An Assessment of the Water Table Dynamics in a Constructed Wetland, Fort McMurray, Alberta

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ABSTRACT

Oil sand mining removes the wetland and forestlands of the Boreal Plains, and replaces this landscape with open pits, tailings ponds and overburden piles to access the oil-bearing formations below. In turn, mine regulators are forced to reclaim the disturbed, post-mined land to pre-disturbance conditions. In 2012, Syncrude Canada Limited (SCL) constructed one of the first of two reclaimed wetlands, the Sandhill Fen Watershed (SFW), to evaluate wetland reclamation strategies. SFW is a 52-ha system atop soft-tailings that includes an inflow/outflow pump system, underdrains, upland hummock areas, and a fen lowland. This study examines trends in water table position and lateral gradients that are developing, as well as observe system response to pump management. Spanning May- Oct 2014 and 2015, precipitation was measured at three meteorological stations across the fen, artificial inflows and outflows were recorded using a series of pumps, and water table position was measured using a network of 27 near-surface wells instrumented with transducers. Water table was maintained near the peat surface for both study seasons, indicating the potential for maintenance of wetland conditions. Though data is limited, upland-lowland interactions are beginning to develop, suggesting the uplands are beginning to supply water to the lowland fen. Flow reversals are reported along the fen lowland in dry periods, and the east and west fens become hydrologically disconnected as the season progresses. Comparison with analogue sites provides reference for hydrologic processes within SFW and provides insight on the influence of pump management on the system.

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TABLE OF CONTENTS

ABSTRACT……………………………………………………………iii

ACKNOWLEDGEMENTS………………………………………………iv

LIST OF TABLES……………………………………………………...vi

LIST OF FIGURES…………………………………………………….vii

TABLE OF CONTENTS………………………………………………..v

CHAPTER 1: INTRODUCTION……………………………………...10

CHAPTER 2: SITE DESCRIPTION AND METHODOLOGY……...17
2.1 The Sandhill Fen – location and design**……………………...17**
    2.1.1 Inflows and outflows**……………………………………17**
    2.1.2 Construction materials and vegetation**………………..18**
2.2 Methodology**…………………………………………………….19**

CHAPTER 3: RESULTS………………………………………………22
3.1 Climate**…………………………………………………………..22**
3.2 Pump Management: Inflows and Outflows**…………………..22**
3.3 Water Table Dynamics**………………………………………...23**
    3.3.1 Heads, Flow Direction, and Flow Reversals**……………24**
    3.3.2 Event-based analysis**…………………………………...26**
        3.3.2.1 Precipitation Events**……………………………26**
        3.3.2.2 Pump events**……………………………………27**
3.4 Peat Physical Properties**……………………………………….28**

CHAPTER 4: DISCUSSION…………………………………………29
4.1 Sustainability of the Sandhill Fen Watershed**………………..29**
4.2 Water table dynamics**…………………………………………...31**
4.3 Management**…………………………………………………….35**

CHAPTER 5: SUMMARY AND CONCLUSIONS…………………37

REFERENCES………………………………………………………...39

TABLES………………………………………………………………46

FIGURES……………………………………………………………..47

LIST OF TABLES

Chapter 3

Table 3.1 - Monthly climate data at SFW for air temperature (Ta, averaged) and rainfall (mm, cumulative) from 2014-2015. Monthly climate normal (CN) data is reported by Environment Canada, 2016 (representative for 1981-2010) with standard deviations shown for air temperature.

Table 3.2. Organic soil hydrophysical properties. Samples are named based on location, depth, and number of samples collected at that depth.

LIST OF FIGURES

Chapter 2

Figure 2.1 – Layout of SFW, including the water storage pond, boardwalks and outlet.

Figure 2.2 – Cross-sectional view of the outflow pump in SFW. Surface and near-surface water flows in from SFW, through the weir building, mixing with water from underdrains in the sump pump and is then discharged.

Figure 2.3 – Instrumentation of SFW including underdrains and near-surface well locations

Chapter 3

Figure 3.1 – Rainfall (bars) and air temperature (lines) for the 2014 and 2015 growing season at Sandhill Fen Watershed. Precipitation is the mean from 3 tipping buckets on SFW. Green, blue and red represent 2014, 2015 and 30-year (1981-2010) climate normal data, respectively.

Figure 3.2 - Cumulative inflow and outflow (normalized to the 17 ha lowland) for the 2014 and 2015 seasons

Figure 3.3 – Water table elevation over the lowland transect in 2014 and 2015. B1, B2, and B3 are located at the inlet, mid-fen and outlet, respectively. The figure on the bottom shows water table position in 2015 with reference to the ground surface.

Figure 3.4 – Change in water table depth over the 2014 and 2015 seasons in the west (B1-W2) and east (B3-W4).

Figure 3.5 – Proportion of time water table depth was at various positions during the 2014 (left, blue) and 2015 (right, green) for May-Oct of both years.

Figure 3.6 – Water table elevation (head) for paired wells TR-W8/TR-W9 in metres above sea level (m.a.s.l) for 2014 and 2015. TR-W8 is located at the toe of a hummock and TR-W9 is located further into the lowland.

Figure 3.7 - Groundwater maps showing larger-scale, deep groundwater movement, provided by Carl Mendoza and BGC Engineering.

Figure 3.8 - Heads (in m.a.s.l) of B1-W2 (inlet) vs. B3W1 (mid-fen). When above the 1:1 line, flow is reversed from the outlet. Bottom figure expresses the magnitude of the gradient (positive values indicate flow towards the mid-fen, negative values indicate flow toward the inlet (Note the change in x-axis scale).

Figure 3.9 - Heads (in m.a.s.l) between the toe of a hummock (TR-W8) and the lowland (B3-W1). When above the 1:1 line, flow is from the lowland towards the hummock. Bottom figure expresses

the magnitude of the gradient (positive values indicate flow towards the lowland, negative values indicate flow toward the hummock. Note the change in x-axis scale).

Figure 3.10 - Heads (in m.a.s.l) between the toe of a hummock (TR-W8) and a paired well further into the lowland (TR-W9). When above the 1:1 line flow is from the lowland towards the hummock. Bottom figure expresses the gradient (positive values indicate flow towards the lowland. Note the change in x-axis scale).

Figure 3.11 – Water table response to the July and September rainfall events in margin (TR) wells and lowland wells.

Figure 3.12 – Response to precipitation event for a well with standing water present (B3-W1) and a well where water table is below the peat surface (TR-W8).

Figure 3.13 – Saturation map for two dates in July 2015 before and after 39 mm precipitation event. Light and dark blue represents before and after the rainfall, respectively. Map provided by Carl Mendoza (U of A) and BGC Engineering.

Figure 3.14 - Rapid response to the pumping event was seen at the outlet (B3-W4), with a slower response seen at margin wells (TR). The outflow pump was on for 56 consecutive hours (3-5 June), removing 9334 m^3 of water.

Figure 3.15 - Saturation map showing the areas of standing water and saturated ground present on 31 May, 2015, prior to the pump event.

Figure 3.16 - Saturation map showing the areas of standing water and saturated ground present on June 10, following the pump event.

Figure 3.17 - Electrical conductivity at the outlet (B3-W4) for the duration of the study season. Grey bar represents the pump event.

Figure 3.18 - Electrical conductivity in the mid-fen (B3-W1) for the duration of the study season. Grey bar represents the pump event.

CHAPTER 1: Introduction

Open pit oil sands surface mining in Northern Alberta is a process that involves stripping the land of its natural boreal landscape and digging large pits to access the oil sand bearing formations below. This process removes all of the materials that overlie the bitumen-bearing McMurray formation, including vegetation, soil, glacial tills and clay (Daly et al., 2012; Rooney et al., 2012). As a result, all ecological and hydrological function of the landscape is lost and instead replaced with overburden and tailings materials (Daly et al., 2012; Elshorbagy et al., 2005; Nwaishi et al., 2015; Price et al., 2010; Rowland et al., 2009). The Athabasca Oil Sands Region (AOSR) has the world's third largest oil reserve, underlying 142,200 km^2 of surface minable area (Government of Alberta, 2016a). As of 2014 the total oil sands production had reached approximately 2.3 million barrels per day, disturbing almost 850 km^2 of Western Boreal Plains (WBP) landscape (Government of Alberta, 2016a). Bitumen is extracted for processing (Daly et al., 2012; Rooney et al., 2012) and caustic hot water (NaOH) is added to the oil-sand ore, separating the bitumen from the sands. Once the bitumen is extracted, a large amount of wet tailings are left behind, which are then treated with gypsum ($CaSO_4$) and result in a slurry of nonsegregating composite tailings, that are stored and later used for reclamation efforts (Chalaturnyk et al., 2002).

Under the Government of Alberta Environmental Protection and Enhancement Act, industry is required to reclaim disturbed landscapes to a state of "equivalent land capability" (Daly et al., 2012; OSWWG, 2000), which consisted of a mosaic of forestlands and wetland systems (Devito et al., 2012). The Alberta Government defines reclamation as "the process by which lands formerly involved in industry…are returned to the state of natural productivity that existed previous to the start of industrial activity. The process of reclaiming the land differs depending on what types of activity took place on the land," (Government of Alberta, 2016b). Upland areas have been the focus of reclamation efforts (Brown et al., 2014; Carey, 2008; Huang et al., 2015; Kelln et al., 2007; Lilles et al., 2010; Rowland et al., 2009; Sorenson et al., 2011), with a shift now towards wetlands, as these systems comprise over 50% of the landscape in this region (Daly et al., 2012; Vitt et al., 1996) and provide many important ecosystem services such as carbon and water storage, biodiversity (Nwaishi et al., 2015; Waddington et al., 2015) and water quality improvement (Kennedy and Mayer, 2002). Historically, wetland reclamation in the AOSR typically focussed on marshes and shallow, open water wetlands, as these wetlands are hydrologically simpler than peatlands and can spontaneously develop in disturbed landscapes (Harris, 2007; Wytrykush et al., 2012). As 90% of wetlands in this region are peatlands (Vitt et al., 1996), government regulators have instructed operators to increase focus on fen reclamation as these have been affected the most (Daly et al., 2012) and will require complete reconstruction of the landscape (Devito et al., 2012).

Fens are mineratrophic systems that have a peat layer of 40 cm or greater, supporting brown mosses and graminoid vegetation such as sedges and grasses with a water table that is at or near the peat surface (National Wetlands Working Group, 1997). These systems are sustained by precipitation and surface and/or groundwater inputs (Ingram, 1983; Price et al., 2010). Some fens may be sustained through significant groundwater inputs (Gilvear et al., 1993; Price, 1997; Price et al., 2010; Smerdon et al., 2005), which act as a buffer during periods with a precipitation deficit, which can exist for multiple years in the WBP (Smerdon et al., 2005). In contrast, some fens with adjacent uplands receive minimal groundwater inputs yet still maintain a fen ecosystem during periods of water deficit (Ferone and Devito, 2004; Thompson et al., 2015). These hydrologic connections between peatlands and their surroundings (i.e. adjacent uplands or ponds) are important to maintain wetness and sustain wetland conditions in the sub-humid region, especially during dry periods. In a pond-peatland complex, when pond water level drops below that of a peatland, lateral flow occurs with peatland discharge towards the pond. Contrasting this, when peatland water table was below that of the pond, lateral flow occurred from the pond towards the peatland. When water table depths (WTD) were similar in both pond and peatland, dynamic water tables were observed, with frequent flow reversals between the two landscape units (Ferone and Devito, 2004; Thompson et al., 2015). Hydrologic connections also exist between peatlands and adjacent uplands. In dry years, peatlands supply adjacent uplands with water, and in wet years, peatlands are recharged by these uplands (Ferone and Devito, 2004). Furthermore, in some upland-peatland systems when the water table is continually lower in the uplands, these upland landforms act as a hydrological sink relative to the peatland, and these peatlands are still capable of maintaining sufficient wetness levels (Thompson et al., 2015). Autogenic feedbacks are present within peatlands to further maintain wetness levels, and are typically controlled by soil properties and vegetation (Devito and Mendoza, 2007; Kettridge and Waddington, 2014; Waddington et al., 2015). These complex mechanisms to maintain moisture include peat subsidence (the shrinkage of pores causes increase in matric potential; Petrone et al., 2008; Price et al., 2003; Waddington et al., 2010), a decrease in hydraulic conductivity as a peatland dries (Price, 2003), and seasonal ice lenses present in the landscape, restricting evapotranspiration (ET) and reducing water loss (Brown et al., 2010; Petrone et al., 2008). It is imperative to understand these mechanisms and linkages in both natural and constructed systems to predict potential successional stages and outcomes of constructed systems. Constructed landscapes will need to be integrated into the WBP, and sustainability of these systems is supported by these interactions with adjacent landscape units to ensure wetness of the systems are maintained. Hydrological interactions between natural peatlands and surrounding areas have been studied (Devito et al., 2005a; Ferone and Devito, 2004; Petrone et al., 2007; Wells and Price, 2015; Wood et al., 2015), but more research must be done on constructed wetlands to determine these interactions in constructed landscapes and to better understand the connectivity between peatlands and adjacent uplands within the post-mined landscape.

Reclamation of wetlands in the WBP faces many challenges, one of which is the influence of the sub-humid climate and the large annual and decadal climate variability (Devito et al., 2012). In this setting, precipitation (P) is often less than ET (Devito et al., 2005a; Ferone and Devito, 2004) and historically, the majority of precipitation occurs in the summer months (Devito et al., 2005a) when potential evapotranspiration (PET) is greatest (Brown et al., 2014; Petrone et al., 2007). This synchronization of maximum P and PET result in little rainfall contributing to runoff, as soil water storage acts as a buffer (Devito et al., 2005a). The sub-humid climate, coupled with the heterogeneous glacial deposits of the region, results in a complex relationship that governs the redistribution of water (Devito et al., 2005a, 2012; Smerdon et al., 2005). Varying soil water storage of the heterogeneous glacial deposits and the connectivity of these geologic units plays a larger role towards water storage capacity than does topography in this region (Devito et al., 2005b, 2012). In addition to the limited water input to the system, elevated salinity levels provide an added challenge within the reclaimed landscape (Purdy et al., 2005; Trites and Bayley, 2009; Wells and Price, 2015). The mined oil sand formation is overlain by the shale and siltstone of the Clearwater formation, which is of marine origin (Hackbarth and Nastasa, 1979). As this formation is removed to reach the oil sand, salts present in this formation can come in contact with the reclamation material (Kessler et al., 2010). The addition of caustic hot water and gypsum ($CaSO_4$) to sand tailings, which is then used in reclamation efforts, can exacerbate salinization concerns (Chalaturnyk et al., 2002; Kessler et al., 2010). Kessler et al. (2010) suggest that diffusion has been the main mechanism driving salt upward from these underlying tailings into placed soil cover materials. The presence of excessive salts in reclamation materials increase ion concentrations and conductivity, posing a potential threat to vegetation (Trites and Bayley, 2009; Vitt and Chee, 1990), particularly species typical of 'freshwater' peatlands in the region (Wells and Price, 2015). Understanding the influence of both of these challenges during the design and construction phases of reclamation is key, as well as observing how they influence the development of the system.

Peatlands are hydrologically more complex than mineral wetlands and therefore are considered more difficult to construct (Price et al., 2003). These complex systems take thousands of years to develop naturally (Clymo, 1983), and fen reclamation attempts in the WBP are intended to speed up this process, skipping initial successional stages (Nwaishi et al., 2015). By designing a landscape in a hydrogeologically favourable setting that can sustain required wetness for fen vegetation and stable hydrologic conditions (BGC, 2015; Nwaishi et al., 2015; Price and Whitehead, 2001; Price et al., 2010), coupled with restoration techniques to establish fen vegetation, fen creation may be possible (Price et al., 2010; Quinty and Rochefort, 2003). In addition, understanding the hydrologic function within a constructed site, as well as how it is integrated into the landscape is required (Ketcheson et al., 2016). While the transfer of donor peat to reclaimed sites will speed up the initiation of peat accumulation processes, it is still unknown as to if the transported peat can sustain the typical ecohydrological functions necessary (Nwaishi et al., 2015). Nwaishi et al. (2015) discusses how in oil sands reclaimed wetlands the end point is relatively unknown, as the successional stages are unclear and can lead to the emergence of new ecosystems. Furthermore, these reclaimed systems may evolve into a hybrid system, defined as a system that is "functionally similar but structurally different…from natural analogues" or a novel system, which differs from natural systems both functionally and structurally (Nwaishi et al., 2015). Construction of these systems causes them to begin at some "non-initial" state, and thus the successional paths they take may lead to these novel systems. Understanding successional pathways and key functional processes in natural systems provides a foundation upon which to identify important ecosystem interactions and specific, quantifiable ecosystem targets of reclaimed sites, shifting the focus to evaluating oil-sands reclamation attempts based on functionality of the system (Nwaishi et al., 2015).

Many metrics can be used to monitor the condition of reclaimed systems, such as above and belowground biomass accumulation, organic matter quality (e.g. C:N ratio), and microbial activity and mineralization rates (Nwaishi et al., 2015). As hydrologic processes govern many biological and ecological functions of wetlands, including spatial distribution of vegetation (Vitt et al., 2016), nutrient dynamics (Wood et al., 2015), and atmosphere-carbon exchange (Waddington and Roulet, 1996), some believe hydrologic processes to be the most important processes of wetlands (Mitsch and Gosselink, 2000). As such, hydrologic metrics, such as WTD, can be used to infer the evolution of biogeochemical and ecological processes occurring within this landscape (Waddington et al., 2015). WTD in both natural and constructed sites within the WBP have been reported (Ketcheson, 2015; Nicholls et al., 2016; Wood et al., 2015) but a more detailed understanding of the water table dynamics at constructed wetland sites is required as these systems develop, helping to fully understand the hydrologic processes evolving and the associated effects on the system.

Syncrude Canada LTD. (SCL) and Suncor Energy have recently begun attempts towards wetland reclamation in the oil-sands. Both have created field-scale projects varying considerably in design and construction, to benchmark these systems as the first two attempts in the WBP. SCL constructed the Sandhill Fen Watershed (SFW), whose design is based off of analogue wetlands in the area (Devito et al., 2012). Suncor Energy's Nikanotee fen was designed from Price et al.

(2010), using a numerical modelling approach to determine the upland/wetland ratio to sustain required moisture for wetland conditions. Both groundwater supply from the upland aquifer and snowmelt runoff from surrounding slopes provide flow to sustain hydrologic functions within the system (Ketcheson and Price, 2016a; Nwaishi et al., 2016). These systems are designed to provide appropriate conditions for fen establishment and development, however, lack of precedent of these type of systems leads to much uncertainty as to the "finished product," and require careful planning of the design and construction.

The aim of this study is to understand the evolution of flow pathways and hydrological gradients within a constructed fen in the oil sands region of Northern Alberta by evaluating temporal spatial patterns of water tables over a two-year period. Evaluation of these patterns can support conceptual models that uplands will begin to supply lowlands with water, and that water tables can be maintained near the surface in the wetland system. The objectives of this thesis are to: 1) examine trends in water table position to understand the dynamics of the developing lateral gradients and 2) observe system response to large precipitation events and pump management strategies. These findings will help understand hydrologic functions within SFW, learning how this system develops, and how to successfully integrate it into the large-scale mine closure plans.

CHAPTER 2: Site Description and Methodology

2.1 The Sandhill Fen- location and design

This study was conducted in SCL's first constructed watershed: the Sandhill Fen Watershed. SFW was constructed as an instrumented system with the intent of developing operational techniques to further guide wetland reclamation at Syncrude. It is located in the WBP region of Alberta, and is ~45 km north of Fort McMurray (57°02′N, 111° 35′W). This region is characterized as sub-humid and experiences cold winters and warm summers. The average (1981-2010) annual air temperature is 1 °C, ranging from -22.5 °C (January) to 23.7 °C (July). Average annual precipitation is 418 mm, of which 76% falls as rain (Environment Canada, 2016). SFW was constructed in the northwestern corner of East-In Pit, a post mined site that was active from 1977-1999. The watershed is built atop 35 m inter-bedded composite tailings (CT; non-segregating tailings slurry of tailings sands and fine tailings with gypsum) overlain by 10 m of a hydraulically placed tailings sand cap, 0.5 m clay (acting as a liner), and 0.5 m of peat as the organic soil layer. SFW is 52 ha in size, approximately 1000 m long and 500 m wide. The landscape is composed of uplands, hummocks, vegetated swales, a freshwater storage pond (WSP), outlet pond, woody berms, an underdrain system, and a fen lowland. The uplands and fen comprise 35 and 17 ha, respectively (Figure 2.1; BGC, 2015; Wytrykush et al., 2012)

2.1.1 Inflows and outflows

Inputs to the system are from the WSP in the west, where water is pumped in from nearby Mildred Lake and stored in the clay-lined pond, where it is slowly diffused through a gravel berm to the lowland. Surface and near-surface water flows through the lowland portion of SFW, collecting in the outlet pond before flowing into a spill box and weir in the weir building on the east most portion of SFW. Underdrains were installed and consist of perforated 8-in high density polyethylene pipes covered with a fine-screen geotextile cloth and installed at a depth of 1-3 m below the ground surface. Underdrains were installed with the intent of creating a downward hydraulic gradient to minimize risk of elevated salinity levels, and to collect any upward movement of groundwater and transport it out of the system. Surface and near-surface water flow through the outlet pond and into the sump, where it mixes with underdrain contributions before it is discharged approximately 1 km south of SFW (Figure 2.2). Both in and outflow of the system are manually controlled, and thus the system has the potential to be highly managed. As initial modelling results indicate that the upland areas will be able to sustain lowland fen conditions, pump management is more geared towards saturating the peat and managing salinity levels in the fen for the first couple of years following commissioning of the system, not as a long-term management strategy (Wytrykush et al., 2012).

2.1.2 Construction materials and vegetation

SFW has 7 large sand hummocks constructed with the intent of supplying water to the lowland fen. Most are approximately 180 x 60 m, rising 3-4 m, with the exception of Hummock 7 that measures approximately 350 x 100 m and rises 8 m above the surrounding topography. Hummocks were mechanically placed and constructed so that the long-axis is parallel to the fen to allow for maximum contact to increase seepage, flushing of salts, and promote upland tree species growth (Wytrykush et al., 2012). These hummocks were then covered with a layer of Pleistocene fluvial sand soil, followed by harvested litter, fibric and humic material (LFH). In the lowland fen, 0.5 m fine-grained clay till was placed to reduce the effects of upward diffusion of salts from the underlying CT. This clay till was then covered with 0.5 m peatland material, acting as the organic soil layer, retrieved from a treed, poor fen north of SCL. Seeding of vegetation took place in the winter of 2011. The planted species in the fen lowland included bog birch (*Betula glanulosa*), many sedge species (*Carex aquatilis, C. diandra, C. paupercula, C. utriculata*), arrow grasses (*Triglochin maritima, T. palustre*) slough grass (*Beckmannia szyigachne*) and rushes (*Scripus lacustris, S. cyperinus*). Upland vegetation included a combination of tree species: trembling aspen (*Populus tremuloides*), jack pine (*Pinus banksiana*) and white spruce (*Picea glauca*), and shrubs: low-bush cranberry (*Viburnum edule*), dogwood (*Cornus stolonifera*), buffaloberry (*Sheperdia canadensis*), green alder (*Alnus crispa*), blueberry (*Vaccinium myrtilloides*), and bearberry (*Arctostaphylos uva-ursi*). Species development and dominance over the initial years is available in Vitt et al., (2016).

2.2 Methodology

The study period spanned May- October 2014 and 2015. Rainfall was measured at three meteorological stations within SFW (stations 1-3, located near the outlet on hummock 6, between the perched fens, and atop hummock 7, respectively; Figure 2.3). Each station was equipped with a tipping bucket rain-gauge (Model CS700, Campbell Scientific Inc., Logan, UT, USA (CSI)) and CR1000 data loggers recorded hourly data (CSI). Daily totals were obtained as an average of the three stations.

Inflow and outflow were measured using Model AT868 AquaTrans Ultrasonic Flow Transmitters for water (General Electric, Fairfield, CT, USA). Water level in the water storage pond was also measured by a transducer (Rosemount Inc., Chanhassen, MN, USA). Outflow water can consist of both surface and near surface groundwater flow, with groundwater flow collected in the underdrains. However, as these underdrains were closed in 2014, contributions were negligible during the study period. Surface and near-surface water entered through the outlet pond and into the weir building where it flowed over a v-notch weir, instrumented with a sensor continuously recording water level.

Water table dynamics were measured with a network of 27 surveyed near-surface wells located over the 52-ha area. Wells were 1.6 m polyvinyl chloride slotted wells, hand-augered to a depth of -0.25 to -1.15 m, instrumented with Solinst Levelogger Junior Edge transducers (Model 3001) and Solinst LTC (level, temperature, conductivity) Levelogger Junior transducers that recorded at 15-minute intervals. These level readings were then corrected for atmospheric pressure with the use of a Solinst Barologger located in SFW. Well locations spanned the lowland/wetland transect, upland areas, and margin (transition) zones in between uplands and wetlands, and are named accordingly: the prefix 'B' denotes a boardwalk, 'TR' denotes an upland-wetland margin, and 'UP' denotes the upland area (Figure 2.3). Levelogger readings were compared with weekly manual measurements obtained using a Solinst Water Level Meter to ensure correctness. Average water table was determined by calculating the average at each individual well, and then averaging these values once again based on well location (i.e., lowland wells or margin wells).

Saturation maps were provided by Dr. Carl Mendoza at the University of Alberta. Data for surface wetness maps were collected by following a well-defined grid and GPS unit to cover all of SFW using the "squishy boot method" and visual observations to classify areas of saturated ground and standing water (Longval and Mendoza, 2014).

16 soil samples were collected using hollow plastic tubes (4.7 cm diameter x 4.9 cm height) driven into the ground at the desired soil depth, ensuring samples remained intact. Samples were wrapped in polyethylene film and carefully transported back to the lab at McMaster University. Polyethylene film was removed and the bottom of each sample covered with a screening material to prevent loss of sample during analysis. Samples were analyzed for specific yield (Sy), bulk density (ρ_b), porosity (ϕ), and percent organic matter following standard methods (Freeze and Cherry, 1979; Klute, 1986), with the exception that samples were oven dried at 80 °C.

CHAPTER 3: Results

3.1 Climate

Air temperature at the site was slightly warmer than climate normals for the region and precipitation values varied from the climate normal for both years of this study. The total precipitation received during the 2014 and 2015 study periods (May-October) was 333 and 238 mm, respectively. 2014 and 2015 received 111% and 80% of the long-term (30-yr) climate normal of 299 mm (Environment Canada, 2016) for May-Oct for the Fort McMurray airport, approximately 45 km S of SFW. In 2014, 34% of the precipitation was received in May, with fairly consistent rain throughout the rest of the season (Figure 3.1). Two large storm events in 2015 resulted in 58% of the precipitation falling during the months of July (35%; 19 mm and 20 mm on 12 July and 16, respectively) and September (23%; 27 mm and 21 mm on 1 and 3 September, respectively). Mean daily air temperatures on the SFW (May-October) were 13.6 °C and 14.0 °C for 2014 and 2015, respectively (Table 3.1, Figure 3.1). Both 2014 and 2015 were warmer than growing season climate normals by 2.1 and 2.5 °C.

3.2 Pump Management: Inflows and Outflows

Management of pumps differed between the study seasons. In 2014, inflow pumps were turned on for two 1-hr events as well as one longer occasion on 19-20 May, pumping for approximately 6 hours at a maximum capacity of 260 m^3/hour, equating to a total of 14 mm of water input into the lowland (17 ha) system for the season. Inflow pumps remained off for all of 2015. Management of outflow pumps also differed between the study seasons. The majority of outflow from the system was surface water collected through the outlet pump as the valve connecting the underdrains to the sump pump was closed at the beginning of the 2014 field season. 2014 was characterized by 5 pumping events ranging from 1-4 hours in length. The shorter, one-hour events occurred on 20 May and 3 July, and the four-hour events on 3-4 June and 6 July. From May-October, a total of 3095 m^3 was pumped out of SFW, equivalent to 18 mm over the 17 ha lowland area. In contrast, there were only two 1-hour pump events in 2015, with one main pumping event (56 consecutive hours) on 3 June. This pumping event removed approximately 9334 m^3 of water from the SFW, which equated to 55 mm (Figure 3.2).

3.3 Water table dynamics

The water table levels in both 2014 and 2015 rose rapidly following snowmelt and spring rain events, with subsequent declines due to evaporative losses (Figure 3.3). The highest water table levels were observed near the start of the growing season during both 2014 and 2015, with a drying trend apparent throughout the summer months (Figure 3.3). Within this general trend, differences can be observed between study years. At the start of the 2015 growing season, the water table position was higher at all locations than the start of the 2014 growing season, despite a drier spring and less snow. Water table levels peaked 1-2 weeks earlier in 2015 than 2014, with 2015 maximums exceeding those in 2014 by 0.22 m at the outlet (B3-W4) and similar maximums at the inlet (B1-W2). Water table minima were generally lower in 2015 than 2014, as driven by the lower precipitation and a larger water removal via pumping. Lower water table depths were observed in the lowland transect in 2015, ranging from 0.26 m lower at the inlet and 0.08 m lower at the outlet than in 2014. WTD along the lowland transect ranged from -0.2 m to 0.4 m in 2014 and -0.4 m to 0.5 m in 2015. Figure 3.4 shows the difference in seasonal water table changes over the 2014 and 2015 study seasons, with the change more pronounced in the west (inlet) than the east (outlet). In the mid-fen (B3-W1) WTD was maintained above the peat surface 100% and 96% of the time in 2014 and 2015, respectively, with means of 0.08 m (2014) and 0.07 m (2015). At the outlet (B3-W4) WTD was above the surface 17% of the time in 2014, 20% of the time in 2015, and was above -0.3 m 100% of the time in both years. The west fen (B1-W2) had a WTD above ground 94% of the time in 2014, while in 2015 this dropped to 69% (Figure 3.5).

WTD in the marginal areas followed similar trends; higher levels were observed near the start of the growing season, decreasing throughout the summer months (Figure 3.6). In 2014 a lateral gradient was established for the majority of the summer months, with flow directed towards the lowland, while in 2015 this lateral gradient was established towards the end of the summer. Water table levels in margin areas were more closely coupled, with paired wells (one in the toe of the hummock and one further towards the lowland) having similar responses to precipitation events and subsequent decline in water table as the summer progressed. Maximum water table heights peaked 2 weeks earlier in 2015 and were 12 cm higher at both TR-W8 and TR-W9. Water table minima in 2015 occurred 4 days later than 2014, and were 2 cm lower and 3 cm higher at TR-W8 and TR-W9, respectively (Figure 3.6).

3.3.1 Heads, Flow direction, and Flow Reversals

The general large-scale, deep groundwater movement was from the South swale north towards the SFW lowland and east towards another reclaimed wetland currently under construction (Figure 3.7). Although the deeper groundwater did not respond strongly to climate variations, the shallow water table dynamics within SFW exhibited high frequency fluctuations.

At the beginning of the 2015 season, the near-surface groundwater flow was typically from the inlet (B1; west) towards the outlet (B3; east; Figure 3.3, Figure 3.8). However, as drying progressed over the summer, a gradient reversal occurred in August. These reversals in gradient can then induce a flow reversal, and will therefore be referred to as flow reversals for this thesis. During this period of reversal, the horizontal gradient was from the outlet (B3; east) towards the inlet (B1; west; Figure 3.8). This flow reversal was temporarily eliminated following a large rainfall event at the beginning of September (48 mm over ~45 hours), with the horizontal water table gradient from B1 (west) towards B3 (east). However, the subsequent decline in water table position produced an additional flow reversal (Figure 3.8). Flow reversals were also observed in 2014, but these were generally weaker and did not last as long. In 2014, flow was reversed for 12 days, reaching a minimum gradient of -0.0004, between B1-W2 and B3-W1. Flow was reversed for a total of 52 days, reaching a minimum gradient of -0.001 in 2015.

Flow reversals were also observed between the hummocks and the lowlands, with upland-lowland lateral gradients changing as the season progressed (Figure 3.9). In 2014, the lateral gradient between the mid-fen (B3-W1) and north hummock (TR-W8) indicated that flow was more directed into the hummock compared to 2015, which was more dynamic and had more frequent flow reversals. Rainfall events throughout the summer caused a rise in water table levels, and differing hydrophysical properties of the construction materials between the upland/hummock areas and the lowland resulted in differences in the magnitude of the water table responses. Responses to rainfall events were greater in the hummocks, with the larger increase in water table elevation resulting in a lateral gradient to be established between the hummock and fen lowland and a corresponding flux of near-surface water movement towards the lowland (Figure 3.9). The subsequent decrease in water table caused a corresponding decrease in gradient. Flow was directed towards the lowland for 99 days in 2015, reaching a maximum gradient of 0.0024 between B3-W1 and TR-W8, while in 2014 a maximum gradient of 0.0016 was observed, and flow was towards the lowland for only 57 days. The large rainfall event (39 mm) in July caused a relatively strong lateral gradient to develop, reaching a maximum value of 0.0014 (between B3-W1 and TR-W8). The subsequent decline in water table over the next month caused the gradient to reverse (-0.0006) with flow toward the hummock. The larger rainfall event in September (48 mm) caused a stronger gradient to develop (0.0024), with flow remaining from the hummock towards the lowland until instrumentation was removed for the season (14 Oct 2015).

Paired wells (TR-W8/TR-W9 and TR-W10/TR-W11) were installed at the base of hummocks to evaluate flow patterns between the upland and lowland (Figure 3.10). TR-W8 and TR-W10 are located at the base of Hummocks 5 and 6, respectively, with TR-W9 and TR-W11 located further into the lowland (Figure 2.3). Flow was from the upland well (TR-W8) towards TR-W9 for 140 and 132 days in 2014 and 2015, respectively, with maximum gradients of 0.009 and 0.007 between TR-W8 and TR-W9, indicating a stronger potential of flow toward the lowland in 2014 (Figure 3.10).

3.3.2 Event-based analysis

3.3.2.1 Precipitation Events

The water table responded more strongly to precipitation events at locations where it resided within the peat layer, with a more rapid and greater water table rise than areas of standing water (Figure 3.11, Figure 3.12). For example, the water table responded weakly to two large precipitation events (19 mm and 20 mm on 12 July and 16 July 2015, respectively) in the mid-fen region where standing water was present and the average WTD was 0.09 m above the ground surface, increasing in elevation only slightly. In contrast, the water table within the margin along the perimeter of the fen lowland, with an average water table of -0.38 m below ground, exhibited strong responses, with an average rise of 0.17 m compared to only 0.05 cm in the lowland portion of the watershed. Saturation maps indicated that there was an 8.6% increase in area of saturated ground after this rainfall event (Figure 3.13).

A second large precipitation event occurred in September (27 mm and 21 mm on 1 and 3 September 2015, respectively). The water table response to this event was much larger than that observed in July (Figure 3.11). Average antecedent water table position was -0.18 m and -0.57 m in the lowland portion of the fen and margin areas, respectively, with water table within the margins rising by an average of 0.34 m and 0.24 m in the lowland portion of the watershed. Sudden responses were observed in margin wells with no standing water (TR-W8, TR-W7, TR-W5) as well as lowland transect wells with no standing water (B3-W4 and B1-W2) while B3-W1, where standing water was present, did not exhibit a strong response. There was a 13% increase in the proportion of wells with standing water (increase from 1 well with standing water to 4 of the 27 total wells), after this rainfall event whereas there was no change in number of wells with standing water surrounding the July rainfall. Sudden responses were observed at B2-W3 following precipitation events for both 2014 and 2015, as this well is located in a sand island.

3.3.2.2 Pump events

Following snowmelt and spring precipitation events, maximum water table elevations were observed in May 2015. WT response to the pumping event on 2-5 June (55 mm water removed normalized to the lowland area) occurred first at the wells closest to the outlet (B3-W4) and was closely followed by a decrease in water table position at B3-W1 and B2-W7, which are located slightly further from the outlet (Figure 3.14). B1-W2 (near the inlet) experienced a slower and more gradual decrease in water table level. With the exception of TR-W9, which is located very close to the outlet and had standing water present at the start of the pump event, margin wells along the edge of the lowland all exhibited a slightly delayed decrease in water table position relative to the lowland wells. Overall, of the 27 near-surface wells, there was a 4% decrease in the proportion of wells with standing water after this pumping event. Saturation maps revealed that there was a 12.3% decrease in standing water present after the pump event and an 8.1% decrease in saturated ground in the lowland fen (Figure 3.15, Figure 3.16).

3.4 Peat physical properties

Soil cores were collected and bulk density, porosity, specific yield (Sy) and organic matter content were evaluated (Table 3.2). With the exception of the hummock-wetland interface, there are no trends with depth in any of the properties. At this interface, bulk density decreases with depth and organic matter content and porosity increase with depth. Average (±standard deviation) bulk density, porosity and Sy within SFW is 0.276 (±0.038), 0.810 (±0.26), and 0.140 (±0.023), respectively. Average organic matter content is 52.9% (±8.009).

CHAPTER 4: Discussion

Oil sands mining severely disturbs the landscape, removing large tracts of Boreal ecosystems, including wetlands. These wetlands comprise a significant portion of the WBP (Vitt et al., 1996), making reclamation of these systems imperative. Due to the sub-humid climate of the region, wetlands in the WBP have complex hydrologic mechanisms and autogenic feedbacks to maintain wetness levels. Hydrology is key in regulating many biogeochemical and ecological functions in wetlands (Vitt et al., 2016; Wood et al., 2015) and establishing overall ecosystem function. When reclaimed wetlands have a water table within an expected range of natural sites in the region, ideal conditions (i.e., nutrient / moisture levels) for vegetation growth and other biogeochemical processes are more likely and can aid in gauging likely successional pathways of these systems (Nwaishi et al., 2015; Wood et al., 2015). Understanding these processes in constructed systems is essential to optimize the design and construction of future reclaimed wetland systems. Evaluating near-surface water table trends will help understand developing hydrologic processes of the system and the concomitant influences on the system and place SFW in the context of the overall mine closure plan, integrating it as part of a large scale reclaimed landscape and providing insight into the overall sustainability of the system.

4.1 Sustainability of the Sandhill Fen Watershed

In the WBP, there are hydrologic connections between landscape units, such as peatlands and uplands (Devito et al., 2005b, 2012; Ferone and Devito, 2004; Price et al., 2005), and these relationships are critical as they influence the wetness or dryness of the landscape, impacting the "eco-hydrologic functionality" of the system (Devito et al., 2012). In wet years, peatlands typically receive recharge from adjacent uplands, while during dry periods the peatlands can provide water to the adjacent uplands (Devito et al., 2005b, 2012; Ferone and Devito, 2004). While the SFW is still in the early stages post-construction, patterns of wetting appear to be occurring at the hummock-lowland transition in 2014 and 2015. Lateral gradients are towards the lowland 40% of the time in 2014 and 65% of the time in 2015, despite a drier year overall (Figure 3.9). Although the data is limited and the gradients small, the rise in WTD in the hummocks (Figure 3.6) and increasing lateral hydraulic gradients (Figure 3.9) suggests that these landforms are beginning to develop saturated zones and supply groundwater flow to the lowland, as per their design. However, Thompson et al., (2015) indicate that peatlands in the WBP do not require significant inputs from regional groundwater or adjacent uplands to exist. This suggests the potential for SFW to maintain wetness levels in the absence of significant inputs from the hummocks.

Flow reversals between uplands, ponds, and peatlands are reported within the WBP (Ferone and Devito, 2004; Thompson et al., 2015) and throughout the Canadian Shield (Devito et al., 1997). At an analogue site located in the Utikima Research Study Area (URSA), frequent reversals occurred during wet periods, with longer lasting reversals occurring during dry periods (Thompson et al., 2015). Similarly, flow reversals developed in SFW following changes in WTD. Short, frequent reversals between the hummock and lowland followed precipitation events, with flow towards the lowland following a greater increase in WTD in the hummock (Figure 3.9). Longer-term reversals were present along the lowland transect during the dry period at the end of summer. When this reversal was present, flow was from the outlet (west) towards the inlet (east; Figure 3.8). Devito et al. (1997) state that a connection with regional groundwater flow is not required to induce a flow reversal, and that reversals may occur more regularly when there is a lack of connection at the regional scale. These reversals are a key hydrologic mechanism of peatland complexes in the WBP. The connection of these landscapes ensures that water is redistributed among landscape units for the respective areas; in the case of wetlands, allowing them to sustain required wetness levels in the sub-humid climate, mimicking levels found in natural analogues of the region (0.1 m to -0.4 m). When there is a lack of connection with regional groundwater flows, or relatively small inputs, these reversals are even more essential, as these hydrologic mechanisms are what maintain wetness levels in the absence of groundwater inputs.

The lateral movement of water associated with flow reversals has implications for biogeochemical and ecological functions of the system, for example, the lateral movement of water and associated salinity can act as a mechanism to flush the system (Wells and Price, 2015) and influence vegetation types and spatial patterns (House et al., 2014; Vitt et al., 2016). These large-scale flow reversals associated with precipitation (or lack thereof) are shown to have a larger influence on electrical conductivity (EC) of near-surface water than the sole influence of precipitation inputs. Following these flow reversals, EC levels are observed to change by ~1000 μs/cm along the lowland fen transect (Figure 3.17, Figure 3.18). This suggests that flow reversals in response to dry periods exert greater control on EC changes within the lowland than large precipitation events, however more research is necessary to fully understand these changes in EC.

4.2 Water table dynamics

Precipitation received during the 2014 and 2015 study periods (May- Oct) was 111% and 80% of the seasonal climate normal, respectively. While natural peatlands of the area have a general range of 0.1 m to -0.4 m, -0.4 to -0.6 m, and approximately -1.0 m for fens, non-permafrost and permafrost bogs, respectively (Vitt et al., 2000), WTD in SFW was slightly higher than expected in comparison to natural fens of the region (Vitt et al., 2000; Wood et al., 2015), despite the difference in rainfall and pump management practices between the study seasons. WTD over the lowland transect in SFW ranged from 0.4 m to -0.2 m in 2014 and 0.5 m to -0.4 m in 2015, with annual average WTD of 0.08 m and 0.07 m for 2014 and 2015, respectively (Figure 3.6). As a comparison, WTD in the constructed Nikanotee fen was typically within ± 0.1 m of the fen surface in 2014 for 62% of the season (Ketcheson, 2015; Nwaishi et al., 2016). The higher WT in SFW could be due to the absence of an outlet from the system, which prevented runoff from the system and allowed the WT to continually rise. As SFW is a part of a larger mine-closure system, when it is integrated into the overall closure landscape, and becomes hydrologically connected to downstream ecosystems, the overall wetness of the system will inevitably change.

Decline in WTD was most pronounced in the west fen (B1; Figure 3.4), and as water table elevation decreased to approximately 313 masl, there was a hydrologic disconnection in the lowland fen between B1 and B2 (Figure 3.15, Figure 3.16). The area around B1 has considerably less upland contributing area than the rest of the lowland fen (Figure 2.3). In contrast, both B2 and B3 are bordered on all sides by upland/hummock areas. The lack of contributing area and the large decrease in WTD indicate that the west portion of the fen may over time develop as a relatively less wet lowland, or potentially as an upland area, if water tables drop during dry periods and tree species establish. Additionally, as upland vegetation develops with time, ET will increase, as was reported at nearby reclaimed site, South Bison Hill (Carey, 2008). This is especially important in the SFW, since Nicholls et al., (2016) found ET to be the largest natural loss of water in SFW, as is also the case in the constructed Nikanotee fen (Ketcheson, 2015). As ET increases, the water table will decrease, causing the system to be less wet and potentially exacerbating the hydrologic disconnection between east and west fens with time. It is important to understand the relation between vegetation development and hydrology of the system to understand how the west fen will develop compared to the east fen.

Water table responses to precipitation and pump events varied across SFW. Precipitation inputs were first observed at locations where the water table was residing in the peat layer, typically in the margin zone, responding with a sharp increase in WTD (Figure 3.11). Standing water was present in the fen lowland, to some extent, for a large portion of the study, and as such had a muted response in WTD to precipitation (Figure 3.12). Pumping events had an immediate response in the east fen, nearest the outflow pump (Figure 3.14). The large pump event in 2015 coupled with the lack of inflow pumping contributed to significant drying in the west fen (Figure 3.15, Figure 3.16), further suggesting the potential of the west fen to develop more similarly towards an upland area.

Vegetation studies at SFW and other boreal watersheds indicate that WTD is one of the most important environmental variables determining plant community composition within the system, followed by the influence of EC (Koropchak et al., 2012; Trites and Bayley, 2009; Vitt et al., 2016). In addition, water levels dictate if constructed systems will develop into fens, marshes or saline wetlands (Vitt et al., 2016). Within SFW, distinct vegetation zones are reported, each located in an area with a distinct WTD (Vitt et al., 2016). This further suggests that WTD is a key factor, not only for vegetation health, but also in determining vegetation species and spatial groupings (BGC, 2015; Vitt et al., 2016).

Fluctuations in WTD can cause changes in peat volume due to the compressibility of peat (Schlotzhauer and Price, 1999). These volume changes alter peat hydrophysical properties, such as bulk density, hydraulic conductivity and water retention capacity (Kennedy and Price, 2004; Price, 2003). Hydrophysical properties influence the transmission of water through soils and subsidence of the peat, a side effect of a changing water table, can alter these properties. The collapse of large pores (Chow et al., 1992) and corresponding shift in pore size distribution influences saturated hydraulic conductivity and water retention properties of the peat (Price, 2003; Schlotzhauer and Price, 1999). These changes are further seen in changes in water storage (Schlotzhauer and Price, 1999) and flow processes (Price, 2003). Characteristics, such as bulk density, saturated hydraulic conductivity and near-surface infiltration capacity, have been found to change following construction due to site specific conditions (Kelln et al., 2007; Ketcheson and Price, 2016b; Meiers et al., 2011) and Ketcheson and Price (2016) found a shift in hydrophysical properties of reclamation materials in the Nikanotee fen caused a shift in the hydrologic role of reclaimed slopes from a role of water transmission to water storage. However, there are large differences in organic soil characteristics based on soil salvage and reclamation practice, and it is difficult to generalize among sites. Mixing peat with mineral soils, salvage and placement practices, etc., all affect the hydrophysical properties and the implications of these changes for different hydrologic mechanisms and autogenic feedbacks (as discussed above) in constructed systems remains unclear.

Northern Canadian peatlands are expected to experience a greater water deficit and drying conditions with the warming climate (Rouse, 1998; Tarnocai, 2006; Waddington et al., 2015). Dry climates provide a challenging setting for the establishment of peatlands (Devito et al., 2012; Waddington et al., 1998), and as such SFW could be affected. Modelling of SFW under dry conditions predicts a decrease in standing water and saturated zones and reduced connectivity between uplands and lowlands (BGC, 2015). This decrease in surface saturation can lead to a shift in vegetation species. If water table drawdown is large, afforestation can pose a potential threat to wetland survival, which may cause further water table drawdown (Waddington et al., 2015) shifting SFW from a peatland ecosystem to more of a forested system. Constructed systems are still relatively new, making the overall response of SFW to a warming climate relatively unknown.

Sustainability of the system depends on the ability of the system design of SFW to provide the hydrological conditions necessary to support biogeochemical and ecologic functions of the system (i.e. providing sufficient moisture for vegetation growth). If sufficient moisture levels are maintained to support these functions, constructing systems with integrated landscape units, such as hummocks and lowlands, on sand-capped soft tailings could be successful.

4.3 Management

The current study provides a baseline understanding of the implications of management strategy of constructed systems. These strategies are key in success of these systems and for progressing the design and construction of future reclamation attempts in the AOSR. While pumps were installed with the intent of controlling elevated salinity levels from upward advection of the underlying tailings sand, they also have a large impact on water table dynamics, and changes in management practice have a direct influence on water table patterns, causing changes in lateral gradients and flow direction. 2014 was characterized by minimal artificial inputs to the system, 2015 was characterized by one large pump event, and both years exhibited a fairly high water table position, suggesting that there is potential for SFW to exist as a self-sustained system, supplying sufficient moisture to maintain wetland conditions in the lowland under fairly normal climatic conditions. Attention should be given to WTD and salinity levels following consecutive years of water deficit. In the absence of pumping, vertical fluxes dominated the water balance of SFW (Nicholls et al., 2016). However, without the addition of freshwater via inflow pumps, SFW is potentially at risk of elevated salinity levels, which is most detrimental on vegetation species and development. In addition, lack of inflow coupled with years of water deficit can lead to changes in the area considered to be the fen lowland.

CHAPTER 5: Summary and Conclusions

Oil sands mining in the AOSR drastically alters the landscape, removing all ecologic and hydrologic function and making reclamation of post-mined sites imperative. Natural peatland development takes thousands of years, but constructed systems are designed to reduce this time by accelerating the establishment of wetland processes by placement of peat substrate and vegetation. Sustainability of SFW is dependent on the system's ability to maintain sufficient moisture levels to maintain vegetation growth and development, carbon sequestration, and overall ecosystem function and development. This study analyzes water table patterns in one of the first constructed watershed-scale peatlands in the WBP. The aim of this research was to understand water table dynamics and the development of lateral gradients as well as observe system response to large precipitation inputs and pump events.

Key findings from this thesis are: 1) the beginning of upland-lowland hydrological exchanges, with uplands beginning to feed the lowlands, as per their design, 2) flow reversals observed along the lowland fen, laterally redistributing water from the inlet towards the outlet, and vice versa during reversals when the fen dries, and 3) drying in the west fen, with a hydrologic disconnection occurring between east and west fens during dry periods.

Pump management differed between study years, with 2014 and 2015 characterized by short pump events and one long pump event, respectively. WTD was maintained slightly higher than observed in analogue sites of the region following both management practices, suggesting that SFW should maintain a water table within an appropriate range in the absence of pumping, sustaining wetland conditions in a portion of the lowland fen area. A high water table, coupled with flow reversals mimicking those found in natural sites, suggest the potential for SFW in its current design to function as a self-sustained system without pump management. These flow reversals are present in natural peatland complexes of the WBP to maintain wetness and wetland conditions in the sub-humid climate, redistributing water in dry periods. Due to the lack of precedent of reclaimed wetlands, it is important for these constructed systems at the field-scale to be monitored to understand how they evolve and develop with time. Manipulation of pumps, and the subsequent change in WTD, can cause changes in peat hydrophysical properties and can potentially further lead to different hydrologic mechanisms and autogenic feedbacks than are observed in natural sites. Research and monitoring programmes will help with the understanding of interactions occurring within the system and to evaluate how they vary in response to climate variability and ecosystem development. In addition, SFW is part of SCL's mine closure plan, integrating a series of watersheds that have the necessary foundation to evolve into a mosaic of self-sustaining wetlands and upland boreal forest landforms (BGC, 2015). Construction of future reclamation sites in the adjacent areas will inevitably influence the hydrology of SFW, making continued monitoring necessary in the interim. Management strategies will also need to be altered following the reclamation of neighbouring sites and addition of a natural outlet, further integrating SFW into the overall mine closure plan. The research emerging from the SFW will provide a baseline for future reclamation attempts in the AOSR, and provides valuable insight for informing future reclamation strategies in similar (soft-tailings) settings.

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TABLES

Table 3.1. Monthly climate data at SFW for air temperature (Ta, averaged) and rainfall (mm, cumulative) from 2014-2015. Monthly climate normal (CN) data is reported by Environment Canada, 2016 (representative for 1981-2010) with standard deviations shown for air temperature.

Month	**Ta (°C)**			**Rainfall (mm)**		
	2014	**2015**	**CN**	**2014**	**2015**	**CN**
Apr	1.6	5.3	3.3 ± 2.3	4.81	4.47	11
May	9.1	12.2	9.9 ± 1.8	114.76	29.12	33.5
June	16.9	18.0	14.6 ± 1.0	41.10	34.44	73.3
July	20.9	18.8	17.1 ± 1.0	45.83	85.09	80.7
Aug	18.7	18.1	15.4 ± 1.8	33.84	26.73	57.1
Sept	10.5	10.4	9.5 ± 1.5	63.56	55.96	38.8
Oct	5.5	6.3	2.3 ± 1.9	33.51	6.64	15.6
Total	-	-	-	337.42	242.44	310

3.2. Organic soil hydrophysical properties. Samples are named based on location, depth, and number of samples collected at that depth.

Samples	**Bulk Density (g/cm^3)**	**Specific Yield (-)**	**Porosity (-)**	**% Organic Matter**
TRW8 0-5	0.352	0.144	0.757	44.075
TRW8 10-15	0.321	0.123	0.779	53.875
TRW8 20-25	0.254	0.145	0.825	60.694
TRW8 25-30	0.264	0.112	0.818	61.220
B3W4 0-5, 1	0.210	0.193	0.855	61.429
B3W4 0-5, 2	0.299	0.114	0.794	46.145
B3W4 5-10	0.253	0.149	0.825	62.850
B3W4 15-20, 1	0.277	0.138	0.809	51.493
B3W4 15-20, 2	0.256	0.125	0.823	53.778
Up 22-27, 1	0.244	0.170	0.832	53.320
Up 22-27, 2	0.298	0.137	0.795	36.819
Up 22-27, 3	0.277	0.132	0.809	48.678
AVG=	0.276	0.140	0.810	52.865
Std Dev	0.038	0.023	0.026	8.009

FIGURES

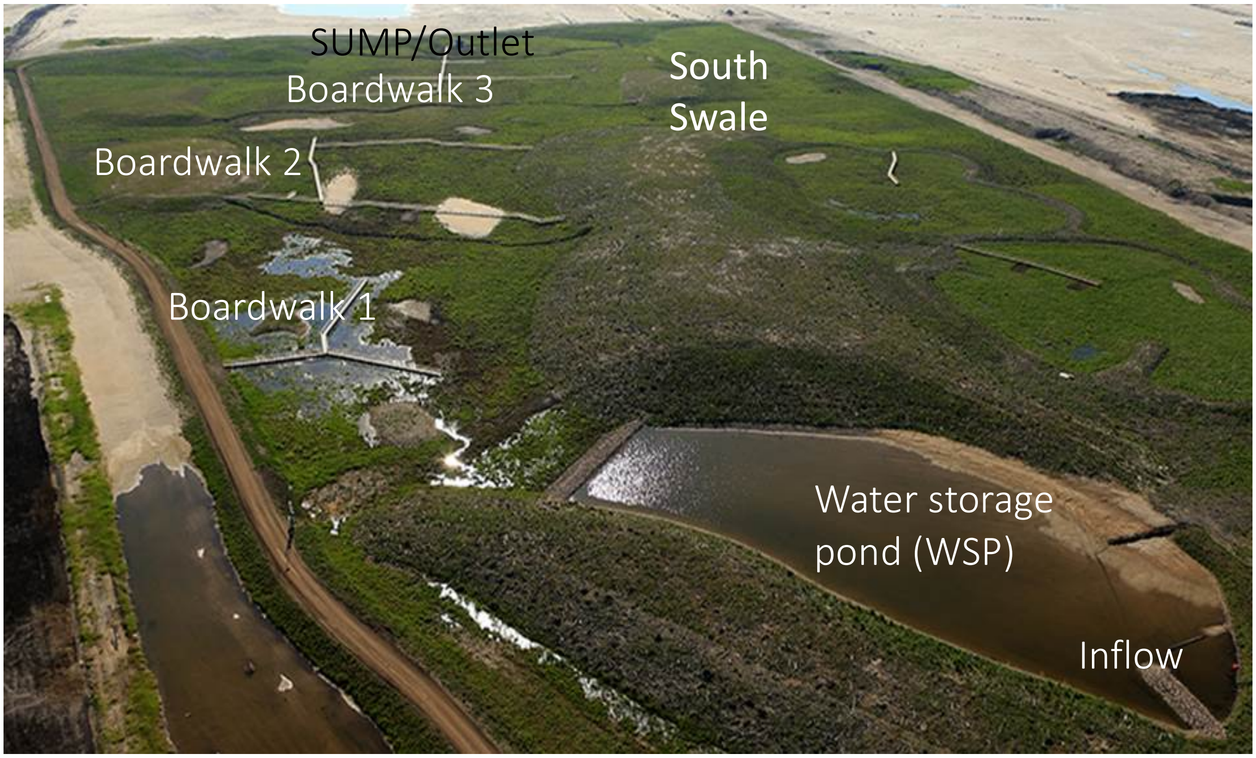


Figure 2.1 – Layout of SFW, including the water storage pond, boardwalks and outlet.

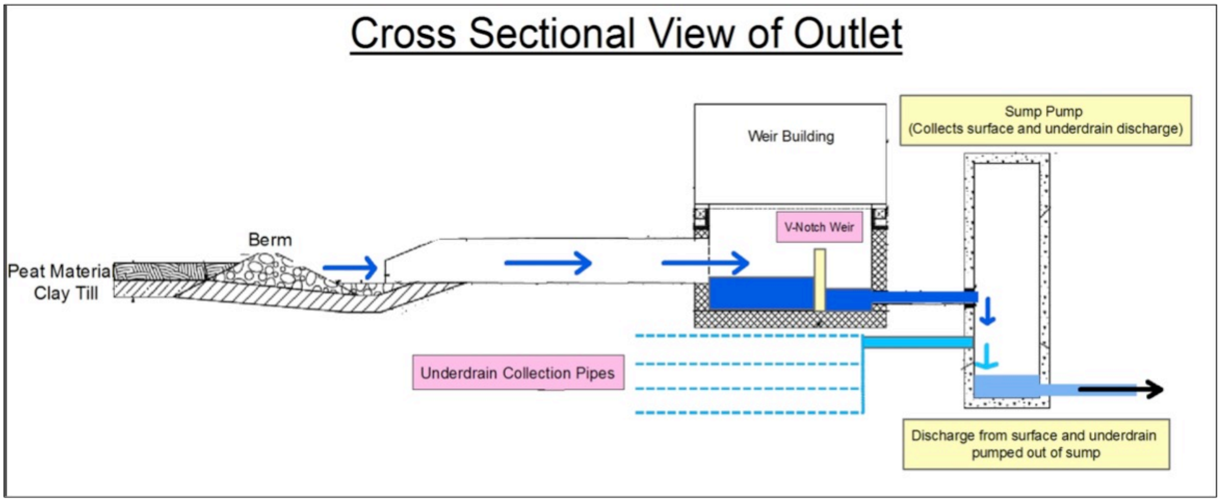


Figure 2.2 – Cross-sectional view of the outflow pump in SFW. Surface and near-surface water flows in from SFW, through the weir building, mixing with water from underdrains in the sump pump and is then discharged.

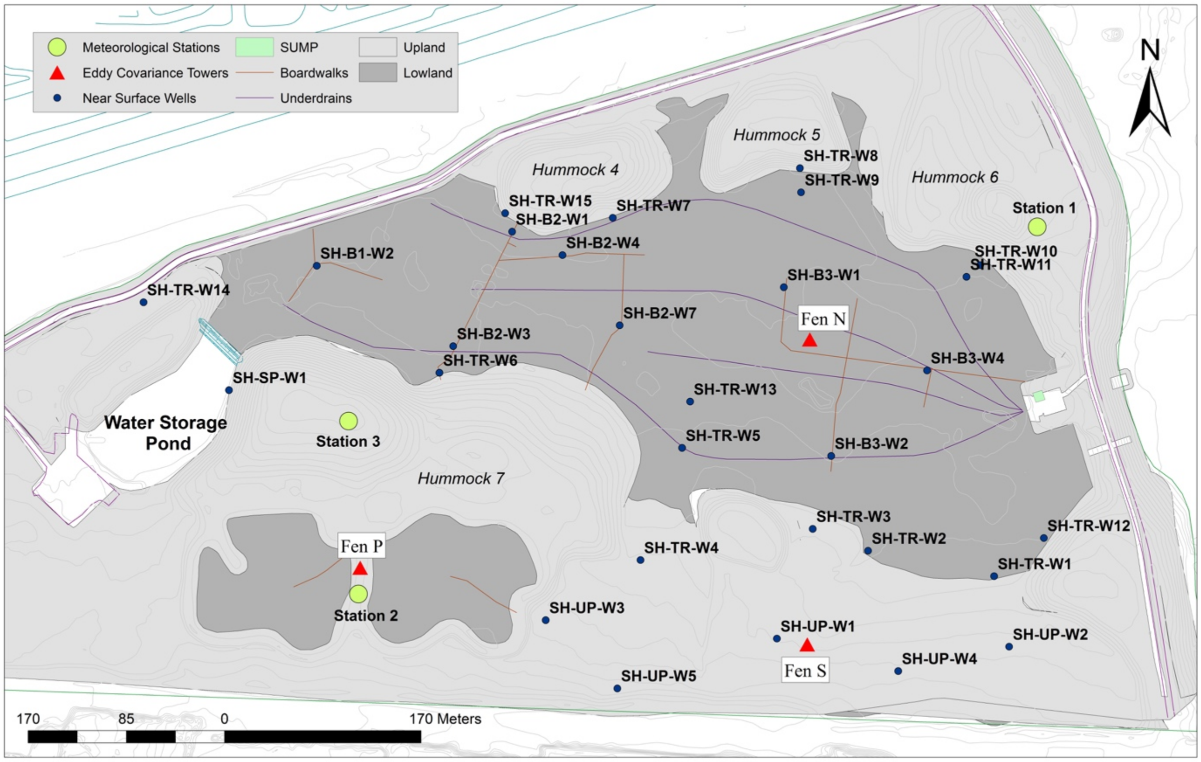


Figure 2.3 – Instrumentation of SFW including underdrains and near-surface well locations

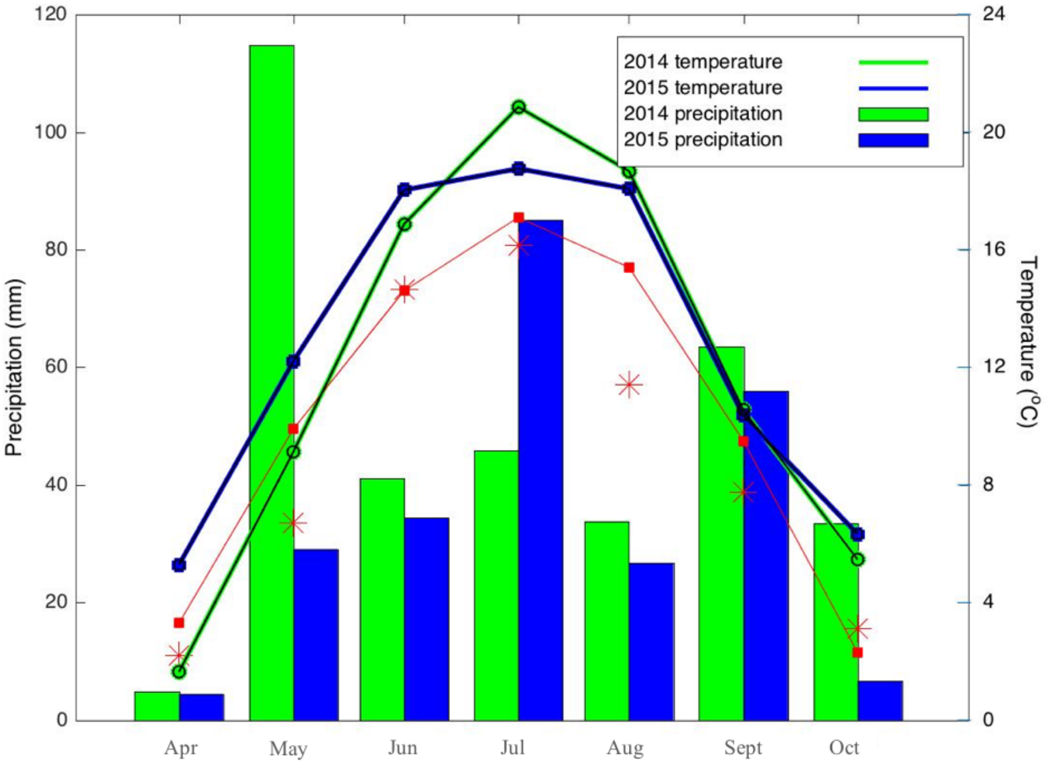


Figure 3.1 – Rainfall (bars) and air temperature (lines) for the 2014 and 2015 growing season at Sandhill Fen Watershed. Precipitation is the mean from 3 tipping buckets on SFW. Green and blue represent 2014 and 2015, respectively. The 30-year (1981-2010) climate normal data is represented by the red line showing air temperature and red stars showing precipitation.

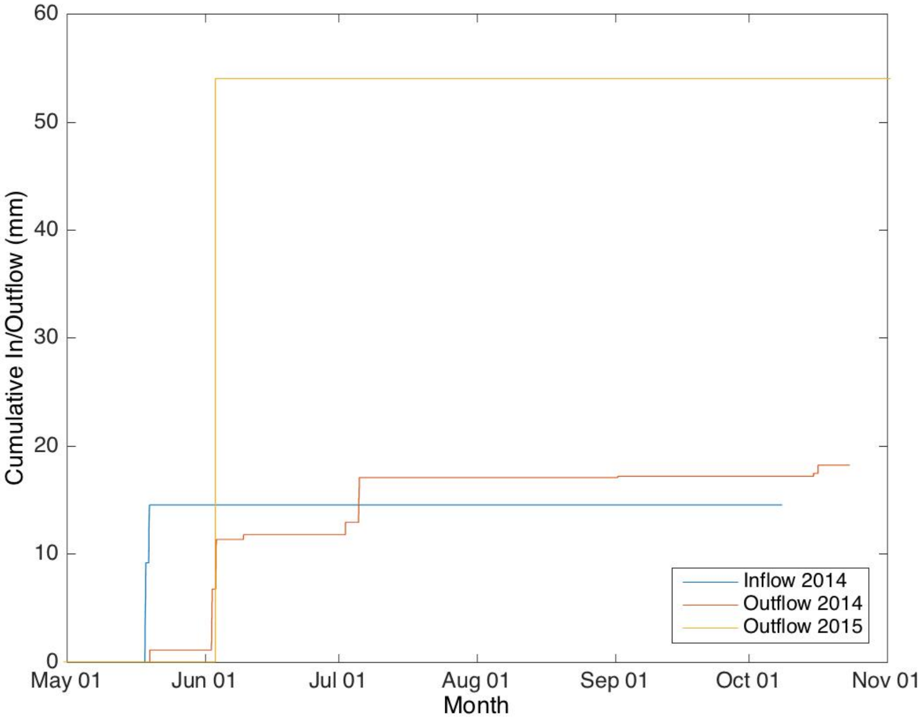


Figure 3.2 - Cumulative inflow and outflow (normalized to the 17 ha lowland) for the 2014 and 2015 seasons

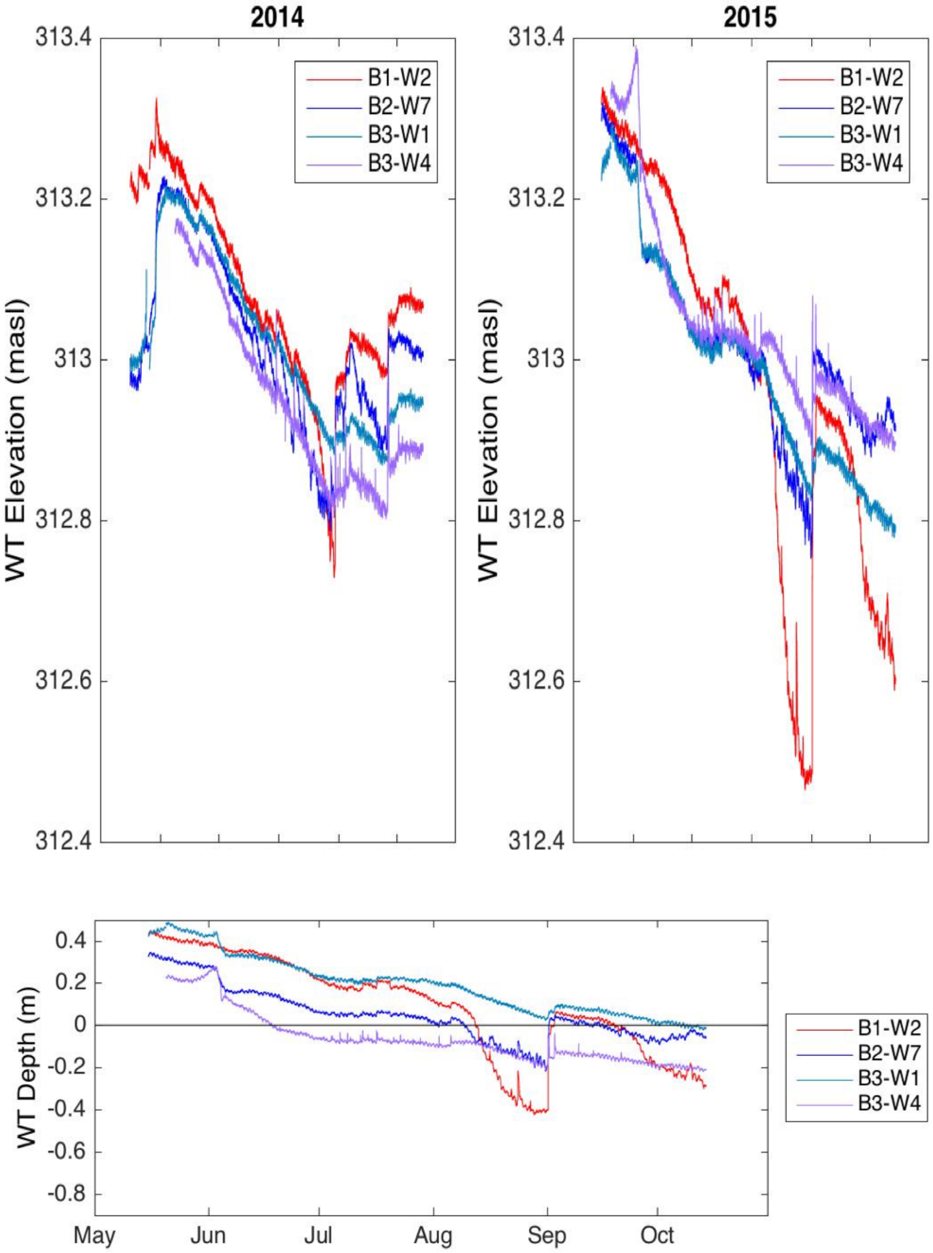


Figure 3.3 – Water table elevation over the lowland transect in 2014 and 2015. B1, B2, and B3 are located at the inlet, mid-fen and outlet, respectively. The figure on the bottom shows water table position in 2015 with reference to the ground.

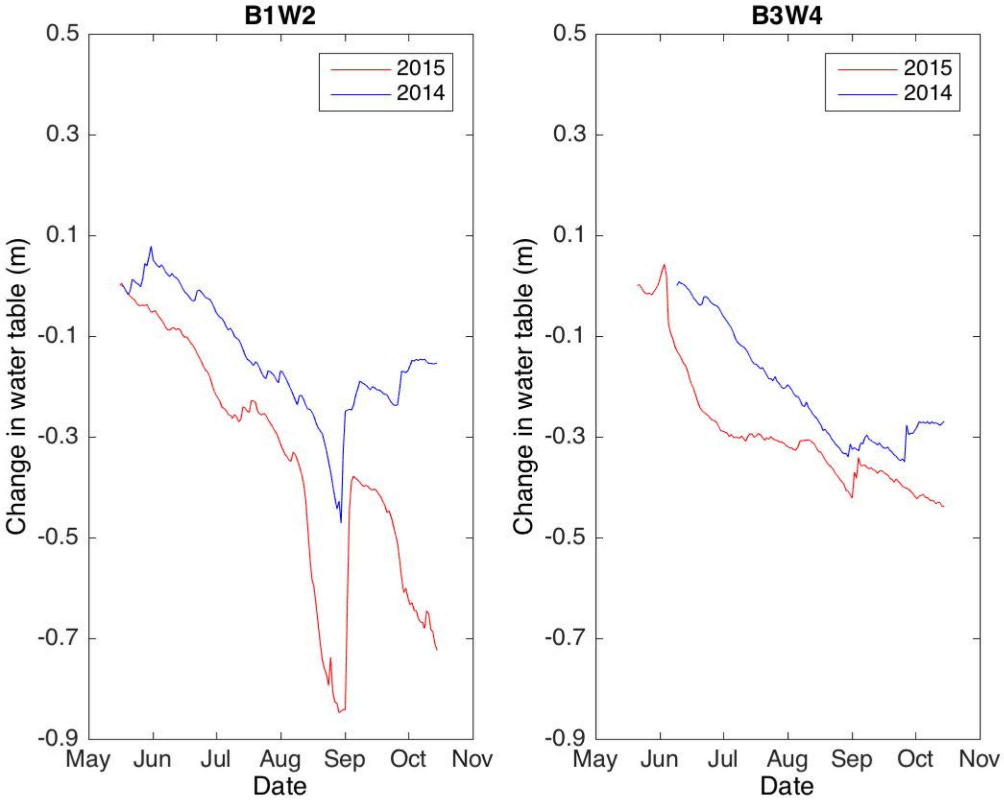


Figure 3.4 – Change in water table depth over the 2014 and 2015 seasons in the west (B1-W2) and east (B3-W4).

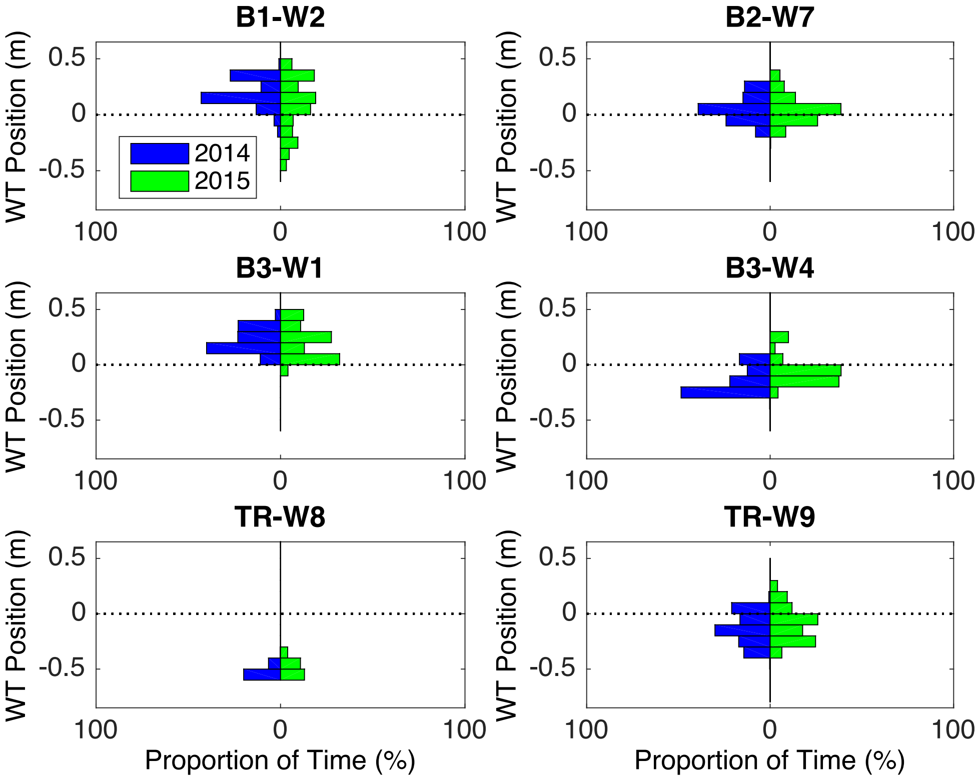


Figure 3.5 – Proportion of time water table depth was at various positions during the 2014 (left, blue) and 2015 (right, green) for May-Oct of both years.

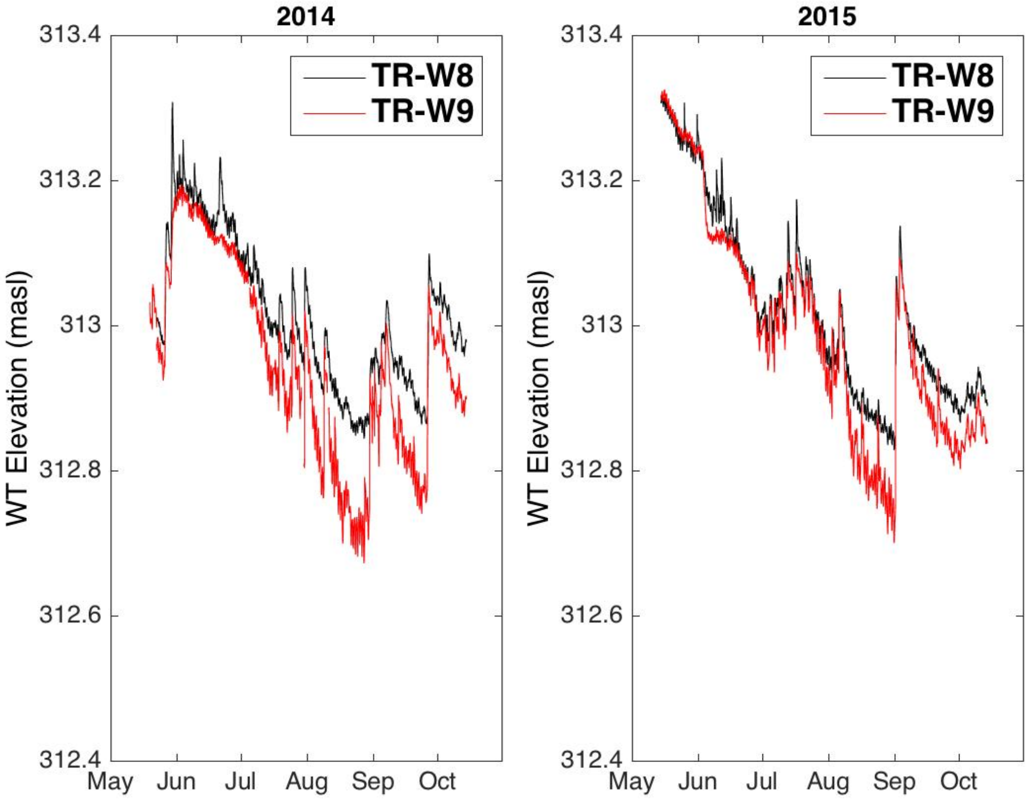
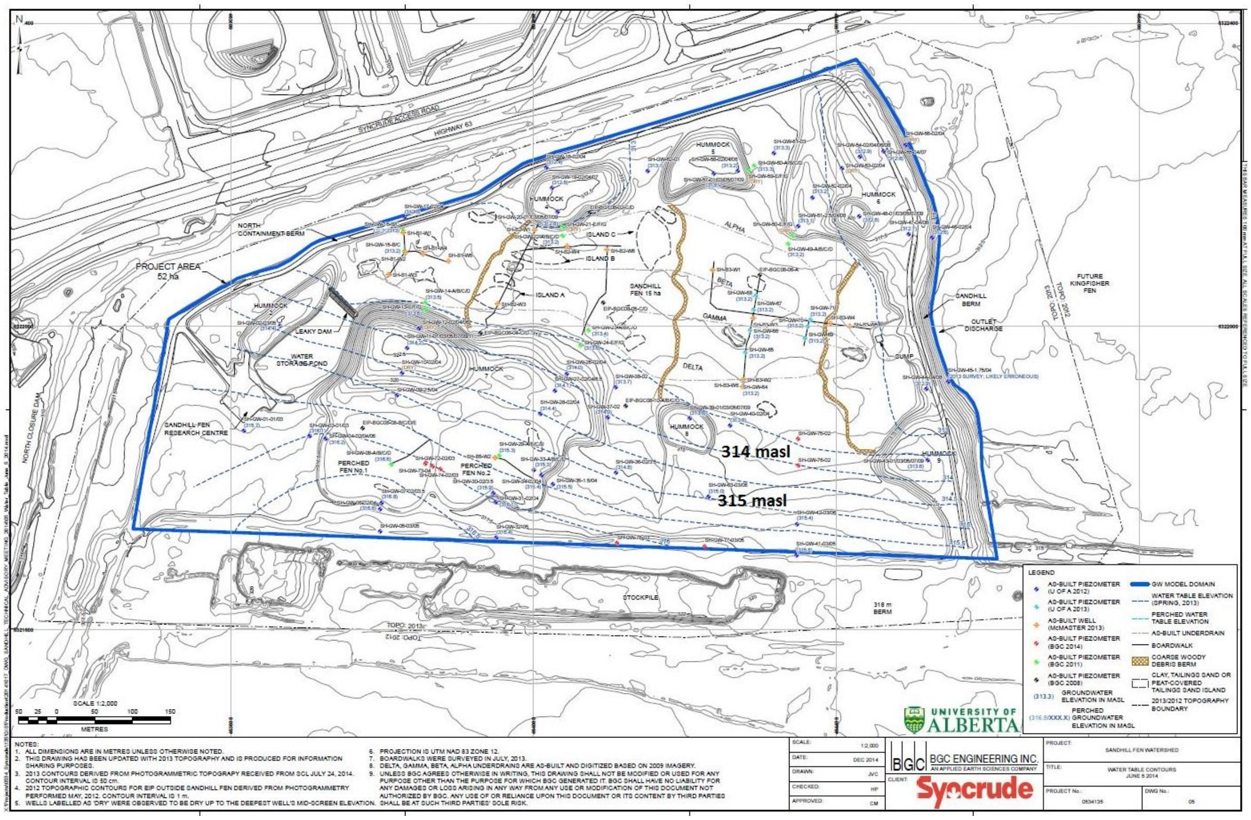


Figure 3.6 – Water table elevation (head) for paired wells TR-W8/TR-W9 in metres above sea level (m.a.s.l) for 2014 and 2015. TR-W8 is located at the toe of a hummock and TR-W9 is located further into the lowland.



NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING HAS BEEN UPDATED WITH 2013 TOPOGRAPHY AND IS PRODUCED FOR INFORMATION SHARING PURPOSES.
3. 2013 CONTOURS DERIVED FROM PHOTOGRAMMETRIC TOPOGRAPY RECEIVED FROM SCL JULY 24, 2014. CONTOUR INTERVAL IS 50 cm.
4. 2012 TOPOGRAPHIC CONTOURS FOR EIP OUTSIDE SANDHILL FEN DERIVED FROM PHOTOGRAMMETRY PERFORMED MAY, 2012. CONTOUR INTERVAL IS 1 m.
5. WELLS LABELLED AS 'DRY' WERE OBSERVED TO BE DRY UP TO THE DEEPEST WELL'S MID-SCREEN ELEVATION.
6. PROJECTION IS UTM NAD 83 ZONE 12.
7. BOARDWALKS WERE SURVEYED IN JULY, 2013.
8. DELTA, GAMMA, BETA, ALPHA UNDERDRAINS ARE AS-BUILT AND DIGITIZED BASED ON 2009 IMAGERY.
9. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

Figure 3.7 - Groundwater maps showing larger-scale, deep groundwater movement, provided by Carl Mendoza and BGC Engineering.

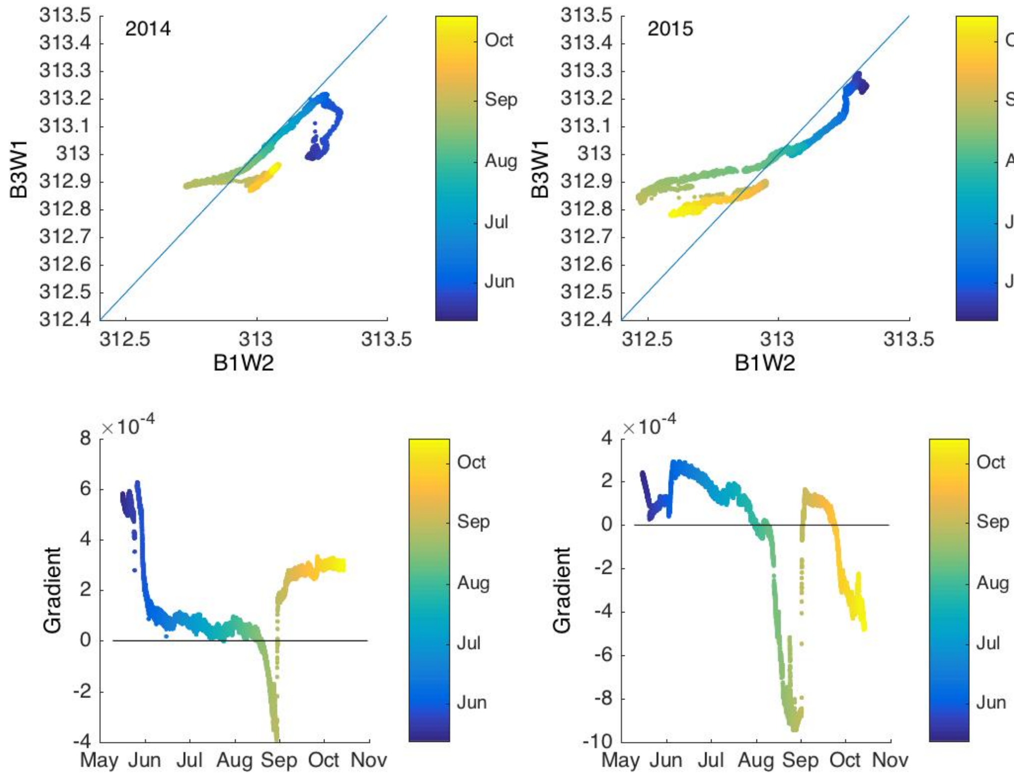


Figure 3.8 - Heads (in m.a.s.l) of B1-W2 (inlet) vs. B3W1 (mid-fen). When above the 1:1 line, flow is reversed from the outlet. Bottom figure expresses the magnitude of the gradient (positive values indicate flow towards the mid-fen, negative values indicate flow toward the inlet (Note the change in x-axis scale).

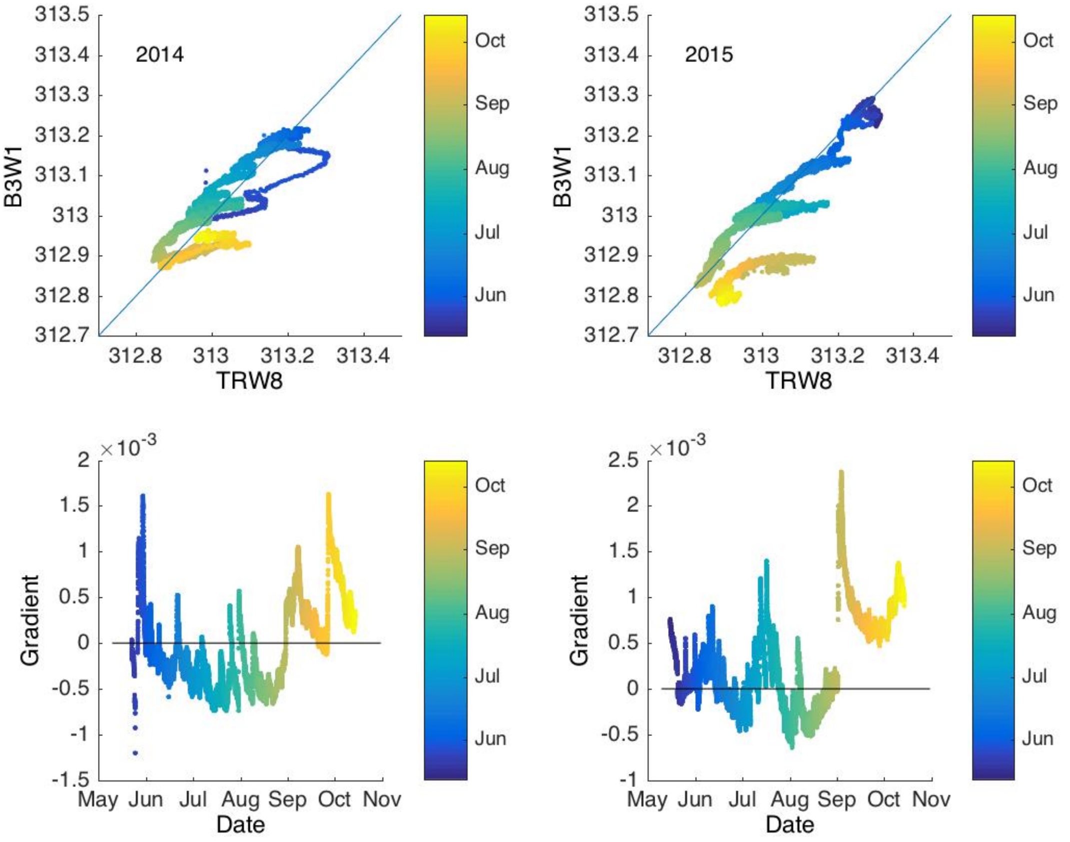


Figure 3.9 - Heads (in m.a.s.l) between the toe of a hummock (TR-W8) and the lowland (B3-W1). When above the 1:1 line, flow is from the lowland towards the hummock. Bottom figure expresses the magnitude of the gradient (positive values indicate flow towards the lowland, negative values indicate flow toward the hummock. Note the change in x-axis scale).

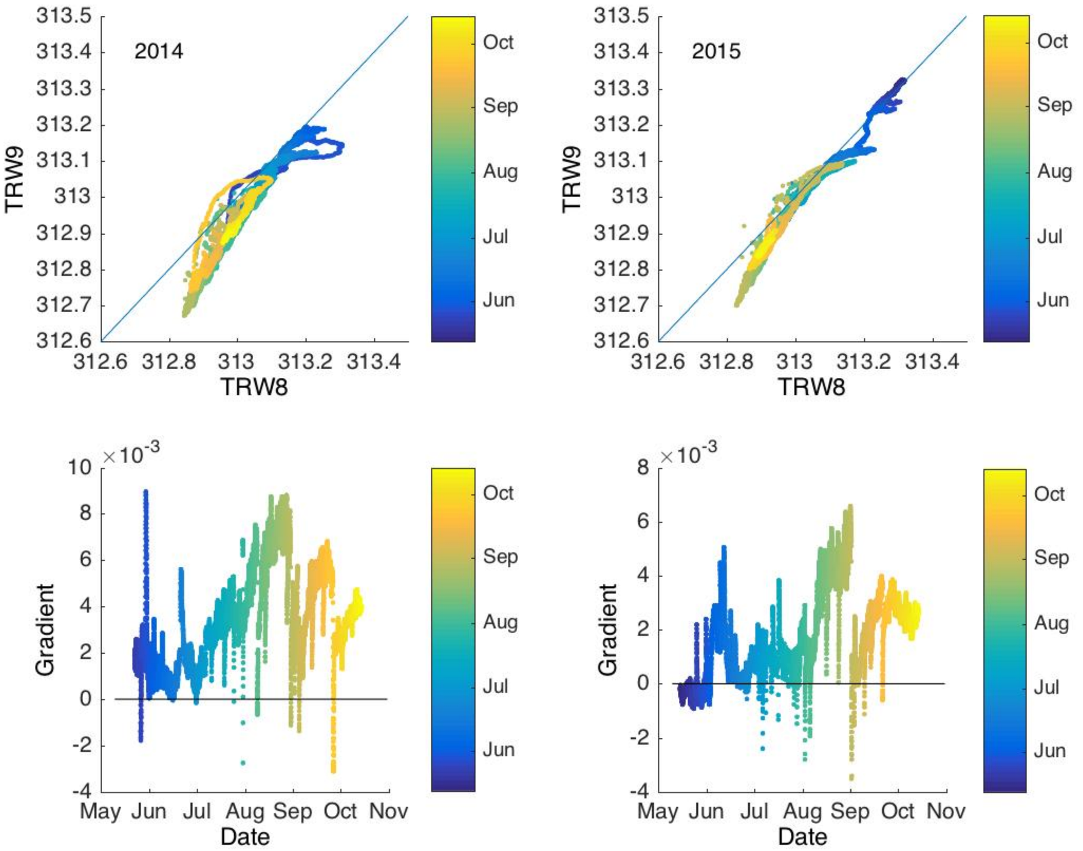


Figure 3.10 - Heads (in m.a.s.l) between the toe of a hummock (TR-W8) and a paired well further into the lowland (TR-W9). When above the 1:1 line flow is from the lowland towards the hummock. Bottom figure expresses the gradient (positive values indicate flow towards the lowland. Note the change in x-axis scale).

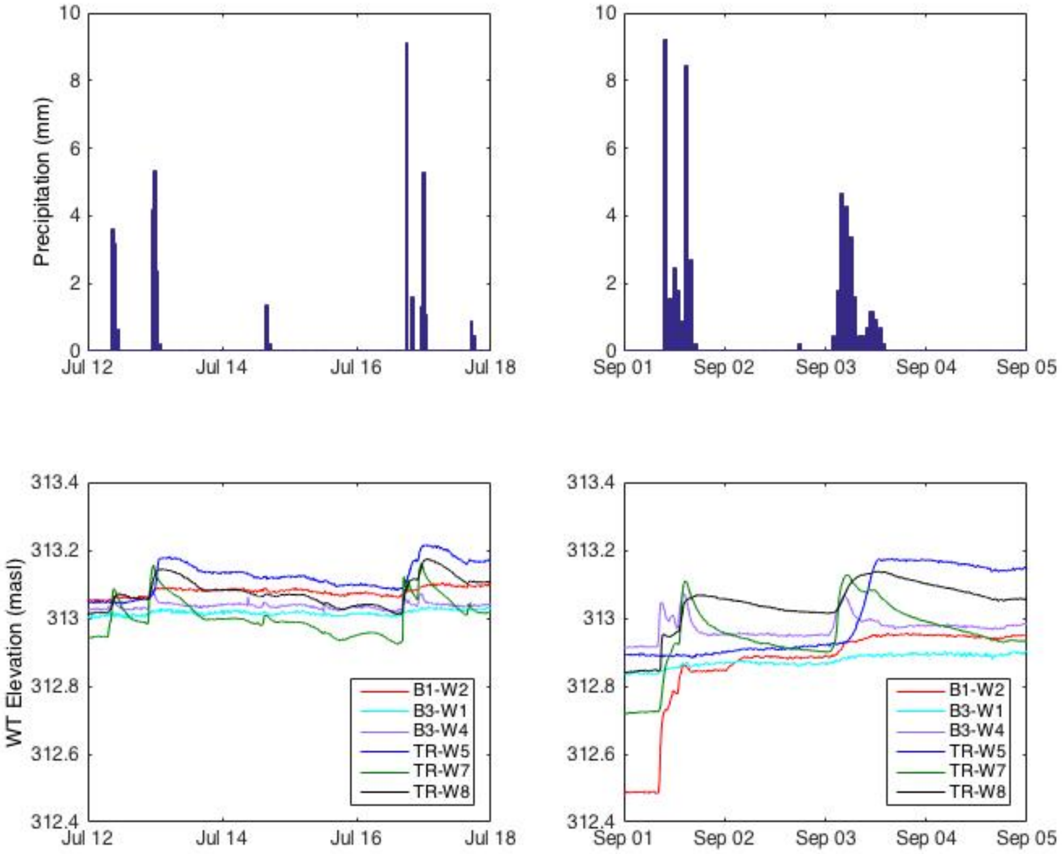


Figure 3.11 – Water table response to the July and September rainfall events in margin (TR) wells and lowland wells.

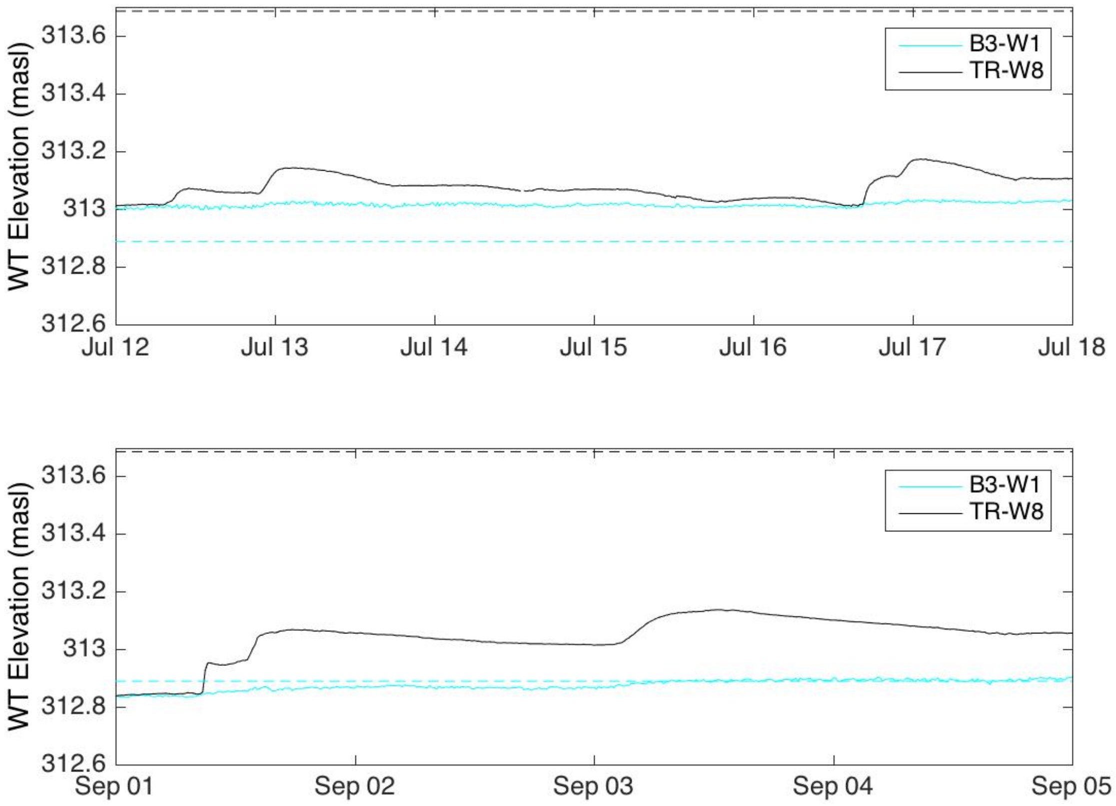


Figure 3.12 – Response to precipitation event for a well with standing water present (B3-W1) and a well where water table is below the peat surface (TR-W8).

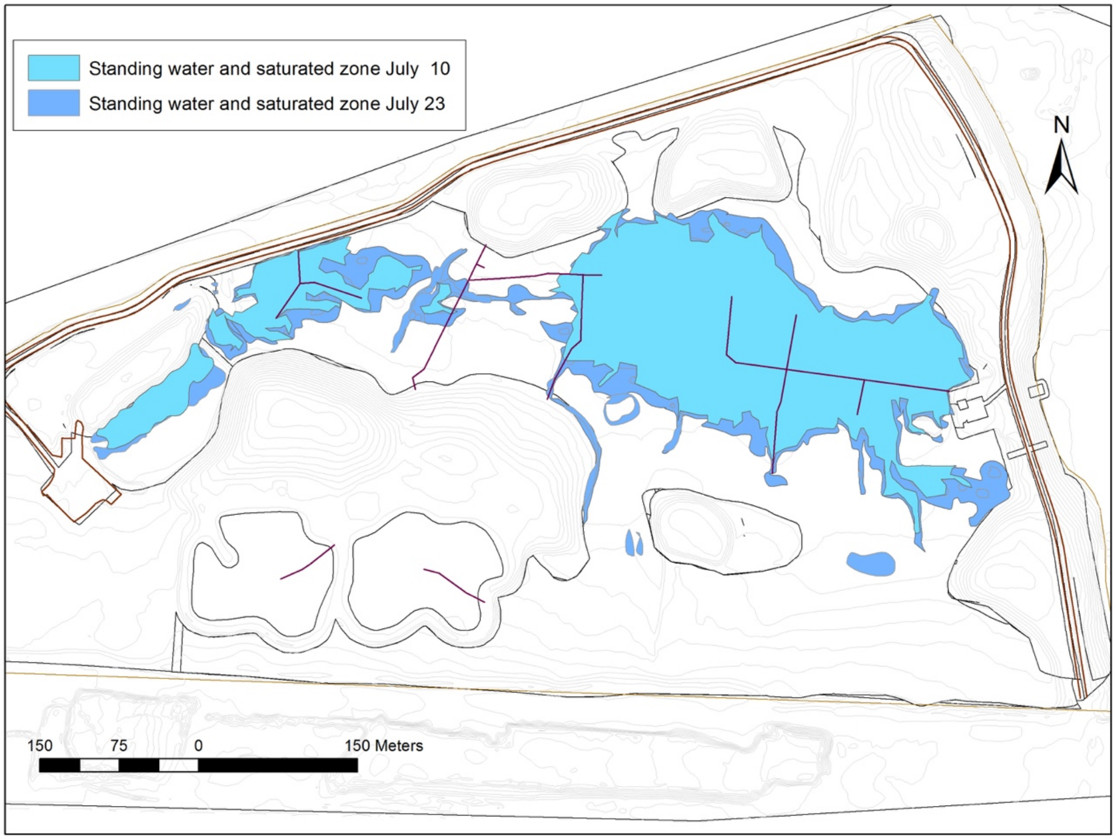


Figure 3.13 – Saturation map for two dates in July 2015 before and after 39 mm precipitation event. Light and dark blue represents before and after the rainfall, respectively. Data for map provided by Carl Mendoza (U of A) and BGC Engineering.

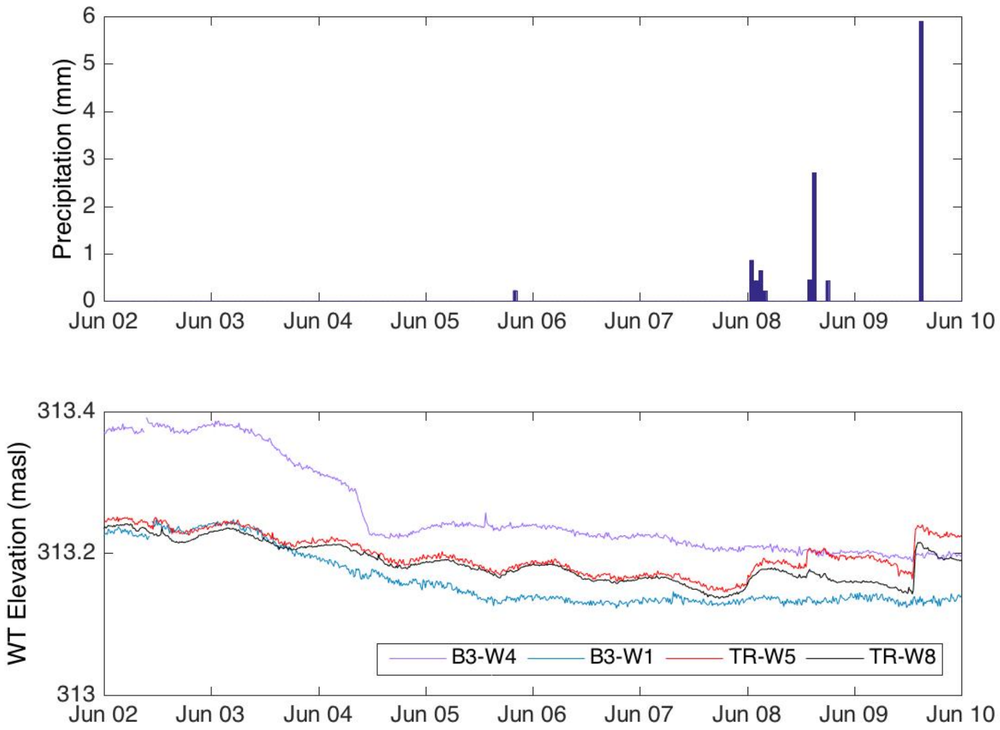


Figure 3.14 – Response to the pumping event at the outlet (B3-W4), mid-fen (B3-W1 and TR-W5), and north hummock (TR-W8). The outflow pump was on for 56 consecutive hours (3-5 June), removing 9334 m^3 of water.

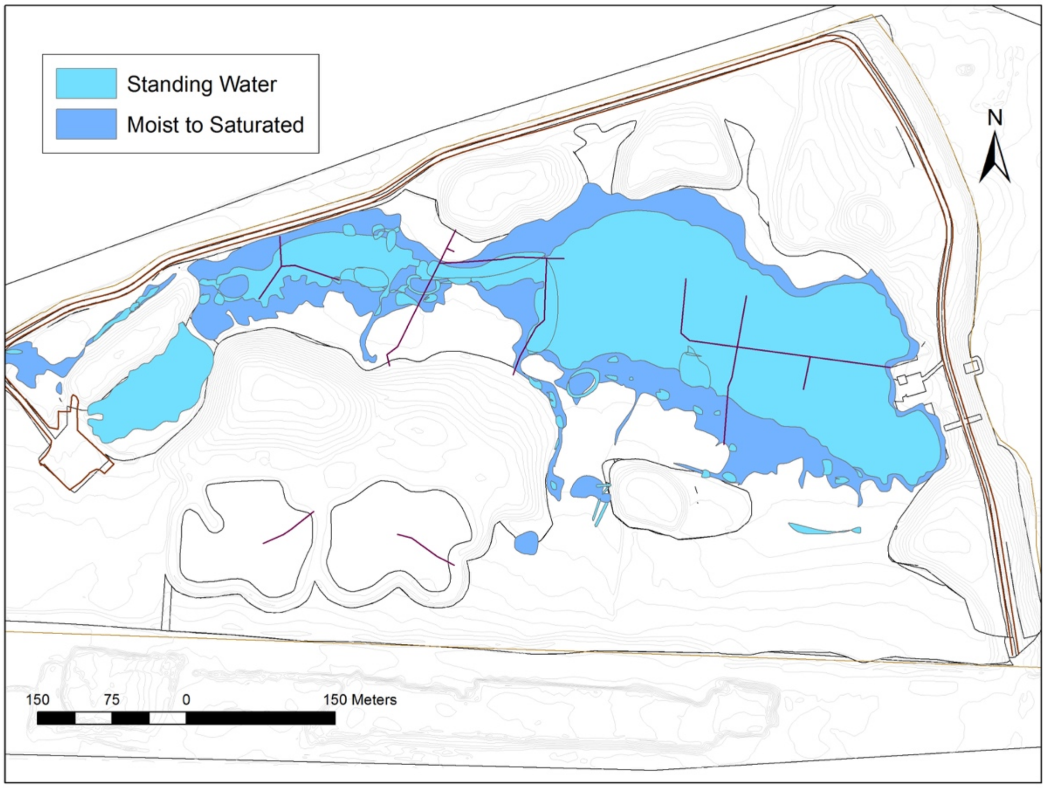


Figure 3.15 - Saturation map showing the areas of standing water and saturated ground present on 31 May, 2015, prior to the pump event. Data for map provided by Carl Mendoza (U of A) and BGC Engineering.

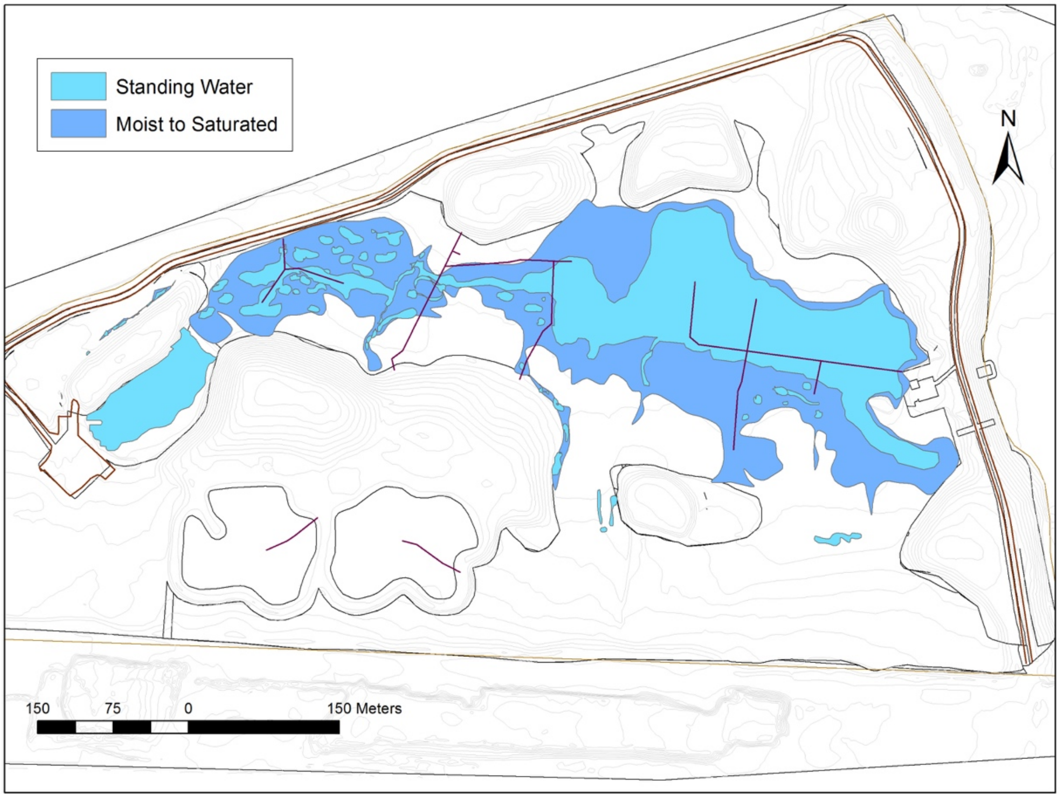


Figure 3.16 - Saturation map showing the areas of standing water and saturated ground present on June 10, following the pump event. Data for map provided by Carl Mendoza (U of A) and BGC Engineering.

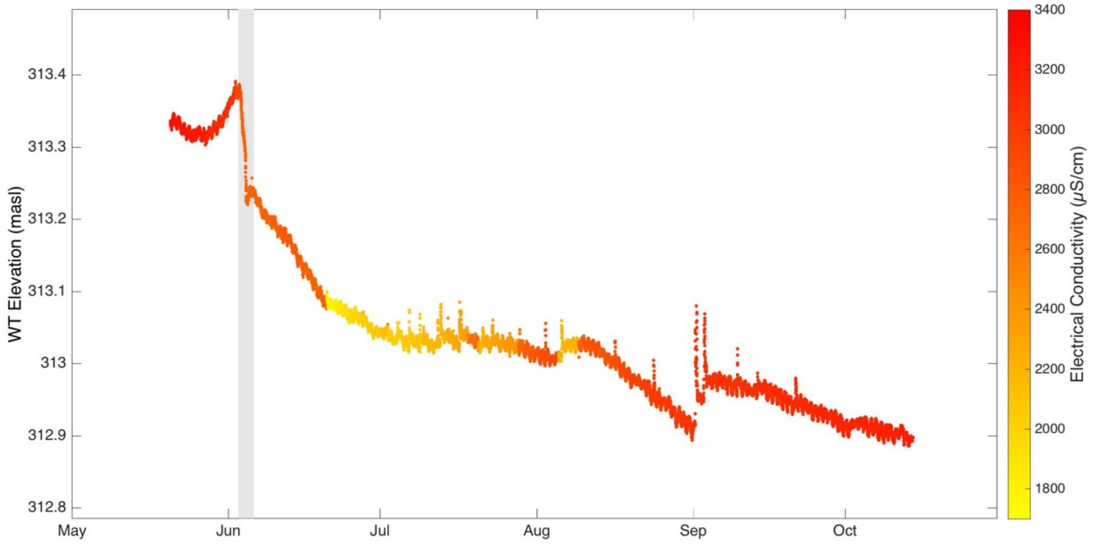


Figure 3.17 - Electrical conductivity at the outlet (B3-W4) for the duration of the study season. Grey bar represents the pump event.

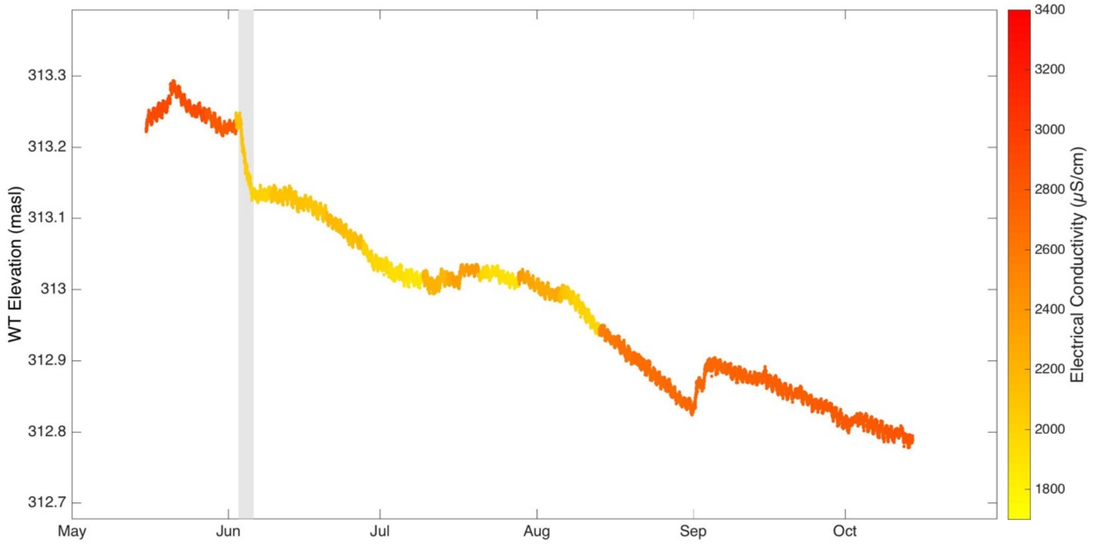


Figure 3.18 - Electrical conductivity in the mid-fen (B3-W1) for the duration of the study season. Grey bar represents the pump event.