position to rain events during the study period, with the exception of a short duration response during early snow melt. Water level positions from a deep well nest on Fine2 remained greater than 180 cm below the surface, indicating perched conditions in adjacent wetlands.

Discussion

Frequency and distribution of OW: implications for landscape-scale processes

Opportunistic wetlands were common (3.7% to 9.7% coverage) in areas not designed as such (i.e., expected and planted to be forestlands) on the three landforms of this study. Existence of such 'opportunistic wetlands' may provide additional wetland areas for closure requirements and the opportunity to mimic ecosystem functions of natural areas on the Boreal Plains. Future assessment of succession of these sites is planned as our survey covered regions differing in time since reclamation. In the future some wetland areas may be lost to forest succession, as runoff and water sources from adjacent slopes can be greater in the first years following construction (Elshorbagy et al. 2005). Conversely, other areas are likely in transition and with time and an impending wet climate cycle (Mwale et al. 2009) may form into wetlands and further contribute to the percent coverage.

The dominant wetland communities observed were willow-sedge swamps and sedge marshes. These are common wetland types at the more southern limits of the Boreal Plains transition and Central Parklands natural subregions (NRC 2006), and may also functionally represent primary mire formation sites (Ruppel et al. 2013; Nwaishi et al. 2015). Opportunistic wooded swamps and sedge marshes have maximum water tables just below or above the ground surface and pose less geotechnical risk than large open water wetlands with considerable depth of standing water (CEMA 2014). The low percent cover of open water systems in this study reflects the design to limit standing water for geotechnical stability, and the large potential for water loss through evaporation associated with these wetland types in a sub-humid climate (Devito et al. 2017). The existence of swamps and sedge marshes not only represent additional wetland areas of relatively low geotechnical risk, but can aid in understanding the interaction of abiotic and biotic factors controlling natural or novel wetland ecosystem formation on the Boreal Plains (Audet et al. 2015; Borkenhagen and Cooper 2016).

Wetland establishment on coarse-textured landforms

The distribution of wetlands observed in our study shows that different controls of wetland establishment and maintenance exist on fine and coarse-textured landforms (Devito et al. 2012; Audet et al. 2015). External groundwater sources are the dominant source of water maintaining wetlands on Coarse1 landform given that wetlands were limited to lower relative elevations at the break in slopes at the landform base, or landform slope terraces with deep or no confining layer. Although Coarse1 is still in construction, it is unlikely that wetlands will form on the upper portion of the dyke. No wetlands were observed on the recently constructed higher elevation benches or extensive flat areas at the crest of benches in lower elevations, where the water table is far below the surface in a coarse-textured landscape (Schoeneberger and Wysocki 2005). However, fines have accumulated during hydraulic placement of process sand in the extensive flat center (over 1 km wide), and wetlands are expected to form (see next section) with settlement following completion of the landform. Hydrogeological investigations confirm that the observed wetlands on Coarse1 are associated with groundwater flow that discharges to these areas on the dyke portion of the material storage landform (Price 2005). Topographic control of groundwater movement through coarse-textured material is well documented at local (Smerdon et al. 2012) and regional scales (Winter 2001; Van der Velde et al. 2013), forms the basis for reliable wetland establishment in reclaimed systems (Price et al. 2010; Ketcheson et al. 2016), and can be used to predict water sources for wetland persistence in the future (Winter 1988).

Wetland establishment on fine-textured landforms

The range in landscape position and characteristic shape of wetlands observed on fine-textured landforms indicates that several mechanisms may control wetland formation and early maintenance. Similar to Coarse1, external contributions from runoff and groundwater surface waters are likely important to many wetlands on fine-textured landforms with larger contributing catchments and topographic positions that encourage formation, such as the long channels or valleys associated with ditching perpendicular to the slope at the base of the landform and toe slopes of benches (Fleming 1994; Kelln et al. 2008). Initially, in early forest succession with limited water uptake, runoff can be higher (Elshorbagy et al. 2005) and may contribute water to wet areas. However, limited erosion and no groundwater seepage was observed following initial vegetation establishment on fine-textured landforms. Forest water levels in this study, as in other studies, indicate reclaimed slopes adjacent to wetlands likely contribute minimal groundwater discharge and limited surface water due to the low hydraulic conductivity of deposits (Meiers et al. 2011), and relatively high storage capacity of capping material (Huang et al. 2015). Relatively large contributing areas would therefore be required to sustain channel wetlands in the future. Further, wetlands associated with valley topographic position indices are primarily constructed swales that run parallel to the landform slope. Little runoff from the outlets of these swales has been observed. This may indicate that the swales either act as effective evapotranspiration sites to remove runoff contributed by adjacent forests, or indicate the potential for internal promotion of surface saturation and runoff generation, as observed in swales of forest catchments on the Boreal Plains (Devito et al. 2005).

This study illustrates the relative importance of internal soil-atmosphere interactions in sub-humid climates influencing primary wetland formation on newly exposed wet mineral soils on fine-textured landforms. Several large circular wetlands span flat tops or terraces, often perched above groundwater (Unpublished data, CA Mendoza), where low relief and smaller contributing areas severely limit proportional contribution from adjacent non-wetland areas. These wetlands occur in large endorheic pans where fine-texture and poor drainage potential promotes frequent surface saturation, shallow water tables and soil anoxia precluding water intolerant forest vegetation, even in sub-humid climates (Rodriguez-Iturbe et al. 2007; Dixon et al. 2017). Gently sloping wetland areas (typically swamps) provide lateral runoff to the adjacent shallow center depression, and internal distribution of water appears to dominate the hydrology and contributes to the complexity in forms of these wetlands. Inherently, small wetlands may occur in locations with sufficient contributions of runoff from non-wetland areas, that at least periodically contribute to the wetland water balance. However, field observations suggest that most of these small wetlands also occupy shallow endorheic pans. Wetlands perched above regional water tables and occupying flat endorheic pans isolated from external sources have been observed globally, and studied in the Boreal Plains (Hokanson et al. 2016), semi-arid South Africa (Melly et al. 2017), and areas heavily influenced by glacial deposits in Indiana, USA (Fleming 1994).

Landform features and wind protection

Along with flat landscape features, wetlands appear to be located with a propensity for the leeward side of the landforms, suggesting they are protected in some capacity from atmospheric drying effects. The role of tree cover on surface wind turbulence and shading control of evapotranspiration in adjacent wetlands (Petrone et al. 2007) is likely limited with early forest succession, but landform surface topography features also influence wetland or lake evapotranspiration (Markfort et al. 2010; Plach et al. 2016). The potential influence of leeward locations on landforms and protection from wind is suggested by lower wetland density and distribution on Fine1 compared to Fine2. Reclamation practices and competition by succeeding forest vegetation may account for some of the difference; however, the dominant wind direction on Fine2 is from the west, while Fine1 receives wind from three directions (Fig. 5), suggesting there is less protected area on Fine1. With low runoff from fine-textured landforms in a sub-humid climate (Huang et al. 2015; Devito et al. 2017), differences in protection from atmospheric drying likely influence wetland distribution. Although inconclusive in this study, the potential consideration of dominant wind direction in landform construction and in anticipating wetland formation on fine-textured landforms warrants further research. Using position and characteristics associated with external or internal mechanisms of wetland formation can help in understanding the range in potential water sources and anticipate the locations for successful wetland formation in the design of fine and coarse-textured landforms.

Size distribution of wetlands

The majority of wetlands in our survey were too small (< 1.0 ha) to be included in many evaluation systems with 1 ha as minimum areas (e.g., Government of Alberta 2015; OMNR 2014). However, small isolated wetlands are important ecotonal systems that influence landscape hydrology, biogeochemistry, and ecology (Calhoun et al. 2003; Cohen et al. 2016). For fine landforms, the presence of many very small isolated systems (< 0.1 ha), that currently maintain hydrophytic vegetation (i.e., sedge marshes, willow swamps), indicate that internal mechanisms driven by confining soils, endorheic pan formation and hydrophytic vegetation may exist, and enable the persistence of wetland conditions year-round (Ollis et al. 2015; Waddington et al. 2015). The size of wetland that will persist with forest succession is difficult to assess. Comparison of the size distribution of wetlands on Fine1, where reclamation has been completed, with the younger Fine2 is confounded by potential wind exposure. Although the density of wetlands is lower on Fine1, similar percent coverage of large and small wetlands occurs on both fine-textured landforms. Small isolated wetlands and vernal pools with similar size distributions have been observed in landscapes with a wide range of geology and climate (Brooks and Hayashi 2002; Cohen et al. 2016), and small isolated marshes with ephemeral water tables (< 0.1 ha) and peatland-swamp complexes (< 0.5 ha) occur across the Boreal Plains (Devito et al. 2005; Hokanson et al. 2016). Very small isolated wetlands (< 0.01 ha) in fine-textured landscapes may disappear with forest succession, having little effect on total wetland area, or may act as ephemeral wet systems with potentially important roles in forest succession, growth, and ecology (Calhoun et al. 2003; Zedler 2003).

Site scale characteristics and distribution of wetlands: role of soil texture

The apparent lack of influence of depth to confining layer and solar radiation reflects the lack of difference between wetland and non-wetland locations, and the ability to discriminate, rather than the importance of these factors in wetland formation. Overall radiation input is low at these high latitudes, which promotes wetland and peatland formation. Further, spatial variability in incident radiation (~ 221 to 224 Wm−2) was low across both wetland and non-wetland sites and the influence of sun incident angle and, similarly, landform-scale aspect, is likely limited in low relief areas. The shallow depth to confining layer and occurrence of fine-textured soils clearly is important in promoting saturation of soils; however, these were similar in both wetland and non-wetland sites on Fine1 and Fine2, and appear to be of less importance on Coarse1 where wetlands receive groundwater.

The lack of discrimination between non-wetland and wetland areas in depth to confining layer highlights the importance of slope and soil property interactions on wetland formation. Higher resolution mapping of transect sub-units show that wetlands occurred in areas with very low slopes compared to non-wetland sites. The influence of low slope is consistent with other studies predicting wetland locations in arid climates (Ollis et al. 2015; Melly et al. 2017), regional paludification in central Canada (Ruppel et al. 2013), and reduction of runoff with increasing regional slope on the Boreal Plains (Devito et al. 2017). At non-wetland sites a slight increase in slope (> 3%) and lateral drainage combined with a break in capillary rise can increase the frequency of deeper water tables (Schoeneberger and Wysocki 2005; Sayama et al. 2011) and feedback to greater vegetation growth, rooting depth, water uptake (Porporato et al. 2002; Bruemmer et al. 2012), soil structure changes and storage potential (Albrecht and Benson 2001; Meiers et al. 2011). This is indicated by the limited water level responses of forest on fine-textured landforms in this study. On Fine1, for example, runoff of less than 10% of precipitation (< 35 mm year−1) has been observed from reclaimed slopes. Limited contributions from runoff are expected from non-wetland areas in general and very low runoff over the long term is predicted for cover thicknesses greater than 75 cm in the Athabasca Oil Sands (Huang et al. 2015).

The lower threshold of 3% slope for wetland formation observed in this study supports other studies showing persistent soil saturation and shallow water tables due to lack of drainage in fine-textured soils with higher water-holding capacity (Schoeneberger and Wysocki 2005; Li et al. 2014). This provides a quantitative value for wetland construction or landscape design, and is of interest in sub-humid climates. Saturated antecedent conditions in very flat areas enhance rapid water table responses during rain events, with greater frequency of soil saturation and concrete ice formation which promote both wetland vegetation and runoff generation (Devito et al. 2005; Dixon et al. 2017). Clay-rich capping and shallow depth to confining layer are key for internal distribution of water and function of wetlands occupying large endorheic pans (explained earlier) on flat expanses of fine-textured landforms and are important when considering construction of isolated wetlands.

Extensive low-relief and clay rich areas with poor drainage not only promote surface saturation and conserve water for wetland development, but also represent potential runoff source areas. This hydrologic function is similar to natural systems where low relief peatlands (Gibson et al. 2002; Devito et al. 2017) and forested wetlands and low relief swales (Devito et al. 2005; Wells et al. 2017) have been shown to be primary areas for runoff generation at regional and small catchment scales, respectively, on the Boreal Plains. Athabasca Oil Sands operations and landscape designs have not fully adopted the concept of constructing wetlands with limited contributing areas from adjacent catchments or, importantly, considered wetlands as areas for runoff generation (CEMA 2014; Ketcheson et al. 2016). Geotechnical stability issues and compromises between commercial forest productivity, with higher water demand, and the functional role of the type of wetland created should be considered. This study challenges the efficacy of active and more expensive reclamation techniques to provide external water sources to establish pre-disturbance wetlands (Price et al. 2010; Nwaishi et al. 2015). Here we suggest that more passive techniques, with subtle manipulation of existing design criteria, will allow for undirected (i.e., spontaneous) succession and adoption of hybrid or novel ecosystem approaches to aid in reaching targets of wetland coverage (Prach and Hobbs 2008; Doley and Audet 2013) and enhance water yield to sustain landscape ecosystem functions (Johnson and Miyanishi 2008; Audet et al. 2015).

Conclusion

Wetland initiation and persistence is controlled by both landscape and site-scale characteristics that promote external sources of water, as well as internal or autogenic processes, even in sub-humid regions. However, where and why wetlands form depends on landform texture and landscape position. This study illustrates the importance of bottom-up frameworks and first considering substrate texture within the context of the regional setting of a sub-humid climate when designing landscapes and determining the potential functional role of wetlands (Devito et al. 2012; Audet et al. 2015; Ollis et al. 2015). On coarse-textured landforms, wetland predictably develop in lower lying locations where the water table intersects the ground surface, and groundwater seeps or discharge maintain wetland conditions. However, coarse-textured landforms and high drainage limit small isolated systems, resulting in significant recharge, groundwater discharge and topographic control of external water sources and wetland distribution. On fine-textured landforms, construction of large, flat areas with low soil storage and very low slope, regardless of landscape position, can promote surface saturation and internal processes that facilitate wetland establishment and persistence. Understanding the controls on wetland formation has large implications in providing design flexibility, such that wetlands maybe utilized for alternative and multiple eco-hydrologic roles (e.g., water sources or receivers) in future reconstructed landscapes. Considering their unplanned nature, and that the frequency and distribution of opportunistic wetlands on reclaimed landforms of differing textures are greater and more varied than anticipated, these ecosystems may provide opportunities for inclusion in regulatory targets for wetland coverage. Combining this improved understanding of wetland formation with appropriate planning can provide the opportunity to direct subtle manipulation of current practices to greatly expand the potential locations and extent of wetland construction, and provides alternative functional hydrologic and ecosystem roles of wetlands and water yield for natural or novel landscapes in reclamation design in sub-humid climates.

References

Albrecht B, Benson C (2001) Effect of desiccation on compacted natural clays. J Geotech Geoenviron Eng 127(1):67–75

Atkinson RB, Cairns J (1994) Possible use of wetlands in ecological restoration of surface mined lands. J Aquat Ecosyst Health 3(2):139–144

Audet P, Pinno BD, Thiffault E (2015) Reclamation of boreal forest after oil sands mining: anticipating novel challenges in novel environments. Can J For Res 45(3):364–371

Bates PC, Sucoff E, Blinn CR (1998) Short-term flooding effects on root suckering of quaking aspen. North J Appl For 15(4):169–173

Boese C (2003) The design and installation of a field instrumentation program for the evaluation of soil-atmosphere water fluxes in a vegetated cover over saline/sodic shale overburden. M.Sc. Thesis, University of Saskatchewan, Saskatoon, SK

Borkenhagen A, Cooper DJ (2016) Creating fen initiation conditions: a new approach for peatland reclamation in the oil sands region of Alberta. J Appl Ecol 53(2):550–558

Brooks R, Hayashi M (2002) Depth-area-volume and hydroperiod relationships of ephemeral (vernal) forest pools in southern New England. Wetlands 22(2):247–255

Bruemmer C, Black TA, Jassal RS, Grant NJ, Spittlehouse DL, Chen B, Nesic Z, Amiro BD, Arain MA, Barr AG, Bourque CP-, Coursolle C, Dunn AL, Flanagan LB, Humphreys ER, Lafleur PM, Margolis HA, McCaughey JH, Wofsy SC (2012) How climate and vegetation type influence evapotranspiration and water use efficiency in Canadian forest, peatland and grassland ecosystems. Agric For Meteorol 153:14–30

Calhoun AJK, Walls TE, Stockwell SS, McCollough M (2003) Evaluating vernal pools as a basis for conservation strategies: a maine case study. Wetlands 23(1):70–81

Carey SK (2013) A 10 year assessment of evapotranspiration and net ecosystem exchange from South Bison Hill Report. Report, Syncrude Canada Ltd

Carrera-Hernandez JJ, Mendoza CA, Devito KJ, Petrone RM, Smerdon BD (2012) Reclamation for aspen revegetation in the Athabasca oil sands: understanding soil water dynamics through unsaturated flow modelling. Can J Soil Sci 92(1):103–116

Cohen MJ, Creed IF, Alexander L, Basu NB, Calhoun AJK, Craft C, D'Amico E, DeKeyser E, Fowler L, Golden HE, Jawitz JW, Kalla P, Kirkman LK, Lane CR, Lang M, Leibowitz SG, Lewis DB, Marton J, McLaughlin DL, Mushet DM, Raanan-Kiperwas H, Rains MC, Smith L, Walls SC (2016) Do geographically isolated wetlands influence landscape functions? Proc Natl Acad Sci USA 113(8):1978–1986

Cumulative Environmental Management Association (CEMA) (2014) Guidelines for wetlands establishment on reclaimed oil sands leases. In: West Hawk Assoc for the Reclamation Working Group and the Aquatic Sub-Group and Wildlife Task Group of the Cumulative Environmental Management Association (ed) 3rd edn. http://cemaonline.ca/index.php/administration/cat_view/2-communications/18-rwg-recommendations

Devito KJ, Creed IF, Fraser CJD (2005) Controls on runoff from a partially harvested aspen-forested headwater catchment, Boreal Plain, Canada. Hydrol Process 19(1):3–25

Devito K, Mendoza C, Qualizza C (2012) Conceptualizing water movement in the Boreal Plains. Implications for watershed reconstruction. Synthesis report prepared for the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Research Group. https://doi.org/10.7939/R32J4H

Devito KJ, Hokanson KJ, Moore P, Kettridge N, Anderson A, Chasmer L, Hopkinson C, Lukenbach MC, Mendoza CA, Morissette J, Peters DL, Petrone R, Silins U, Smerdon B, Waddington JM (2017) Landscape controls on long-term runoff in sub-humid heterogeneous Boreal Plain catchments. Hydrol Process 31(15):2737–2751. https://doi.org/10.1002/hyp.11213

Dixon SJ, Kettridge N, Moore PA, Devito KJ, Tilak AS, Petrone RM, Mendoza CA, Waddington JM (2017) Peat depth as a control on moss water availability under evaporative stress. Hydrol Process 31(23):4107–4121

Doley D, Audet P (2013) Adopting novel ecosystems as suitable rehabilitation alternatives for former mine sites. Ecol Process 2:22. https://doi.org/10.1186/2192-1709-2-22

Elshorbagy A, Jutla A, Barbour L, Kells J (2005) System dynamics approach to assess the sustainability of reclamation of disturbed watersheds. Can J Civil Eng 32(1):144–158

Environment Canada (2013) Historic climate data. 2013. http://climate.weather.gc.ca/. Accessed 4 Feb 2018

Fenton MM, Waters EJ, Pawley SM, Atkinson N, Utting DJ, Mckay K (2013) Surficial geology of Alberta, MAP 601 scale 1:1,000,000. http://ags.aer.ca.login.ezproxy.library.ualberta.ca. Accessed 5 Oct 2017

Fleming AH (1994) Origin and hydrogeologic significance of wetlands in the interlobate region of Northwestern Allen county, Indiana. Proc Indiana Acad Sci 103(3/4):147–166

Gibson JJ, Prepas EE, McEachern P (2002) Quantitative comparison of lake throughflow, residency, and catchment runoff using stable isotopes: modelling and results from a regional survey of Boreal lakes. J Hydrol 262(1–4):128–144

Government of Alberta (2015) Alberta wetland identification and delineation directive. https://open.alberta.ca/publications/9781460123638. Accessed 5 Feb 2018

Halsey LA, Vitt DH, Bauer IE (1998) Peatland initiation during the Holocene in continental western Canada. Clim Chang 40(2):315–342

Hokanson KJ, Lukenbach MC, Devito KJ, Kettridge N, Petrone RM, Waddington JM (2016) Groundwater connectivity controls peat burn severity in the boreal plains. Ecohydrology 9(4):574–584

Huang M, Barbour SL, Carey SK (2015) The impact of reclamation cover depth on the performance of reclaimed shale overburden at an oil sands mine in Northern Alberta, Canada. Hydrol Process 29(12):2840–2854

Hutchinson GB (1957) A treatise on limnology. Volume 1. Geography, physics, and chemistry. Wiley, New York

Ireson AM, Barr AG, Johnstone JF, Mamet SD, van der Kamp G, Whitfield CJ, Michel NL, North RL, Westbrook CJ, DeBeer C, Chun KP, Nazemi A, Sagin J (2015) The changing water cycle: the Boreal Plains ecozone of Western Canada. Wiley Interdiscipl Rev Water 2(5):505–521

Jackson RB, Jobbagy EG, Nosetto MD (2009) Ecohydrology in a human-dominated landscape. Ecohydrology 2(3):383–389

Jenness J (2006) Topographic position index (tpi_jen.avx) extension for ArcView 3.x, http://www.jennessent.com/arcview/tpi.htm. Accessed 3 Feb 2018

Johnson EA, Miyanishi K (2008) Creating new landscapes and ecosystems—the Alberta oil sands. N Y Acad Sci Year Ecol Conserv Biol 1134:120–145. https://doi.org/10.1196/annals.1439.007

Kelln C, Barbour SL, Qualizza C (2008) Controls on the spatial distribution of soil moisture and solute transport in a sloping reclamation cover. Can Geotech J 45(3):351–366

Ketcheson SJ, Price JS, Carey SK, Petrone RM, Mendoza CA, Devito KJ (2016) Constructing fen peatlands in post-mining oil sands landscapes: challenges and opportunities from a hydrological perspective. Earth-Sci Rev 161:130–139

Li X, Chang SX, Salifu KF (2014) Soil texture and layering effects on water and salt dynamics in the presence of a water table: a review. Environ Rev 22(1):41–50

MacCormack KE, Atkinson N, Lyster S (2015) Sediment thickness of Alberta, Canada. Alberta Energy Regulator. AER/AGS Map 603, scale 1:1,000,000. http://www.ags.gov.ab.ca.login.ezproxy.library.ualberta.ca/publications/abstracts/MAP_603.html. Accessed 30 Oct 2017

Markfort CD, Perez ALS, Thill JW, Jaster DA, Porte-Agel F, Stefan HG (2010) Wind sheltering of a lake by a tree canopy or bluff topography. Water Resour Res 46:W03530

Marshall IB, Schut PH, Ballard M (1999) A National ecological framework for Canada: attribute data. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research, and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch. Ottawa/Hull Canada. http://sis.agr.gc.ca/cansis/nsdb/ecostrat/1999report/index.html. Accessed 8 Nov 2017

Meiers GP, Barbour SL, Qualizza CV, Dobchuk BS (2011) Evolution of the hydraulic conductivity of reclamation covers over sodic/saline mining overburden. J Geotech Geoenviron Eng 137(10):968–976

Melly BL, Schael DM, Gama PT (2017) Perched wetlands: an explanation to wetland formation in semi-arid areas. J Arid Environ 141:34–39

Millar JB (1971) Shoreline-area ratio as a factor in rate of water loss from small sloughs. J Hydrol 14:259–284

Mwale D, Gan TY, Devito K, Mendoza C, Silins U, Petrone R (2009) Precipitation variability and its relationship to hydrologic variability in Alberta. Hydrol Process 23(21):3040–3056

Natural Regions Committee (NRC) (2006) Natural Regions and sub-regions of Alberta. Compiled by DJ Downing and WW Pettapiece; Government of Alberta. Pub. No. T/852 T/852 https://www.albertaparks.ca/media/2942026/nrsrcomplete_may_06.pdf. Accessed 4 May 2016

Nwaishi F, Petrone RM, Price JS, Andersen R (2015) Towards developing a functional-based approach for constructed peatlands evaluation in the alberta oil sands region, canada. Wetlands 35(2):211–225. https://doi.org/10.1007/s13157-014-0623-1

Ollis DJ, Ewart-Smith JL, Day JA, Job NM, Macfarlane DM, Snaddon CD, Sieben EJJ, Dini JA, Mbona N (2015) The development of a classification system for inland aquatic ecosystems in South Africa. Water 41(5):727–745

Ontario Ministry of Natural Resources (OMNR) (2014) Ontario wetland evaluation system—southern manual. Queens Printer, Toronto, Ontario. http://files.ontario.ca/environment-and-energy/parks-and-protected-areas/ontario-wetland-evaluation-system-southen-manual-2014. Accessed 30 Aug 2016

Palta MM, Grimm NB, Groffman PM (2017) “Accidental” urban wetlands: ecosystem functions in unexpected places. Front Ecol Environ 15(5):248–256

Payette S (1988) Late-Holocene development of subarctic ombrotrophic peatlands: allogenic and autogenic succession. Ecology 69(2):516–531

Petrone RM, Silins U, Devito KJ (2007) Dynamics of evapotranspiration from a riparian pond complex in the Western Boreal Forest, Alberta, Canada. Hydrol Process 21(11):1391–1401

Plach JM, Petrone RM, Waddington JM, Kettridge N, Devito KJ (2016) Hydroclimatic influences on peatland CO2 exchange following upland forest harvesting on the Boreal Plains. Ecohydrology 9(8):1590–1603

Porporato A, D’Odorico P, Laio F, Ridolfi L, Rodriguez-Iturbe I (2002) Ecohydrology of water-controlled ecosystems. Adv Water Resour 25(8–12):1335–1348

Prach K, Hobbs RJ (2008) Spontaneous succession versus technical reclamation in the restoration of disturbed sites. Restor Ecol 16(3):363–366

Prach K, Lencova K, Rehounkova K, Dvorakova H, Jirova A, Konvalinkova P, Mudrak O, Novak J, Trnkova R (2013) Spontaneous vegetation succession at different central European mining sites: a comparison across seres. Environ Sci Pollut Res 20(11):7680–7685

Price A (2005) Evaluation of groundwater flow and salt transport within an undrained tailings sand dam. MSc Thesis, University of Alberta, Department Earth and Atmospheric Sciences

Price JS, McLaren RG, Rudolph DL (2010) Landscape restoration after oil sands mining: conceptual design and hydrological modelling for fen reconstruction. Int J Min Reclam Environ 24(2):109–123

Rawls WJ, Brakensiek DL, Saxtonn KE (1982) Estimation of soil water properties. Trans ASAE 25(5):1316–1320

Raymond P (2004) Erosion control and vegetation establishment of Alpha Swale in W1 Dump. W1 Reclamation Project, Terra Erosion Control Ltd./Fort Mc Kay Environmental LP, Syncrude Canada Ltd. http://www.terraerosion.com/projects/IndustrialReclamation-SyncrudeCanadaAlphaSwaleW1Project.htm. Accessed 5 Nov 2017

Rehounkova K, Prach K (2006) Spontaneous vegetation succession in disused gravel-sand pits: role of local site and landscape factors. J Veg Sci 17(5):583–590

Rodriguez-Iturbe I, D'Odorico P, Laio F, Ridolfi L, Tamea S (2007) Challenges in humid land ecohydrology: interactions of water table and unsaturated zone with climate, soil, and vegetation. Water Resour Res 43(9):W09301

Rooney RC, Bayley SE, Schindler DW (2012) Oil sands mining and reclamation cause massive loss of peatland and stored carbon. Proc Natl Acad Sci USA 109(13):4933–4937

Rooney RC, Robinson DT, Petrone R (2015) Megaproject reclamation and climate change. Nat Clim Chang 5(11):963–966

Rowland SM, Prescott CE, Grayston SJ, Quideau SA, Bradfield GE (2009) Recreating a functioning forest soil in reclaimed oil sands in northern Alberta: an approach for measuring success in ecological restoration. J Environ Qual 38(4):1580–1590

Ruppel M, Väliranta M, Virtanen T, Korhola A (2013) Postglacial spatiotemporal peatland initiation and lateral expansion dynamics in North America and Northern Europe. The Holocene 23(11):1596–1606

Sayama T, McDonnell JJ, Dhakal A, Sullivan K (2011) How much water can a watershed store? Hydrol Process 25(25):3899–3908

Schoeneberger P, Wysocki D (2005) Hydrology of soils and deep regolith: a nexus between soil geography, ecosystems and land management. Geoderma 126(1–2):117–128

Smerdon BD, Mendoza CA, Devito KJ (2012) The impact of gravel extraction on groundwater dependent wetlands and lakes in the Boreal Plains, Canada. Environ Earth Sci 67(5):1249–1259

Thien SL (1979) A flow diagram for teaching texture-by-feel analysis. J Agron Educ 8(1):54–55

Tongway DJ, Ludwig JA (2011) Restoring disturbed landscapes: putting principles into practice. Island Press, Washington, DC

United States Department of Agriculture (USDA 2017) SSM—CH.3 Examination and description of soil profiles. In: Ditzler C, Scheffe K, Monger HC (eds) Soil survey manual, USDA Handbook 18. Government Printing Office, Washington, DC, pp 83–233. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054253. Accessed 3 March 2017

Van der Velde Y, Lyon SW, Destouni G (2013) Data-driven regionalization of river discharges and emergent land cover–evapotranspiration relationships across Sweden. J Geophys Res Atmos 118:2576–2587. https://doi.org/10.1002/jgrd.50224

Waddington JM, Morris PJ, Kettridge N, Granath G, Thompson DK, Moore PA (2015) Hydrological feedbacks in northern peatlands. Ecohydrology 8(1):113–127

Wells C, Ketcheson S, Price J (2017) Hydrology of a wetland-dominated headwater basin in the Boreal Plain, Alberta, Canada. J Hydrol 547:168–183

Winter T (1988) A conceptual-framework for assessing cumulative impacts on the hydrology of nontidal wetlands. Environ Manage 12(5):605–620

Winter T (2001) The concept of hydrologic landscapes. J Am Water Resour Assoc 37(2):335–349

Wytrykush C, Vitt DH, McKenna G, Vassov R (2012) Designing landscapes to support peatland development on soft tailings deposits. In: Vitt D, Bhatti J (eds) Restoration and reclamation of boreal ecosystems: attaining sustainable development. Cambridge University Press, Cambridge, pp 161–178

Zedler P (2003) Vernal pools and the concept of “isolated wetlands”. Wetlands 23(3):597–607

Table 1 Total area covered by the survey transects; total wetland coverage (%) and density (# wetlands ha−1) of polygons in the transect swaths; percentage of the wetland cover designated for each wetland type for the landform overall of Fine1 and Fine2 (fine-textured overburden deposit) and Coarse1 (coarse-textured processed sand deposit) on the Syncrude Mildred Lake lease (see Fig. 1 for landform and transect locations)

	Total transect area (ha)	Total wetland area (ha)	Number of wetlands	Wetland proportion (%)	Wetland density (# ha^{-1})	% of wetland type		
						% swamp	% marsh	% open water marsh
Overall fine-textured deposits	125.3	9.3	97	7.5	0.77	49.4	49.3	1.3
Fine1 landform	46.5	1.7	23	3.7	0.50	22.8	76.8	0.4
Fine2 landform	78.8	7.6	74	9.7	0.94	55.4	43.0	1.5
Coarse-textured deposit	17.0	1.4	13	8.3	0.77	74.4	15.9	9.7
All landforms	142.2	10.7	110	7.6	0.77	52.7	44.9	2.4

Base of Fine1 and the top of Coarse1 deposits were not accessible and not included in the survey

Table 2 Dominant vegetation forms (community types) and percent coverage by landform for areas of entire wetlands intersected by survey transects

Landform	Wetland type: OMNR (2014)	Wetland type: Alberta	No. dom. forms	Dom. veg. form	No. polygons (n)	Total area (ha)	Total area (%)	Common name dom. species (no. zones)	Scientific names
Fine	**Open water**				**26**	**2.6**	**8.8**		
	Open water marsh	Shallow open water	1	u	19	2.5	8.7	Open water (15), bare ground (4)	Not applicable
	Others		1	m	7	0.0	0.1	Brown moss (7)	Not applicable
	Marsh				**123**	**15.8**	**53.8**		
	Marsh, ne	Marsh, Gramminoid	1	ne	66	10.4	35.4	Sedge (45), bluejoint grass (6), slough grass (4), horsetail (2); sedge and blue	*Carex* spp., *Calamagrostis canadensis*, *Beckmannia syzigachne*, *Equisetum* spp.

Landform	Wetland type: OMNR (2014)	Wetland type: Alberta	No. dom. forms	Dom. veg. form	No. polygons (n)	Total area (ha)	Total area (%)	Common name dom. species (no. zones)	Scientific names
								joint/horsetail (7), bluejoint grass and horsetail (2)	
			2	ne–m	7	0.4	1.2	Sedge or bluejoint grass and brown moss (7)	*Carex* spp., *Calamagrostis canadensis*
	Marsh, re	Marsh, Gramminoid	1	re	23	4.2	14.4	Cattail (23)	*Typha latifolia*
			2	re–ne, re–m	27	0.8	2.8	Cattail and sedge (20), or grass (3), or horsetail (2); cattail	*Typha latifolia*, *Carex*spp., Poaceae, *Equisetum* spp.

Landform	Wetland type: OMNR (2014)	Wetland type: Alberta	No. dom. forms	Dom. veg. form	No. polygons (n)	Total area (ha)	Total area (%)	Common name dom. species (no. zones)	Scientific names
								and brown moss (2)	
	Swamp				**71**	**11.0**	**40.5**		
	Swamp, ls	Swamp, shrubby	1	ls	2	0.0	0.1	Willow (2)	*Salix* spp.
			2	ls–ne, ls–re	13	4.3	14.5	Willow and bluejoint grass (4), or horsetail (4), or sedge (4); willow and cattail (1)	*Salix* spp., *Calamagrostis canadensis, Equisetum*spp., *Carex*spp., *Typha latifolia*
			2	ls–gc, ls–m	5	0.2	0.6	Willow and grass (1), or sow thistle (2);	*Salix* spp., Poaceae; *Sonchus* spp.

Landform	Wetland type: OMNR (2014)	Wetland type: Alberta	No. dom. forms	Dom. veg. form	No. polygons (n)	Total area (ha)	Total area (%)	Common name dom. species (no. zones)	Scientific names
								willow and brown moss (2)	
	Swamp, ts	Swamp, wooded	1	ts	11	0.6	2.0	Willow (9); willow and balsam poplar (2)	*Salix* spp., *Populus balsamifera*
			2	ts–ne, ts–m, ds–ne, ds–m	40	5.9	20.2	Willow or balsam poplar and sedge (26), or bluejoint grass (7), or grass (1), or horsetail (1); willow and brown moss;	*Salix* spp., *Populus balsamifera*, *Carex* spp., *Calamagrostis canadensis*, Poaceae, *Equisetum*spp., dead *Picea glauca*

Landform	Wetland type: OMNR (2014)	Wetland type: Alberta	No. dom. forms	Dom. veg. form	No. polygons (n)	Total area (ha)	Total area (%)	Common name dom. species (no. zones)	Scientific names
								dead white spruce (1) or dead willow (2) and sedge; dead willow and brown moss (2)	
Coarse	**Open water**				**10**	**1.9**	**9.2**		
	Open water marsh	Shallow open water	1	u	10	1.9	9.2	Bare ground (6), open water (4)	Not applicable
	Marsh				**40**	**14.5**	**69.2**		
	Marsh, ne	Marsh, Gramminoid	1	ne, ne–m	22	7.5	36.1	Sedge (20) or horsetail (1); grass and brown	*Carex* spp., *Equisetum*spp., Poaceae

Landform	Wetland type: OMNR (2014)	Wetland type: Alberta	No. dom. forms	Dom. veg. form	No. polygons (n)	Total area (ha)	Total area (%)	Common name dom. species (no. zones)	Scientific names
								moss (1)	
	Marsh, re	Marsh, Gramminoid	1	re	9	1.4	6.9	Bulrush (5), cattail (4)	*Schoenoplectus*spp., *Typha latifolia*
			2	ne–re	9	5.5	26.3	Cattail and sedge (8); bulrush and dead sedge (1)	*Typha latifolia*, *Carex*spp., *Schoenoplectus*spp.
	Swamp				**10**	**4.5**	**21.5**		
	Swamp, ls	Swamp, shrubby	2	ls–ne	5	3.5	16.7	Willow and sedge (5)	*Salix* spp., *Carex* spp.
	Swamp, ts	Swamp, wooded	2	ts–ne	5	1.0	4.9	Willow and horsetail (4); willow and sedge (1)	*Salix* spp., *Equisetum*spp., *Carex*spp.

Wetland types and vegetation forms a based on OMNR (2014) and compared with Government of Alberta (2015) wetland classification

Dominant vegetation form is defined as covering > 25% of the area. Vegetation forms from OMNR (2014): ds dead shrubs, ts tall shrubs (woody 1 to 6 m), ls low shrubs (woody < 1 m), re robust emergents, ne narrow leaved emergents, u unvegetated, gc groundcover (herbs), m moss

Table 3 Number of wetlands within or intersected by the survey transect swaths; the median, minimum and maximum area, shape, and relative elevation; and the percent occurrence of the two most common topographic position indices (TPI) of the entire wetland boundaries (in and outside the transect) for the landform overall and relative to each landform position (top, slope, base)

	Wetlands	Wetland area (ha)			Wetland shape (>1)			Relative elevation (%)			TPI		
Landform and position	n	Median	Min	Max	Median	Min	Max	Median	Min	Max	Class	n	%
Overall fine-textured deposits	**98**	**0.03**	**0.001**	**4.93**	**1.30**	**1.00**	**6.66**	**70.5**	**7.7**	**90.3**	**Flat**	**58**	**59**
											Valley	**19**	**19**
Fine1 landform	23	0.02	0.001	1.08	1.25	1.02	3.43	45.8	7.7	90.3	Flat	12	52
											Valley	6	26
Top of landform	6	0.03	0.001	0.37	1.17	1.02	1.99	79.4	77.2	90.3	Flat	5	83
											Toe slope	1	17
Slope of landform	17	0.03	0.002	1.08	1.28	1.02	3.43	44.2	7.7	53.3	Flat	7	41
											Valley	6	35
Fine 2 landform	75	0.03	0.001	4.93	1.45	1.00	6.66	73.4	10.4	87.5	Flat	46	61
											Toe slope	14	19
Top of landform	48	0.02	0.001	4.33	1.25	1.01	3.62	79.0	61.3	87.5	Flat	39	81

										Toe slope	6	13
Slope of landform	26	0.05	0.003	1.20	1.51	1.00	6.66	47.8	11.1	77.9	Valley	10	38
										Toe slope	8	31
Base of landform	1	4.93	4.93	4.93	3.07	3.07	3.07	10.4	10.4	10.4	Flat	1	100
Overall coarse-textured deposit	**14**	**0.50**	**0.003**	**9.25**	**1.97**	**1.01**	**4.85**	**31.0**	**4.6**	**53.2**	**Flat**	**11**	**79**
										Toe slope	**2**	**14**
Slope of landform	3	1.65	2.16	4.10	4.10	1.16	4.85	38.5	25.2	53.2	Flat	3	100
Base of landform	11	0.31	9.25	1.17	1.71	1.01	4.17	22.5	4.6	40.3	Flat	8	73
										Toe slope	2	18
All landforms	**112**	**0.04**	**0.001**	**9.25**	**1.43**	**1.00**	**6.66**	**61.8**	**4.6**	**90.3**	**Flat**	**69**	**62**
										Valley	**20**	**18**

Wetland shape is defined using the Hutchinson (1957) shoreline index which is dimensionless and values are greater than one. Relative elevation is percent of the wetland elevation relative to the total change in elevation of each landform top-slope-base sequence. TPI as defined by Jenness (2006)

Table 4 Results of binomial logistic regression comparing characteristics of point site soil and physical characterizes for discriminating (a) non-wetland sites versus wetland edge sites and (b) non-wetland sites versus wetland center sites

	(a) non-wetland vs wetland edge					**(b)** non-wetland vs wetland center				
	Estimate	Std. Error	z value	*p*		Estimate	Std. Error	z value	*p*	
Intercept	34.34	27.70	1.24	0.216		63.24	33.56	1.88	0.060	
Categorical Variables										
Moderate Drainage	-1.52	0.63	-2.41	0.016	*	-2.43	0.81	-3.01	0.003	*
High Drainage	14.81	1466	0.01	0.992		14.03	1460	0.01	0.992	
Local N Aspect	-0.96	1.10	-0.87	0.383		-1.41	1.33	-1.06	0.287	
Local NE aspect	-1.13	0.99	-1.14	0.256		-1.52	1.21	-1.25	0.211	
Local NW aspect	-0.30	1.06	-0.28	0.781		-1.01	1.35	-0.75	0.454	
Local S aspect	0.00	1.05	0.00	0.999		-1.58	1.19	-1.33	0.182	
Local SE aspect	0.41	1.10	0.37	0.709		0.94	1.33	0.71	0.481	
Local SW aspect	-0.60	1.03	-0.58	0.562		-0.28	1.23	-0.23	0.819	
Local W aspect	-0.55	1.33	-0.42	0.678		1.15	1.40	0.82	0.415	
Slope TPI	0.19	1.31	0.15	0.884		0.35	1.43	0.24	0.808	
Toe Slope TPI	3.82	1.24	3.07	0.002	*	5.25	1.49	3.53	0.001	*
Valley TPI	4.29	1.42	3.02	0.003	*	5.57	1.67	3.34	0.001	*
Continuous Variables										
Depth to CL (cm)	0.01	0.01	1.66	0.098		0.02	0.01	2.40	0.016	*
Slope of site (%)	-0.41	0.11	-3.70	0.001	*	-0.57	0.13	-4.27	0.001	*
Relative elev FHLU	0.003	0.01	0.26	0.795		0.01	0.01	0.09	0.932	
Solar Radiation	-0.14	0.12	-1.16	0.246		-0.27	0.15	-1.81	0.070	
	Cox Snell	0.36	Correc AIC	137		Cox Snell	0.44	Correc AIC	119	

(a) Accuracy

	Forest	Wetland	%
Forest	26	11	70.3
Wetland	11	78	87.6
		All	84.9

(b) Accuracy

	Forest	Wetland	%
Forest	31	6	83.8
Wetland	8	81	91.0
		All	88.9

Table 5 Depth (cm) to confining layer (CL) in the secondary mineral capping material, depth (cm) of primary capping material (1° CM), and depth (cm) of water level (WL) or soil saturation from the ground surface (+ is above ground, − is below ground surface) of sites in the (a) center, (b) edge of the wetland, and (c) an adjacent non-wetland (early forest) for the three landforms

Site location	**Wetlands**	**Depth CL (cm)**			**Depth 1° CM (cm)**			**Depth WL (cm)**		
	n	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
(a) Overall—wetland center	91	37	0	100	30	0	95	− 15	< − 100	27
(b) Overall—wetland edge	91	32	0	100	25	0	95	− 50	< − 100	14
(c) Overall—non-wetland	37	29	1	100	20	0	75	− 75	< − 100	− 22

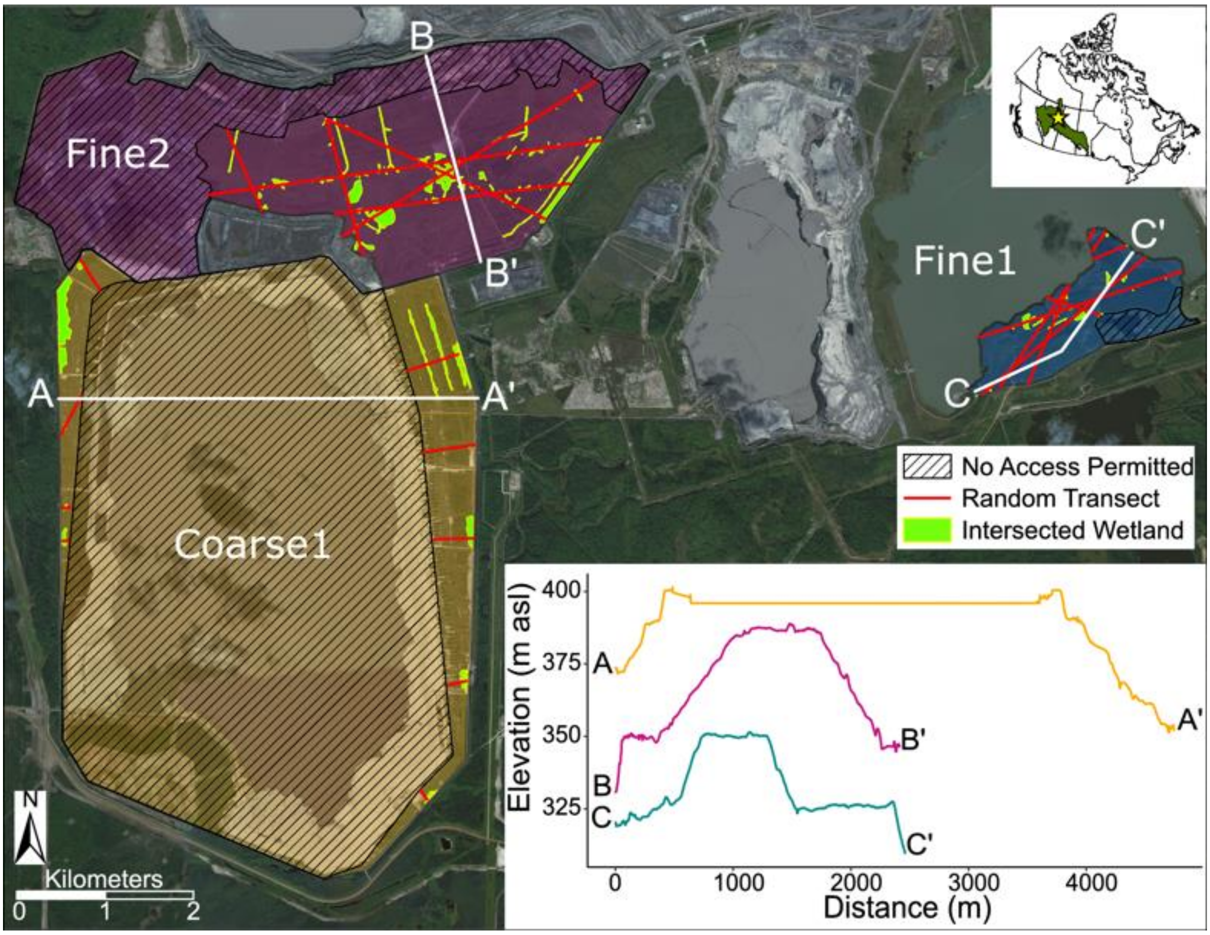

Fig. 1 Constructed landforms and locations of survey transects for the three material storage areas: Southwest Sands Storage (A–A′) deposit composed of coarse-textured processed oil sands deposits (Coarse1), and South Bison Hills (C–C′) (Fine1) and W1 (B–B′) (Fine2) deposits constructed of fine-textured Clearwater shale overburden on the Syncrude Mildred Lake lease. Typical elevation profile illustrating landform top, slope and bottom for each landform is shown. The inset shows the location of Athabasca Oil Sands (star) and Boreal Plains (green) within Canada

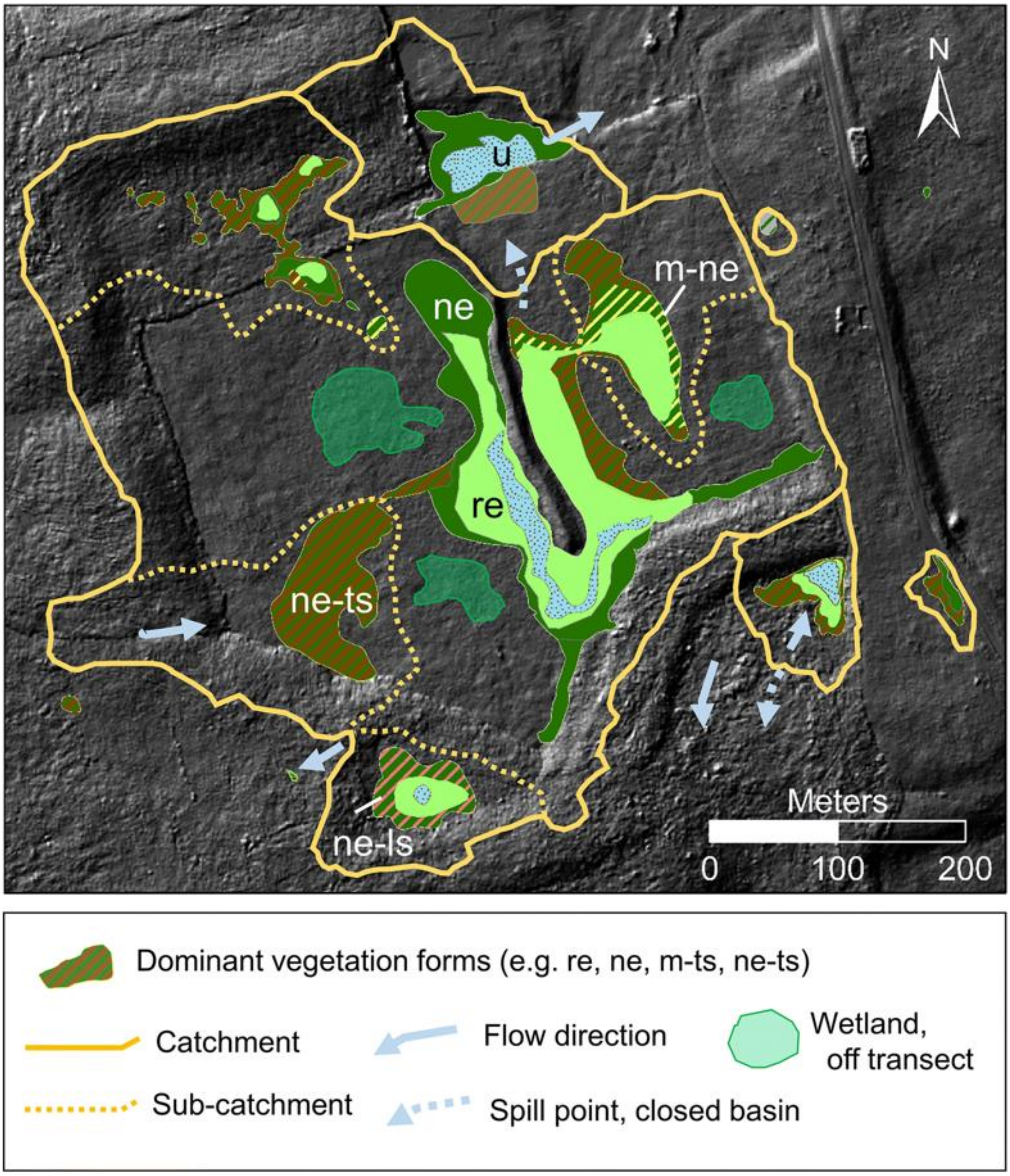

Fig. 2 Example of configuration of dominant vegetation forms (OMNR 2014) and associated topographic catchment boundaries of wetland complexes that intersected transects on the flat top of Fine2 landform (see Fig. 1). Wetlands not intersected by survey transects and not included in wetland or vegetation form area covered calculations are shown in pale green. Underlay is grey scale for 1 m^2 resolution DEM. See Table 2 for labels for vegetation forms

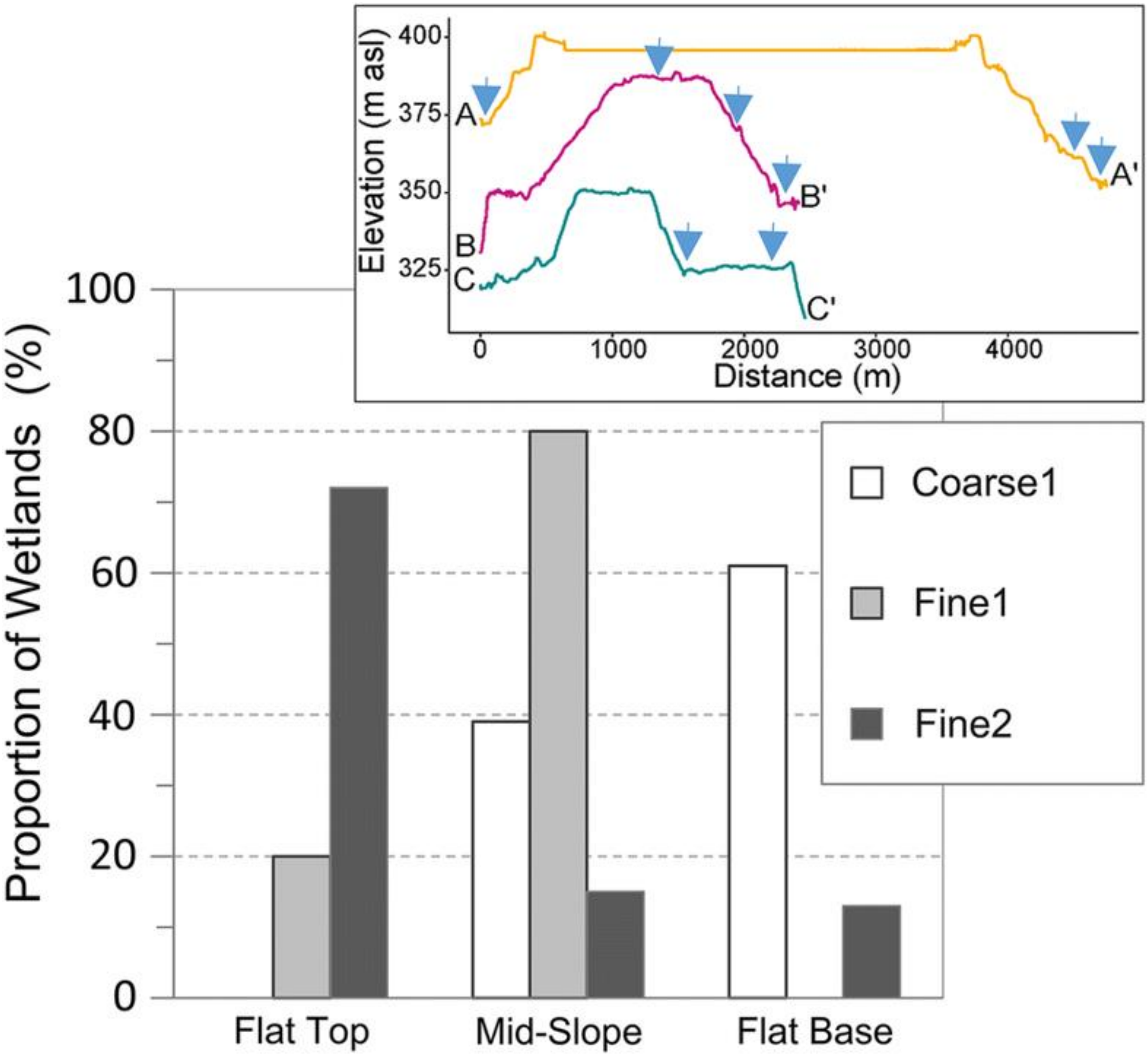

Fig. 3 Proportion of all wetland areas observed on the landform tops, slopes, and base. Arrows indicate predominant locations of wetlands relative to cross section for the study landforms

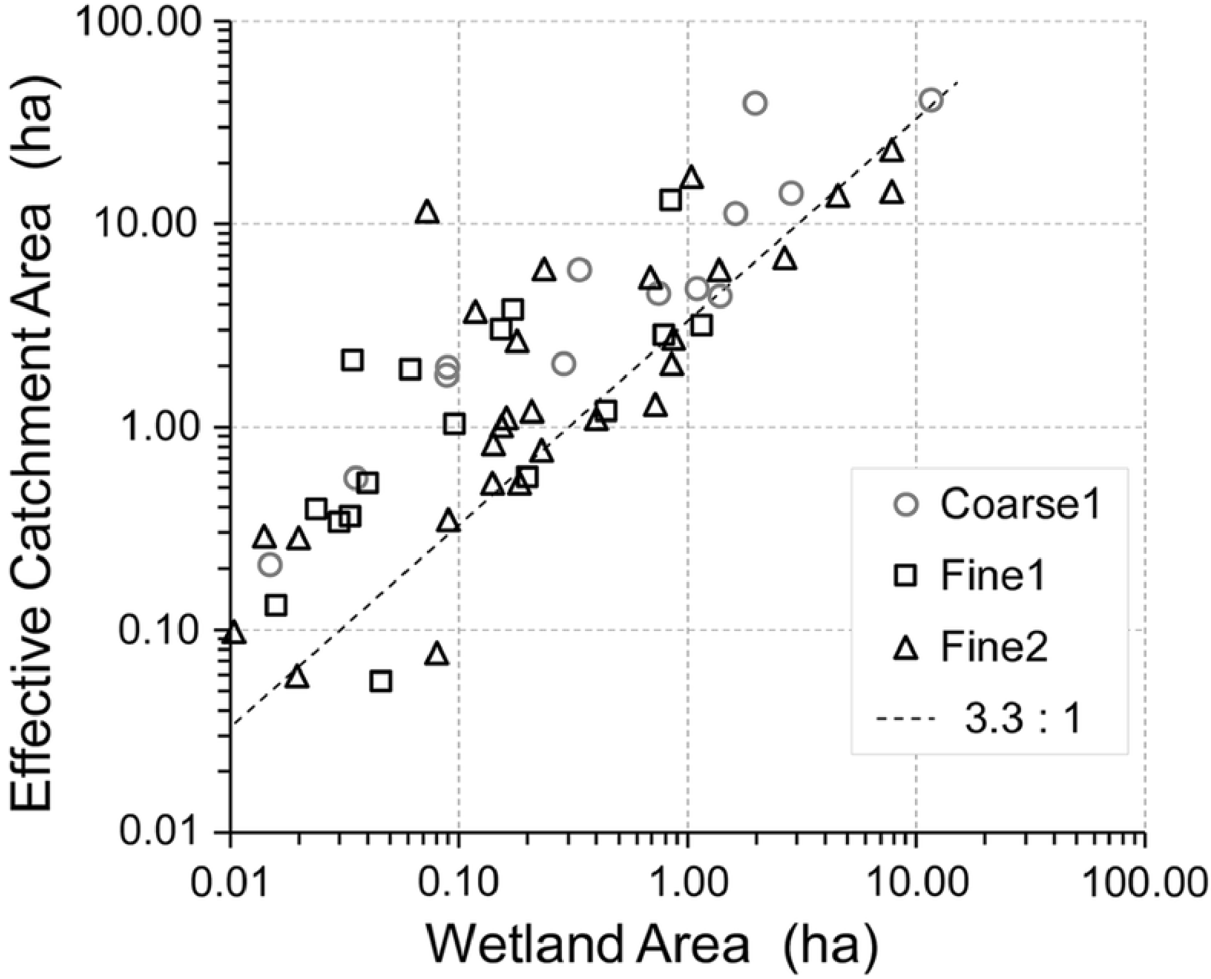

Fig. 4 Effective catchment area (ha) with potential to accumulate surface runoff in relation to total wetland area for n = 66 catchments delineated on the study landforms. The 3.3 to 1 line represents the ratio of non-wetland area estimated to compensate for regional moisture deficit where precipitation – evapotranspiration equals 100 mm, assuming runoff of ~ 30 mm (Huang et al. 2015; Devito et al. 2017)

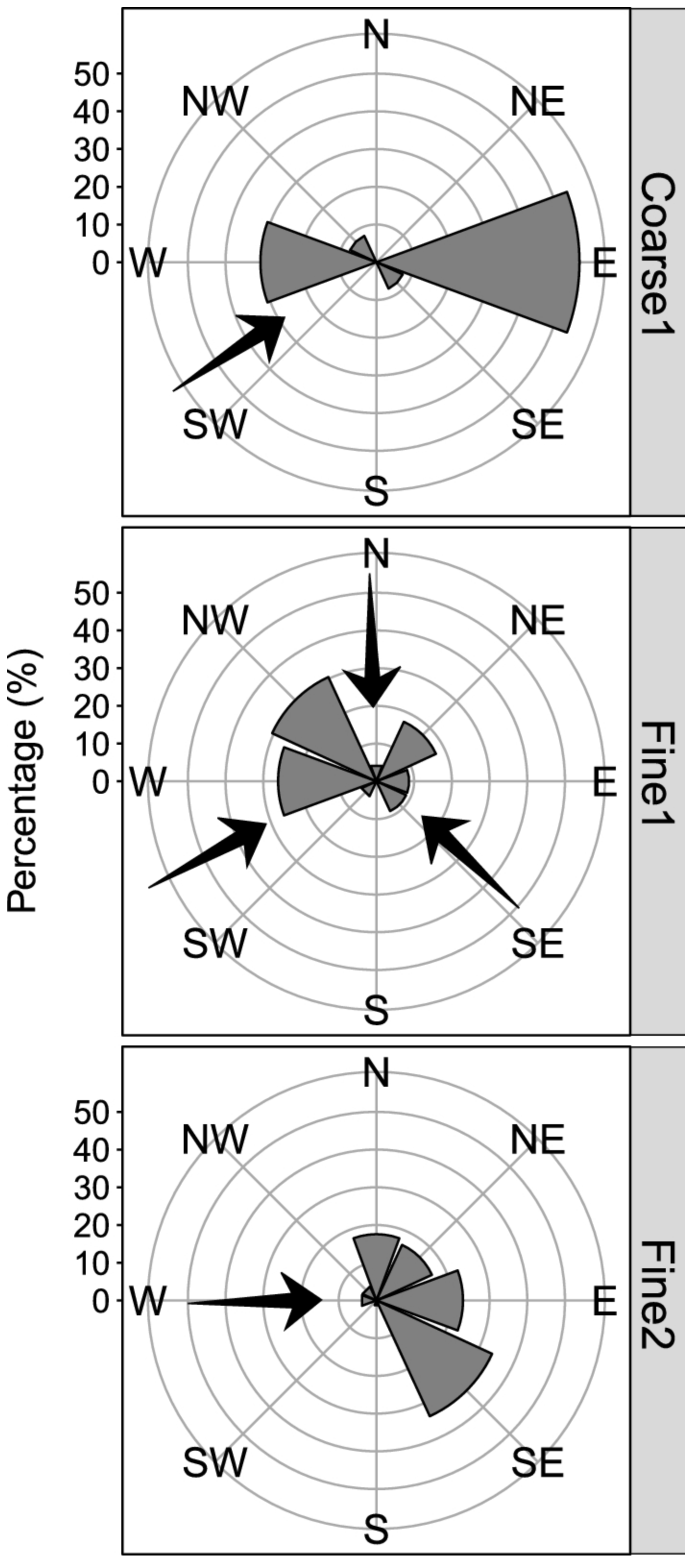

Fig. 5 Wetland location relative to the generalized landform-scale aspect on coarse-textured (Coarse1) and fine-textured (Fine1 and Fine2) landforms using 100 × 100 m pixel size compared to dominant wind directions during the growing season (May to Sept). Dominant wind flow (arrows) determined from local meteorological stations (Carey 2013)

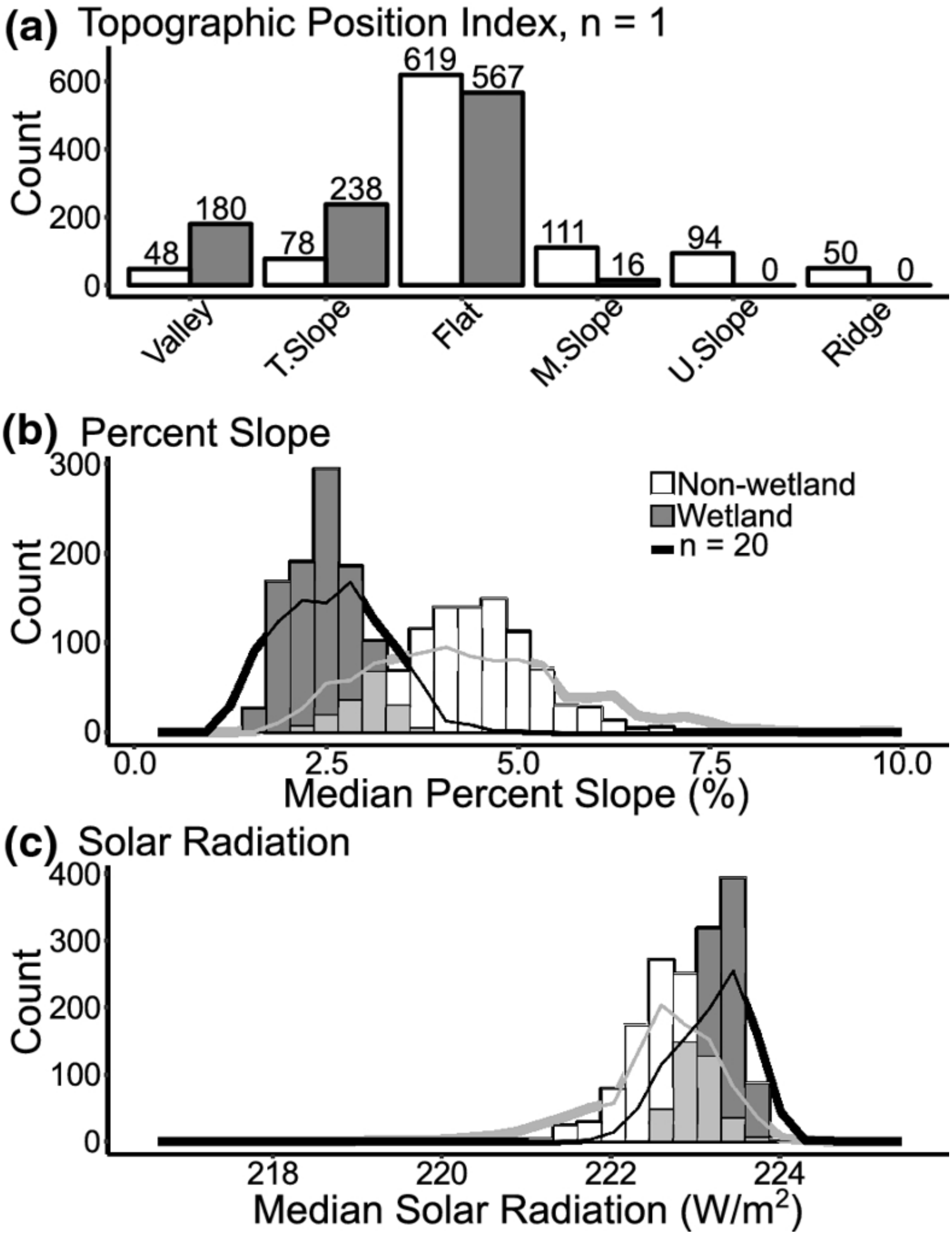

Fig. 6 Comparison of measured wetland random subsets within transect swaths (45 or 60 m wide) (n = 146) and generated non-wetland (early forest) subsets (n = 4560) for all three landforms combined for: (a) distributions of modal summary statistics for topographic position index for 1000 iterations using sample size n = 1; and distributions of median summary statistics for (b) slope and (c) solar radiation for 1000 iterations using sample size n = 20, and n = 50. Sample size n = 50 is represented by the histogram; n = 20 is represented using density curves. Light grey on bars (b and c) represents overlap of the two distributions

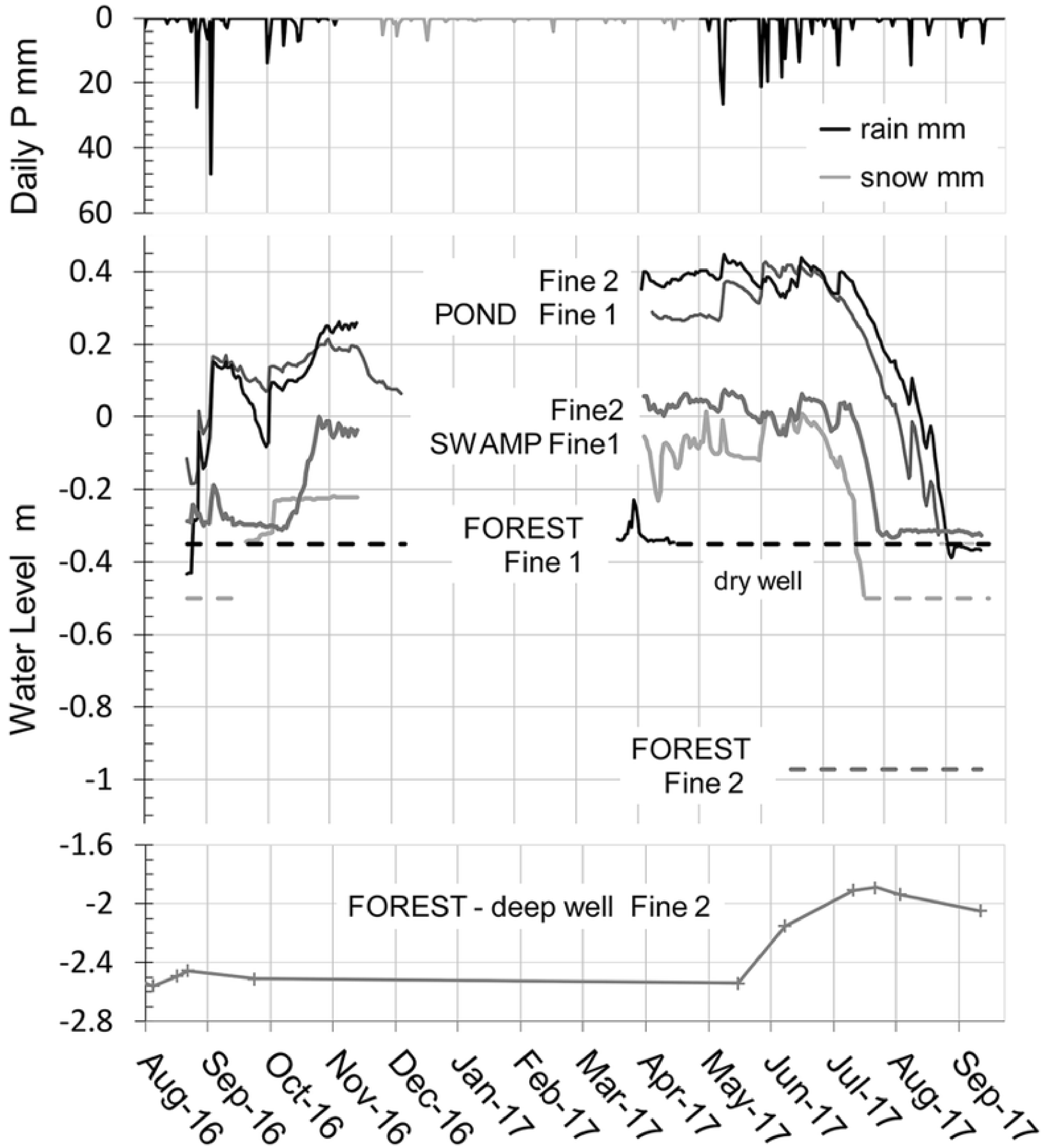

Fig. 7 Daily precipitation (mm) and response of water levels relative to the ground surface for selected wells in non-wetland (early forest), woody swamp and open water vegetation forms on Fine1 and Fine2 landforms during the study period. Dashed lines indicate the well was dry and the water level is below the bottom of the well. Negative values represent water levels below the ground surface