MULTI-YEAR WATER BALANCE DYNAMICS OF A NEWLY CONSTRUCTED WETLAND, FORT MCMURRAY, ALBERTA.

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Title: Multi-year water balance dynamics of a newly constructed wetland, Fort McMurray, Alberta

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ABSTRACT

Oil sands mining in Alberta completely transforms the natural boreal landscape of upland forests, wetlands and lakes into open pits, tailings and overburden piles. By law, industry is required to return the landscape to its pre-disturbance land capability. While previous reclamation efforts have mainly focused on upland forest ecosystems, rebuilding wetland systems on soft tailings has only recently become a research focus. The dry, sub-humid climate and high salinity levels of underlying mining material complicate reconstruction of wetlands within this region. In 2012, Syncrude Canada Ltd. completed construction of the Sandhill Fen Watershed (SFW), a 52-ha upland-wetland system to evaluate wetland reclamation strategies. SFW includes an active pumping system, upland hummocks, a fen wetland and underdrains. This study examined the watershed-scale water balance in the first two years after commissioning (2013 and 2014). The first paper presents a semi-distributed water balance approach examining the fluxes and stores of different landscape units. Artificial pumping controlled the water balance in 2013, with approximately double the annual precipitation pumped in and out from May-Oct 2013, causing large water table fluctuations. In 2014, pump management was more passive, and water balance controlled by vertical fluxes. In the second paper, growing season ET rates and controls were assessed using data from three eddy covariance towers in the uplands and lowlands. Average ET rates between uplands and lowlands were similar, with average rates of 2.41 – 2.52 mm d^{-1}. ET was radiatively controlled at all sites. Energy partitioning and ET rates are similar to natural boreal peatlands within the area, however upland areas are expected to increase in ET rates as LAI increases and vegetation matures. This study provides critical quantitative data on the early years of a highly managed watershed. Long-term monitoring is necessary, as water balance dynamics will evolve with vegetation development and climate cycles.

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Chapter 1: Introduction

1.1 Introduction

The world's third largest crude oil reserve is found in Alberta, Canada (ERCB, 2013). Since the 1970s, extraction of this resource through surface and sub-surface mining has accelerated (Paskey, Steward, & Williams, 2013). In 2012, total bitumen production reached 1.9 million barrels per day (mbpd), and is expected to rise to 3.8 million mbpd by 2022 (ERCB, 2013). The surface mining process completely removes the previous ecologic and hydrologic functions of the landscape, and leaves behind overburden piles, large pits and tailings facilities (Elshorbagy et al., 2005). The spatial extent of this process is significant, currently disturbing almost 800 km^2 within the Western Boreal Plain (WBP) (Government of Alberta, 2013). This disturbance is within a region made up of a mosaic of upland forests and wetlands (Devito et al., 2012). Wetlands, and specifically peatlands, make up over half the boreal landscape (Rooney et al., 2012; Price et al., 2010) and perform critical ecosystem services, such as water storage and transmission, carbon storage and biodiversity (Waddington et al., 2015). Provincial legislation under the Government of Alberta Environmental Protection and Enhancement Act, requires industry to reclaim the disturbed land back to its equivalent land capability (OSWWG, 2000), which therefore means both upland forests and peatlands must be reconstructed.

It is the responsibility of mine operators to design and construct new watersheds from mine overburden and stockpiled soil into features that restore functions of natural boreal watersheds, such as habitat, production and carrier functions (Elshorbagy et al., 2005). While upland areas have been successfully reclaimed (Carey, 2008; Lilles et al., 2010; Rowland et al., 2009; Sorenson et al., 2011), construction of peatland-containing watersheds is extremely challenging due to the sub-humid climate of the WBP, where potential evapotranspiration (PET) typically exceeds precipitation (P). Most precipitation also occurs during the summer months, where evaporative demand is high and is not available for storage (Devito et al., 2005). Estuarine and marine sediment deposits and deep saline aquifers are exposed during the mining process, and salts from these sources as well as soft tailings material may leach into reclaimed ecosystems (Trites and Bayley, 2009). Assessing the sustainability of various reclamation designs requires evaluating the ability for establishment of vegetation, minimizing the detrimental effects of highly saline water leaching (Elshorbagy et al., 2005), and minimizing water loss through evapotranspiration (ET) (Devito et al., 2012). To evaluate current reclamation strategies for wetland reconstruction on top of soft tailings, Syncrude Canada Ltd. (SCL) has constructed one of the first full-scale wetland containing watersheds, the Sandhill Fen Watershed (SFW), which finished construction in 2012. The 52 ha watershed contains 17 ha of low-lying peat, 35 ha of uplands, vegetated swales, an artificial pumping system and an underdrain system (Vitt and Bhatti, 2012).

This study aims to understand the influences of design and management practices on the hydrology of SFW during the first two years after commissioning: 2013 and 2014. Chapter 2 presents the watershed-scale water balance, including the timing and magnitude of each hydrological flux of the SFW from January 2013 to December 2014. This chapter also presents a long-term water balance monitoring framework, and assesses the influence of management practices on water fluxes and the sustainability of this newly constructed watershed. Because ET dominates the water balance in the WBP, Chapter 3 documents how growing season ET and energy partitioning vary inter-annually between uplands and lowlands. Using the Penman-Monteith equation, this chapter evaluates the climatic, atmospheric and physiological factors influencing ET and compares these values to natural peatlands to place the SFW within the context of the boreal landscape.

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Chapter 2: Multi-Year Water Balance Assessment of a Newly Constructed Wetland, Fort McMurray, AB

2.1 Abstract

Oil sands mining in northern Alberta completely removes the natural boreal landscape and leaves behind open pits, tailings and overburden piles. While previous reclamation efforts have mainly focused on upland forest ecosystems, research into rebuilding wetland systems in the Western Boreal Plain (WBP) has only recently begun. The success of constructed wetland systems is dependent on the sustainable supply and storage of water to promote wetland vegetation, peat accumulation and limit elevated salinity, which is particularly challenging due to the dry and variable climate of the boreal region. In 2012, Syncrude Canada Ltd. completed construction of the Sandhill Fen Watershed (SFW), a 52-ha upland-wetland system to evaluate wetland reclamation strategies. The watershed includes artificial pumps, upland hummocks, vegetated swales, a fen wetland and an underdrain system. This study developed a long-term water balance monitoring framework for the SFW and aimed to understand the influences of management practices on water fluxes and watershed sustainability. A semi-distributed water balance approach was taken to examine the fluxes and stores of upland and lowland units. Freshwater was pumped into a storage pond from a nearby lake, and outflow was measured at a weir and sump that collected surface and subsurface drainage. ET was measured using three eddy covariance towers at upland and lowland locations. Precipitation was quantified using tipping buckets, snow surveys, and continuous depth and SWE sensors. A series of near surface wells were installed to measure water table depth fluctuations. Results begin in 2013 and run through October 2014. In 2013, lateral inflow and outflow dominated

hydrological fluxes and precipitation was higher than the climatic normal. In 2014, pumps remained mostly off, with vertical fluxes controlling the water balance. Water table (WT) in 2013 fluctuated greatly, while in 2014, WT slowly declined throughout the summer and responded to large rain events in the fall. Lateral movement was observed with the upland supplying lowland areas. Similar ET rates were observed between upland and lowland towers in both years. With 2013 highly managed, and 2014 climatically normal with little artificial controls, comparisons between these years provide insight on how management practices influence the hydrologic dynamics and the overall water balance of the SFW.

2.2 Introduction

2.2.1 Oil Sands Mining and Disturbance within the Western Boreal Plain

Oil sands mining in northern Alberta plays a critical role in Canada's economy. In 2012, total bitumen production reached 1.9 million barrels per day (mbpd), and is expected to rise to 3.8 million mbpd by 2022 (ERCB, 2013). Currently, the Oil Sands Administrative Area (OSAA) covers over 14 million ha of boreal forest of which approximately 490,000 ha have been disturbed (Lee and Cheng, 2009). During mining, the surficial glacial soil and peat are stripped away, followed by the overburden to access the oil-bearing Fort McMurray formation (Elshorbagy and Barbour, 2007), resulting in up to 100 m of landscape removal (Johnson and Miyanishi, 2008). This surface mining process completely disrupts the natural ecosystem functioning and hydrologic cycle (Elshorbagy et al., 2005; Carey, 2008; Keshta et al., 2011; Huang et al., 2015) and transformed the boreal landscape into open pit mines, tailings ponds, mine waste, and overburden piles (Elshorbagy et al., 2005; Lee and Cheng, 2009).

According to the Government of Alberta's Environmental Protection and Enhancement Act, industry is required to return the disturbed landscape back to the pre-disturbance land capability (OSWWG, 2000). It is important to note that although these landscapes are termed 'disturbed', the entire hydrologic and ecologic systems have been completely altered. Reclamation is defined as the "creation of [ecosystems] on disturbed land where they did not formerly exist or where their previous form has been entirely lost" (Alberta Environment, 2008), and therefore the aim is not to restore, but reconstruct watersheds entirely. The reclamation process begins with mine planning and responsibility is only exonerated once certification has been issued. Certification evaluation depends on the ability of the reclaimed landscape to reproduce natural watershed roles such as habitat (diverse aquatic and terrestrial species), production (biomass) and carrier functions (fate and transport of dissolved and suspended material) that existed in the WBP before disturbance (Elshorbagy, 2005). To date, most reclamation strategies have focused on the sustainability of upland reforested systems (Rowland et al., 2009; Lilles et al., 2010; Sorenson et al., 2011). Although uplands are complex, developing under the influence of local climate, landform, topography, parent material and soil, the critical aspects of rebuilding forest ecosystems are generally understood (Vitt and Bhatti, 2012). The overburden is contoured and capped with soil (Elshorbagy and Barbour, 2007), and ecosystem functions can be accelerated by encouraging rapid re-establishment of forest vegetation (Vitt and Bhatti, 2012).

Despite efforts to reclaim forested sites, a complete mine closure plan must restore the same ratio of upland to wetland hydrologic units (Vitt et al., 1996). While specific ratios vary depending on each mine lease, the entire oil sands area was initially wetland rich (Rooney et al., 2012), covering between 20-60% of the pre-disturbance landscape. Wetlands are areas with the WT at, or near the land surface promoting hydric soils, hydrophytic vegetation and biological activities of wet environments. Wetlands are classified as mineral soil wetlands (marshes, shallow water and some swamps) that produce little or no peat or peatlands (bogs, fens and some swamps), which are characterized by waterlogged conditions in which accumulation of peat exceeds 0.4 m (National Wetlands Working Group, 1988; Price and Waddington, 2000). Peatlands make up over 90% wetlands within the pre-disturbance landscape of northeastern Alberta (Vitt et al., 1996), of which 72% are fens (Vitt et al., 2000). Peatlands in this area are of particular significance as they store and release water in alternating years of water deficit and surplus. Saturated fens on gentle slopes are important for storm runoff and distribution of nutrients down slope (Devito and Mendoza, 2003). In dry periods, peatlands provide water to adjacent slopes through capillary action or root uptake (Ferone and Devito, 2004; Harris, 2007). The importance processes of carbon cycling, methane production and oxidation pathways in peat are due to the proximity of aerobic and anaerobic zones within the peat deposit (Lee and Cheng, 2009). Despite the dominance and importance of peatlands within the OSSA, marshes and shallow open water wetlands have been the focus of reclamation projects as they are hydrologically simpler than peatlands and may form spontaneously in poorly drained areas (Alberta Environment, 2008; Raab and Bayley, 2012).

Syncrude Canada Ltd. (SCL) constructed the Sandhill Fen Watershed (SFW) as an instrumented research watershed to evaluate operational techniques and design recommendations for future wetland reclamation. The site assessment was completed in 2008, the final tailings deposition in 2009, topography (hummocks and berms) placed in 2010, reclamation material in 2011 and finally vegetation was introduced in 2012 (Figure 2.1). A long-term research plan is in place to monitor the watershed's hydrology, hydrogeology, salt water and carbon balance, and vegetation establishment. (Vitt and Bhatti, 2012). A reclaimed fen project is currently being researched at Suncor (Nwaishi et al., 2015), however the design of the two projects differs greatly. The SFW is equipped with a managed water supply and constructed with 35 ha upland and 17 ha lowland, while the Suncor fen is smaller (3 ha) and is surrounded by reclaimed slopes and an active mine haul-road. The Suncor fen relies on the upland slopes to provide adequate water to the lowland (Vitt and Bhatti, 2012; Nwasishi et al., 2015). Within the Boreal Plain, topographic position rarely dictates whether an area will be a forest or wetland (Devito et al., 2005), however in these studies, upland refers to area with planned forest area, while lowland refers to areas designed for peatland development. These two projects are the oil sands industry's first attempt to construct fen wetlands on a soft tailings sand deposit.

2.2.2 Challenges in Peatland Reclamation

Peatland reclamation is particularly challenging in this environment due to the ubiquitous presence of excessive salts in reclamation material that increase conductivity and ion concentrations, which may harm peatland vegetation (Trites and Bayley, 2009; Vitt and Chee, 1990). These challenges are exacerbated by complex interactions of climate, geology and topography in the WBP (Devito, Creed and Fraser 2005). The region is characterized by a long-term water deficit, where annual P inputs are less than the annual PET (Brown et al., 2010), and heterogeneous geology that varies largely in depth and water-storage capacity. In this area, climate controls the largest fluxes of ET and P and storage within the unsaturated zone dominates the water balance rather than lateral hillslope flow and topographic influences (Devito et al., 2005; Winter, 2001; Devito et al., 2012).

Price et al. (2009) determined a minimum 2:1 ratio of upland to peatland to maintain surface wetness adequate for peatland function. The complexity between upland-wetland interactions combined with a propensity for vertical flow complicates wetland reclamation design (Devito et al., 2012). Within the uplands, subsurface and macropore flow dominates and ET is typically greater than PET as large root networks can access deeper water. Large storage capacity of upland areas with mineral soil differs from the limited storage ability of low-lying wetland areas containing organic soils (Devito et al., 2005) that may be underlain with impermeable layers of frozen soil, or fine-grained confining layers (Carey and Woo, 1998). In wet years, wetlands become hydrologically connected to uplands, and overland flow may dominate (Devito et al., 1996). When the water table exceeds depression storage capacity, peatlands have shown rapid responses during spring runoff, while during dry periods, pools may become disconnected into micro-catchments (Quinton and Roulet, 1998).

Hydrology is considered the most important process regulating wetland function, controlling the chemical and biotic dynamics in peatlands (Mitsch and Gosselink, 1993). When designing constructed peatland-containing watersheds within an oil sands reclamation and closure plan, it is critical to understand all dynamics of the water balance, and in turn the influence of climate, geology, and human influence on the watershed hydrology. No previous study has examined the water balance of a constructed wetland-containing watershed atop soft tailings. With the vast area of land requiring reclamation within the OSSA, understanding the hydrology of the SFW is a critical first step in evaluating the efficacy of wetland design. The objective of this study is to examine the water balance dynamics of the SFW in the first two years after commissioning, and determine whether the design and initial conditions are appropriate to promote the development of a self-sustaining fen wetland. Establishing the factors controlling the rate and timing of water fluxes is critical in guiding future reclamation efforts. We present the timing and magnitude of each water balance component of the SFW between January 2013 to December 2014, develop a long-term water balance monitoring framework, and assess the influence of management practices on water fluxes and the sustainability of this newly constructed watershed.

2.2.3 Study Site: Sandhill Fen Watershed

2.2.3.1 Location and Design

The SFW is located approximately 40 km north of Fort McMurray, Alberta in SCL's East-In Pit (57°02' N 111°35' W). The climate is characterized as sub-humid continental, with cold winters and warm summers. The average (1981-2010) annual air temperature is 1°C, ranging from -17.4°C (January) to 17.1°C (July). The area receives 419 mm of precipitation annually, 34% as snow (Environment Canada, 2014). The area was mined from 1977 to 1999 and was filled with 35 m of inter-bedded composite tailings (non-segregating tailings slurry of tailings sand and fine tailings with gypsum) and tailings sand layers underneath a 10 m sand cap. The watershed is 52 ha, approximately 1000 m long and 500 m wide (Figure 2.2). The wetland area to perimeter ratio is similar to natural fen wetlands, a design chosen based on 6000 natural sites (Vitt and Bhatti, 2012).

The design of the SFW includes upland hills (referred to as hummocks), vegetated swales, woody berms, a freshwater storage pond, a fen wetland and a fen underdrain system (Figure 2.2). Perched fens isolated from regional groundwater flow are common in the boreal landscape, often formed in areas with considerable fine-textured silt or clay content restricting water transmission (Alberta Environment, 2008). Two perched fens (total 2.4 ha) were constructed to determine if isolated perched fen-like wetlands can succeed with only precipitation inputs. Boardwalks, access roads and a heated weir building and sump at the fen outlet were also installed (Vitt and Bhatti, 2012).

To provide a mineral soil base for the lowland fen and minimize diffusion of tailings pore water into the fen, 0.5 m of fine-grained material (clay-till) was placed directly over the tailings sand. Another 0.5 m of salvaged peatland material was placed on top as an organic soil layer. On five of the hummocks, clay-till or fluvial sand subsoil (0.3-0.4 m) and harvested litter, fibric, humic (LFH) material was placed from a forest floor of a jack pine ecotype. Two hummocks and surrounding swales are deposited with a clay-till subsoil (0.3-0.4 m) and harvested LFH from a moist aspen/white spruce ecotype (Vitt and Bhatti, 2012).

2.2.3.2 Hydrology and Water Supply

Water supply on the SFW is highly managed. Preliminary groundwater modeling results showed the design of the fen should allow uplands to provide sustainable water levels in the fen, however high salinity levels rising from the underlying tailings pose a major threat to wetland vegetation health. Because of this, freshwater is supplied to the watershed from Mildred Lake Reservoir – a lake just north of SFW. This water is piped in and discharged into a clay-lined pond and diffused to the fen through a leaky gravel berm (Figure 2.2). The two perched fens are also designed with pipes to supply water from Mildred Lake until vegetation is established. This freshwater influence is not intended to act as a long-term water supply to the fen, but rather limit elevated salinity to assist in plant species survival for the first few years after commissioning.

To further control the risk of elevated salinity, an underdrain system was installed in the fen. Perforated 8-inch high-density polyethylene pipes covered with a fine-screen geotextile cloth were installed prior to reclamation material placement and lie 1-3 m below the fen surface. The intention is to keep the vertical gradients downwards to prevent upward salt migration (Vitt and Bhatti, 2012). Surface water flows into a heated weir building, through a V-notch weir and into a sump, which also collected the underdrain water (Figure 2.3). The total drainage of surface and underdrain water is pumped from the sump and discharged away from the fen into East-In Pit.

2.2.2.3 Topography and drainage

A major research question surrounding the SFW is whether or not the topographic design and placement of material will support long-term upland to lowland movement of water, and if this is sufficient to sustain a wetland system. Seven hills (termed hummocks) of mechanically placed tailings of varying size were built to create distinct upland recharge areas to supply a sustainable source of water to the lowland (Figure 2.2). Most hummocks are approximately 180 m by 60 m and rise 3-4 m above surrounding topography, totaling 825 000 m^3. Hummock 7, located in the centre of the watershed, is the largest, rising 8 m and is approximately 350 m by 100 m. The hummocks were designed with the long axis to run parallel to the fen to maximize seepage face contacting the lowland (Syncrude, 2008) to allow for long term flushing of salts and lower the WT to promote upland tree species (Vitt and Bhatti, 2012).

2.2.3.4 Vegetation

Wetlands in a post-mined landscape are expected to be considerably more saline than natural systems, and therefore it is likely reclaimed peatlands will develop with more salt-tolerant species. Trites and Bayley (2009) recommended planting wetland vegetation to achieve landscapes capable of certification within a reasonable time frame. Species planted from seed include bog birch (*Betula glandulosa*), a variety of sedges (*Carex aqualtilis, C.diandra, C.paupercula, C.utriculata*), arrow grasses (*Triglochin maritima* and *T.palustre*), rushes (*Scirpus lacustris* and *S. cyperinus*) and slough grass (*Beckmannia syziagachne*). Upland vegetation was planted in early June of 2012. Species composition of these areas was determined by the donor ecosite soil, with varying proportions of trembling aspen (*Populus tremuloides),* jack pine (*Pinus banksiana),* black spruce (*Picea mariana*), white spruce (*Picea glauca),* dogwood (*Cornus stolonifera*), and green alder (*Alnus crispa)* (Vitt and Bhatti, 2012).

2.3 Methods

The study period spanned January 2013- December 2014. The water balance of the WBP can be summarized by the following equation:

$$\Delta S = P\text{-}ET + (R_{in} - R_{out}) + (GW_{in}\text{-}GW_{out}) \quad (1)$$

where ΔS is the change in storage, P is precipitation, ET is evapotranspiration, GW_{in} and GW_{out} are groundwater fluxes in and out of the watershed, and R_{in} and R_{out} represent inflow and outflow, which in this context is comprised of the artificial in and outflow controlled by pumps.

Precipitation was measured at three meteorological towers on the fen (Figure 2.2) each equipped with a tipping bucket rain gauge (Model CS700, Campbell Scientific, USA) to measure rainfall, a *Campbell Scientific CS725* snow water equivalent (SWE) sensor, and a SR50A sonic ranger to monitor snow depth. *Campbell*

Scientific CR1000 data loggers recorded hourly data. 50 and 64-point snow surveys were completed on 17 and 19 March 2013 and 13 March 2014 respectively. Each survey point was classified as flat (lowland or upland), plateaus (top of hummocks), or slopes (valleys or transitional areas). Areal proportions within the watershed were 75% flat, 9% peaks and 16% valleys.

Near surface WT fluctuations were measured using 11 (2013) and 30 (2014) 1.6 m PVC slotted wells augered to a depth from 0.48 -1.02 m below ground and instrumented with Solinst Junior Edge leveloggers (Model 3001) programmed to record water level and temperature from May-October at 15-minute intervals. Levels were corrected for barometric pressure using a Solinst Barologger. Wells in 2013 were installed mainly within the lowland area, with 1 installed near the Fen S tower in the upland. In 2014, a total of 22 wells were installed with a wider distribution through the uplands and transitional upland-wetland transitional areas. Wells are named according to their position within the watershed; the suffix B represents the boardwalk number, TR transitional areas and UP is upland areas (Figure 2.2).

Lateral inflow was measured using ultrasonic flowmeters as well as a transducer measuring the level in the water storage pond using a Rosemount manufactured transducer. Outflow consists of surface flow and underdrain contributions (Figure 2.3). Surface drainage flows through a V-notch weir, instrumented with a sensor to continuously record level, and then into the sump, where underdrain water is collected and total discharge is pumped away from the fen. Flowmeters for inflow and outflow used Model AT868 AquaTrans™ Ultrasonic Flow Transmitter for Water (1- and 2-

Channel). There were considerable errors in measurement associated with the flowmeters. While inflow began on 29 May 2013, dataloggers did not begin functioning until 26 July 2013. Inflow during this time was inconsistent and pumping capacity was frequently adjusted; therefore these values are based on manual readings of the pump logger. Outflow data records begin in April 2013.

ET was measured using the eddy covariance technique at three towers (Figure 2.2). The towers, Fen South (S), Fen North (N) and Fen Perched (P), were constructed in May of 2012, 2013 and 2014 respectively and continuously measured turbulent fluxes of energy, momentum, and scalars. Fen S and P operate May-October, while Fen N functions year-round. Photos of Fen S and N are shown in Figure 5.1 and 5.2 (Supplemental Data). Instrumentation at each tower consisted of a three-dimensional sonic anemometer measuring the three orthogonal components of wind speed (Fen P and S: CSAT3; Campbell Scientific, USA, Fen N: R3-50, Li-Cor, USA) and a fine wire thermocouple situated in the center of the sonic head. An open-path infrared gas analyzer (LI-7500, Li-Cor, USA) (IRGA) measured water vapour and carbon dioxide mass density at each tower. Fen N was equipped with an enclosed-path IRGA (LI-7200, Li-Cor, USA) drawing air from directly below the sonic anemometer (tube length 1 m, diameter 9 mm). Wind speed and gas concentration measurements were measured at a frequency of 10 Hz. Covariance were computed at 2 fifteen-minute intervals and averaged to provide fluxes every 30 minutes. Net all-wave radiation as well as down and up-welling long- and short-wave radiation was measured at Fen S using a NRLite net radiometer (Campbell Scientific, USA) and 2 SP Lite2 pyranometers (Kipp and Zonen, Netherlands), at Fen P using a NRLite2 net radiometer (Kipp and Zonen, Netherlands) and at Fen N using a CNR4 net radiometer (Kipp and Zonen, Netherlands). In addition, horizontal wind speed and direction at Fen P and Fen N were measured using a wind monitor Model 05103-10 (R.M. Young Co., USA) while horizontal wind speed was measured at Fen S using a 3-cup anemometer. ET over the entire watershed was computed as the product of LE fluxes for the uplands (mean of Fen S and P) and lowlands (Fen N) and the weighted area of each landscape unit.

2.4. Results

2.4.1 Climate

Air temperature varied between years, with 2013 being slightly warmer. Mean daily air temperatures on the SFW were 1.94°C and 1.32°C for 2013 and 2014 respectively. Average daily temperature for the Fort McMurray Airport is 1.0°C (+/- 1.3°C) (Environment Canada, 2014), located approximately 45 km south of the SFW. Temperature deviations in 2013 and 2014 from the climatic normal were computed using data from Fort McMurray airport, where a long-term data record exists. Winter months in both years were colder than normal. With respect to the growing season, May and September 2013 were warmer than normal, with differences of 2.8°C and 3.9°C (Figure 2.4). The rest of 2013 was warmer than normal, with all months excluding July exceeding normal temperatures by more than 1.4°C. In 2014, temperatures were colder in April and May and warmer in all subsequent months.

2.4.2 Snowfall

Snow inputs were greater and more variable during the 2013 season than 2014. Snow depth measurements ran continuously beginning in November 2012. Maximum depth measured at automated snow sensors throughout winter 2013 was 0.59, 0.25 and 0.44 m at Stations 1-3 respectively. In March 2014, the maximum snow depth peaked at 0.27, 0.3 and 0.25 m respectively. Normal snow depth in the Fort McMurray airport is 0.3 m. Station 2 located between the two perched fens generally had the lowest SWE, while Station 1, located on the side of Hummock 6 exhibited the highest SWE (Figure 2.5). Higher SWE was found in the valleys relative to peaks and flat ground in both years. SWE values ranged from 12.3-312 mm in 2013 and 14.9-406 mm in 2014. The areal-weighted average SWE in 2013 and 2014 is 160 mm and 62 mm respectively. Snow cover was completely gone by late April in both years.

2.4.3 Rainfall

Timing and magnitude of rainfall events varied between study years. While both years received slightly more rainfall than the 30-year climate normal for Fort McMurray of 316 mm, neither year was exceptionally wet or dry. Comparing study seasons, 2013 was wetter than 2014, receiving 367 mm while 2014 received 316 mm. With respect to rainfall timing, 2013 received more rainfall in mid-summer months than 2014. Historically, 67% of annual rainfall is received between June and August (Environment Canada, 1981-2010). 86% of total rainfall fell between June and August in 2013, while only 36% of total rainfall fell during this period in 2014. Between 1 May – 31 October, 2013 received 354 mm (299 mm normal), while in 2014, 300 mm fell during this period (Figure 2.6). Rainfall in this area usually falls during convective storms, in high intensity and short duration events. The SFW only received 5 mm of rainfall in May 2013, but received its largest rain events in June, the largest events occurred 8 June (26 mm), 9 June (42 mm), 28 July (38 mm) and 30 Sept (31 mm). In 2014, the rainfall was heavy earlier on, receiving 103 mm in May 2014. The largest rainfall events fell on 15 May (18 mm), 26 May (21 mm), 29 May (40 mm) and later in the season on 26 Sept (28 mm).

2.4.4 Evapotranspiration

Daily mean upland and lowland ET rates are similar for all locations in all years, ranging from 2.22 +/-1.8 mm d^{-1} to 2.54 +/- 1.19 mm d^{-1} (Table 2.1). Over the growing season (May to September), the cumulative ET for each tower in all years fell within 50 mm, ranging from 339-389 mm. The lowland location exhibited slightly higher ET rates compared to the two upland towers, however rates were similar amongst all sites and years. Maximum mean monthly ET occurred in July each year, excluding Fen P, which reached maximum ET in June 2014 (Figure 2.7).

ET/P ratios are useful within the WBP, as the vertical water balance will dominate where groundwater inputs are small. Periods where ET/P is less than one indicate large precipitation inputs, where excess moisture is available to satisfy a potential moisture deficit, while ET/P greater than one indicate periods where soil storage may be depleted. The ET/P ratios for the growing season of May to September of 2013 and 2014 on the SFW were 1.05 and 1.27 respectively, indicating a vertical water deficit during the growing season in both years (Table 2.2). May 2013 was abnormally dry, with an ET/P ratio of 19, only receiving 5 mm of precipitation, and high temperatures resulted in summertime peak ET summing to 95 mm lost over the month. Excluding May 2013, this growing season experienced fairly low ET/P ratios, ranging from 0.63-1.18, vertically undergoing a water surplus June and September. In contrast, May 2014 was very wet (ET/P = 0.5), while the ET/P ratio was much higher in the rest of the months relative to 2013.

2.4.5 Inflow

Management of inflow pumping regimes differed between years. In 2013, inflow began in late May and continued steadily for the growing season, with two periods of no flow, 1 July-27 July and 10 Sept to 9 Oct. Pumping rates varied between 8-217 m^3/hour before inflow pumps were turned off on 17 Oct (Figure 2.8). Over the 17 ha lowland, this pumping regime resulted in a total of 809 mm (1.38 x 10^5 m^3), equal to almost double the annual total precipitation for this area (Figure 2.9). In contrast, in 2014, inflow was turned on 19-20 May, pumping at a maximum capacity of 260 m^3/hour for approximately 6 hours in total and was turned off for the rest of 2014 providing only 14 mm (2470 m^3). These variations in management practices resulted in total inflow in 2014 making up less than 2% of inputs of 2013.

2.4.6 Outflow

Management of outflow pumps also varied between study years. In 2013, the outflow pump was on beginning early in April, and was active until October. Discharge reached 283 m^3/hour at its peak, but fluctuated greatly (Figure 2.8). Total 2013 outflow values are estimated at 1.5 x 10^5 m^3, or 883 mm over the lowland area. Underdrains were left open for during 2013, dominating outflow and contributing over 90% of total discharge. Comparatively, the 2014 season was managed through planned drainage "events" lasting 1-4 hours. Short discharge events (~1 hour) occurred on 20 May, 10 June, 3 July and 16 October. Larger events lasting up to 4 hours occurred on 3-4 June and 6 July. The valve connecting the underdrains to the sump was closed at the beginning of the 2014 field season. Although a small amount of leakage did occur, surface contributions largely dominate discharge in 2014. In total, 3095 m^3 was pumped out of the watershed from May-October, equating to 18.2 mm over the 17 ha lowland area, representing just 2% of the total outflow in 2013 (Figure 2.9).

2.4.7 Storage/WT Depth Changes

Temporal WT patterns differed substantially between study years, mainly due to pump management. The 2013 season is characterized by intense pumping, both in and out, punctuated with periods when the pump was off. In 2013, the inflow pump was turned on 29 May, and ran continuously, other than 11-13 June and 3-27 July (Figure 2.8). WT responses to these adjustments were sudden, with rapid rises in WT when inflow was on, and steady evaporative driven decline when off. The pump was turned back on 27 July, resulting in an immediate increase in WT, which subsequently declined after pumping ceased (Figure 2.10). This decline was especially pronounced at B3-W1 and B3-W4, due to the outflow pump running at full capacity at the east side of the fen. This pattern of large WT fluctuations and rapid responses to pumping events continues throughout 2013.

When inflow was on, responses and maximum WT heights in wells on the third boardwalk (B3-W1, B3-W4) were more gradual and lagged behind WT response at B1-

W2. Maximum WT depth occurred 6 days earlier at B1-W2 on July 3 (313.33 masl/0.44 m above ground). Maximum WT height occurred on July 9 for B3-W1 (313.168 masl/0.36 m above ground) and B3W4 (313.176 masl/0.01 m above ground). The highest WT occurs near the outlet in 2013, due to underdrains transporting water down and directly to the outlet, leaving less water to distribute to the east fen.

In 2014, WT dynamics were influenced primarily by precipitation events and evaporative demand, resulting in a different temporal pattern than 2013. Levels increase following snowmelt and spring rain events, and decrease throughout the rest of the season. WT rise observed in late May at all locations is attributed to large rain events in May and the only inflow events of the year on 19-20 May (Figure 2.11). These increases were especially pronounced at well locations at Boardwalk 2 and 3. B2-W3 is located in a sand island, and exhibited extremely rapid responses to rain and pumping events. A steady drying throughout the summer occurs in all wells, in addition to a general movement of water from west to east. In late August, B1-W2 dries more rapidly than east fen locations, due to little upper fen contributing area at this location. Absolute highest WT at this time occurs at B3-W1 and the hydraulic gradient reverses with water movement towards the storage pond. 15 mm of rain fell from 30 August – 30 September and 28 mm on 26 September causing rapid increases in WT, returning the hydraulic gradient in the fen from west to east.

The closing of the underdrains in 2014 resulted in a large disparity between WT in the west and east fen. Due to steady pumping into the storage pond in 2013, B1-W2 maintained a high WT with little fluctuation over the season (Figure 2.10), while in 2014 this location declined more substantially in late summer, drying by 0.59 m (Figure 2.11). In contrast, closer to the outlet in B3-W1, the WT in 2013 fluctuated greatly, and declined substantially when the outflow pumps were on, while in 2014, maintained a fairly constant WT. This can be attributed to the influence of underdrains in 2013 lowering the WT at east fen locations, as a large volume of water was drained downwards and directly into the sump without reaching the third boardwalk. In contrast, in 2014 a high WT is observed at the third boardwalk after rainfall and pumping events as water moves laterally from the inlet towards the outlet with almost no drainage through the underdrains.

In 2014, paired wells were installed at the base of hummocks (TR-W8/TR-W9 and TR-W10/TR-W11) to indicate whether the water movement is towards the fen or upland. TR-W8, located at the base of Hummock 5, and TR-W9, situated on the same slope further upland, show the hydraulic gradient almost entirely from upland to the lowland well, becoming more pronounced as later in the summer as ET dries the fen (Figure 2.12). This trend is consistent in TR-W10 and TR-W11 located in Hummock 6.

Despite differences in seasonal temporal patterns and fluctuations between sites, a high water table was maintained in both years (Figure 2.13). B1-W2 and B3-W1, the two wells located in the centre of the lowland, both showed WT above the peat surface over 90% of the time. B3-W4, located near the outlet almost always had a WT greater than -0.3 m and similarly, B2-W4, located near the edge of the main lowland typically showed WT greater than -0.5m. UP-W1 showed a wider range of WT depths and was higher in 2013 than 2014.

It is important to note that 'upland' and 'lowland' areas within this study are dynamic throughout the season. Upland typically refers to the well-drained, planted forested area, while lowland refers to the wetland area. These terms are used not only because of topographic position, but also because of soil type placement within the fen. Figure 2.14 shows the changes that occur in throughout the growing season in terms of surface saturation (courtesy of Carl Mendoza and BCG Engineering Inc.).

2.4.8 Groundwater

Carl Mendoza and the University of Alberta supplied groundwater data. Groundwater movement was from the south berm to the east, moving towards a wetland reclamation site currently under construction, King Fisher (Figure 2.15). The fluxes through the fen were negligible compared to other water balance components, and were therefore ignored within this balance.

2.5 Discussion

2.5.1 Water Balance Dynamics

Reconstructing wetland watersheds after mining is challenging in the WBP, as the water balance is dependent on the interactions between a climate characterized by a long term water deficit, punctuated with seasonal and decadal wet and dry cycles, and a complex geology with a large storage capacity (Devito et al., 2012). While conceptual models (Devito et al., 2012), studies on small scale-test cells (Faubert and Carey, 2014), and studies within the natural WBP (Devito et al., 2005) have examined the hydrology of wetlands within the region, this study is the first to quantify the water balance components on a full-scale peatland-containing watershed on soft tailings. To perform wetland functions, the SFW must maintain a water position near or at the peatland surface, and exhibit similar water chemistry of a natural wetland (National Wetlands Working Group, 1997). There was concern that elevated salinity would prevent development of wetland vegetation, so in 2013, artificial pumping was intense, resulting in double the annual precipitation pumped through the watershed. In 2014, pumps were mainly off, and the water balance was dominated by vertical fluxes of P and ET (Figure 2.16; Table 2.2). Future reconstructed wetland systems are not likely to be designed with active pumping systems, and therefore 2014 provided enhanced insight into the hydrologic function of the SFW undergoing a passive management approach.

Considering overall storage changes throughout the season, 2013 exhibited much larger monthly surpluses and deficits than 2014 (ranging -199 mm to 198 mm) while 2014 storage variations were less variable (ranging – 62 mm to 66 mm) (Table 2.3). Excluding May, the ET/P ratio in 2013 was lower than 2014. Extremely large storage deficits occurred in July and August, due to the intense pumping regime, indicating that despite climatic influences and timing of precipitation events dominating natural hydrologic regimes, artificial pumping regimes completely alter the water balance of this constructed system.

2.5.2 Pump Management and WT

Despite varying influences dominating the water balance in 2013 and 2014, both years maintained a WT depth within the range of a natural peatland. WT depth in the lowland ranged from -0.5 m to 0.4 m in 2013 and -0.2 m to 0.4 m in 2014, with means of

0.11 and 0.08 m in each year respectively. Within the center of the lowland, WT was either at, or above the ground surface over 90% of the time. These levels were generally higher than those observed in natural peatlands, which usually range from -0.4 to 0.1 m above the surface (Gignac et al., 1991; Nicholson et al., 1997), indicating artificial pumping may not be required to sustain high enough WT to promote peat accumulation, and hydrophilic vegetation growth.

The high WT in both years is critical for two reasons: 1) ET may be affected if WT drops below a specific threshold and 2) WT depth impacts physical peat properties leading to feedbacks in hydrologic function. Lafleur et al. (2005) and Faubert and Carey (2014) found weak correlation between WT and ET when the WT was at or near the ground surface. Similar results were found in this study, with weak correlation between WT and ET at all sites except Fen N in 2014, where a weak positive correlation is observed. This may be attributed to the WT rising above most wetland vegetation and evaporating as an open water system. The lowland was never water-limited, and evaporated at near potential rates; however, artificial drainage, open underdrains or natural periods of drought could lead to a much lower WT. The effects of a lower WT on ET are typically limited by feedbacks, where decreases in surface evaporation due to a lower WT are compensated by increased transpiration from vascular vegetation (Kim and Verma, 1996). However, depending on which vegetation dominates the lowland area, WT decreases below the rooting depth may limit ET losses.

Secondly, the exposed, dry peat before pumps were turned on and high WT afterwards may lead to changes in physical peat properties. Exposed peat may increase in bulk density, therefore increasing retention capacity and decreasing conductivity (Schlotzhauer and Price, 1999). These changes could lead to increases in effective stress causing surface subsidence and peat volume changes, impacting the WT depth, variability and elevation relative to the ground surface (Waddington et al., 2015; Whittington and Price, 2006). The heterogeneous peat material placed within the lowland combined with varying degrees of saturation affecting the physical peat properties may affect the ability of peat to allow capillary movement of water to sustain surface moisture, impacting decomposition and carbon storage within the system. Further analysis of the peat properties is required to fully understand this relationship.

It is also critical to note that while the WT was largely above the surface, the large fluctuations may be detrimental to vegetation. In July 2013, the rapid decline in WT due to pump failure led to visible stress in plants, and promotes weed growth while limiting successful development of desirable species. A more stable WT is necessarily for the overall health of the watershed (House et al., 2013).

2.5.3 Climate Variability and Vertical Water Balance

Timing and magnitude of precipitation events fell near normal for the area, however the WBP undergoes long term precipitation cycles of three to five dry years (PET:P=1.2 to 1.8) per decade, alternating with three to five mesic years of lower PET:P ratios (0.9 to 1.1). These cycles are interrupted by short periods of significantly wet years occurring every 2-3 decades (Devito et al., 2012). A changing climate may alter these cycles, as the Boreal region is expected to warm, increasing evaporative demand and experience greater rainfall variability (IPCC, 2013), which will alter the timing and magnitude of moisture deficit and surplus. Varying cycles and dynamics in precipitation timing and phase may lead to the SFW's inability to maintain a high WT during consecutive years of drought. Within the growing season, ET exceeded P in almost all months of both years, while P tended to surpass ET during spring and fall months (Table 2.2).

Significant differences in snowfall between years as observed between the 2013 and 2014 season can considerably impact WT and overall water balance. As 65-75% of annual precipitation falls as rain during summer months, corresponding with high PET, snow accumulation and contributions from melt are important for replenishing storage deficits when plants are dormant and evaporative demand is low. Depending on antecedent moisture conditions, this surplus at snowmelt can move into the ground as storage for plant use, salt flushing or nutrient redistribution. In 2013, 30% of annual precipitation fell as snow, while in 2014, snowfall constituted 16% of total P. While total snowfall between years was variable, snow accumulation spatially across the fen did not show large differences between the lowland and the upland. Accumulation is expected to increase in the upland areas as vegetation matures and traps more snow, which could supply more water to the lowland and help sustain moisture levels. However, interception efficiency increases with increasing leaf area index (Hedstrom and Pomeroy,1998; Metcalfe and Buttle (2001)), which could lead to increased sublimation, limiting the quantity of snow input to the system.

2.5.4 Management Implications

While definitive management strategies should be developed through long-term studies, the preliminary hydrologic data collected during this study provides a strong baseline and framework for future management practices and design of constructed watersheds within the OSAA. Artificial pumping designed to control upward advection of saline water has a significant effect on WT, and inconsistent pumping regimes could lead to WT fluctuations that change peat properties and limit paludification. Artificial pumps and underdrains were intended for use during only the first few years of commissioning. Long-term analysis of all water balance components is necessary as the fen matures, however as further wetland reclamation construction is currently underway. Pumps and underdrain systems are not a design feature of these future sites, and as such 2014 provides a baseline of water balance dynamics with little pumping influence. Long term monitoring of this constructed system is necessary through the inter-annual and seasonal variations of timing and magnitude of precipitation (Devito et al., 2012), as well as changes in upland/lowland ET rates as vegetation matures.

2.6 Conclusions

It is estimated that 66000 ha of wetlands will need to be reclaimed in the post-oil sands mining landscape (Trites and Bayley, 2009). Reconstructing self-sustaining peatland-containing watersheds at this scale is complicated by the dry, variable climate and complex geology of the WBP. SFW represents one of the first attempts to construct a wetland atop soft tailings in the OSSA. Results from this long-term research project will provide insight for mine closure planners on design and management practices. Artificial management controlled the water balance in 2013, while in 2014 the dominant fluxes were ET and P. ET rates between years and upland and lowland locations were similar during the growing season. While both years received climatically normal precipitation, WT fluctuations were much greater in 2013 due to artificial pump management, and differed between upland and lowland landscape units. Without the artificial influence of pumping, vertical fluxes dominate the water balance. As vegetation growth continues on the SFW, the water balance dynamics will evolve, with upland areas likely to increase ET loss. Construction of another instrumented wetland research project is currently underway at Syncrude Canada Ltd, and while long-term data is ideal for planning, this study provides valuable water balance data of the SFW in the first two years of operation and developed a framework for analyzing the hydrologic controls of this unique watershed.

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2.8 Figures

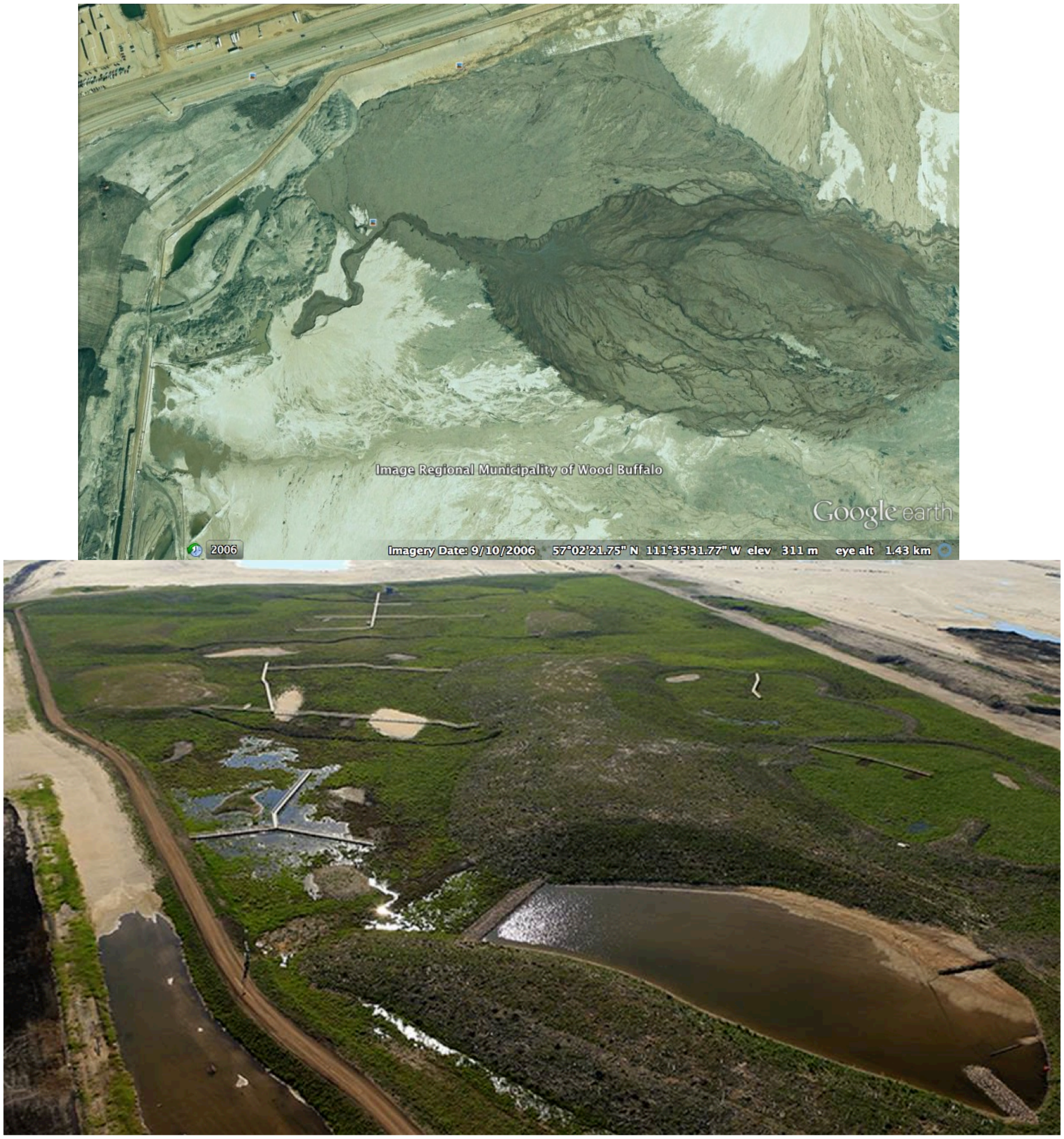

Figure 2.1. Aerial photographs of SFW before construction in 2006 (top) (Google Earth, 2015) and in 2014 (bottom).

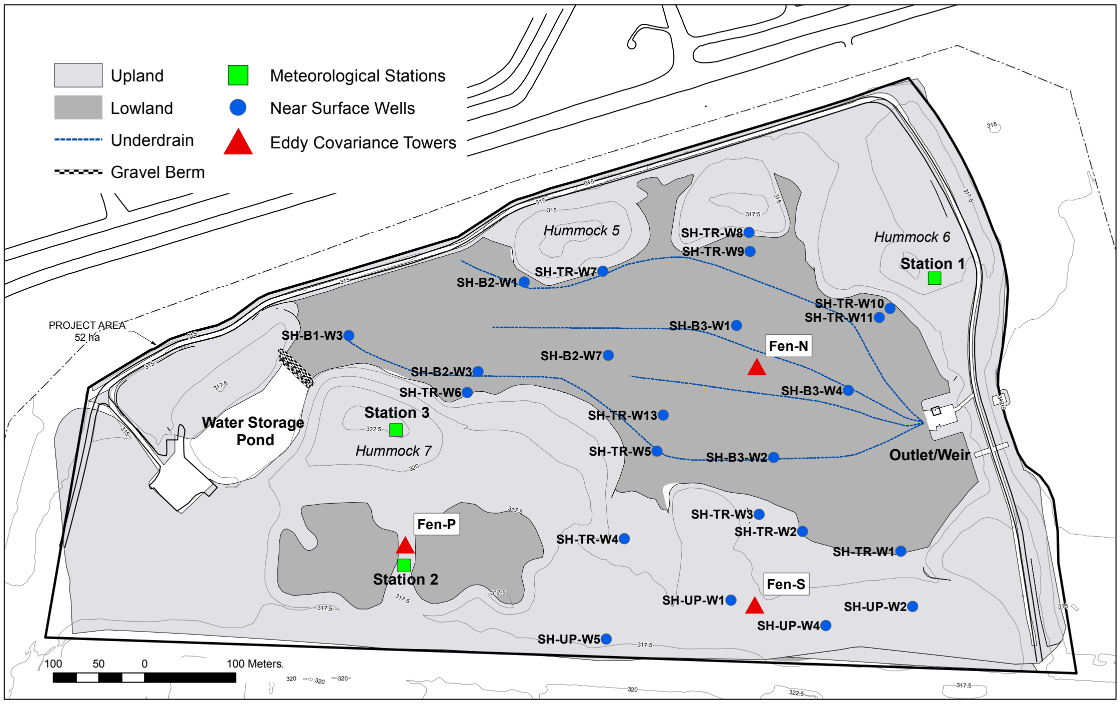

Figure 2.2. Instrumentation map of SFW. Eddy covariance towers Fen S and Fen P represent the upland (terrestrial) area, while Fen N represents the lowland (wetland) area. Fen S was constructed in 2012, Fen N in 2013, and Fen P in 2014.

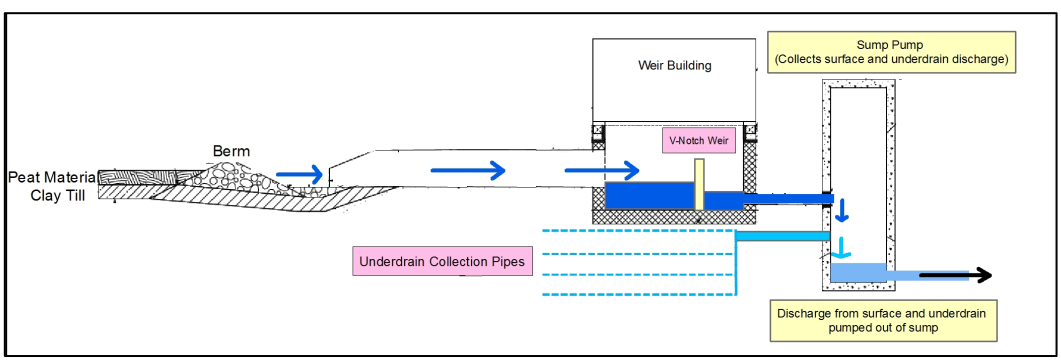

Figure 2.3. Schematic cross-section of outlet and weir building on the SFW.

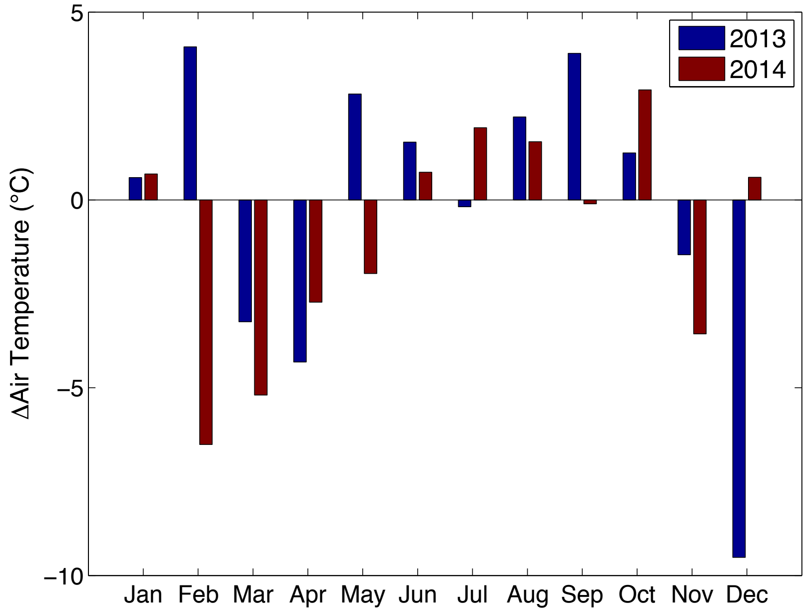

Figure 2.4. Monthly mean temperature differences in 2013 and 2014 from climatic normal at the Fort McMurray airport (1981-2010) (Environment Canada, 2014).

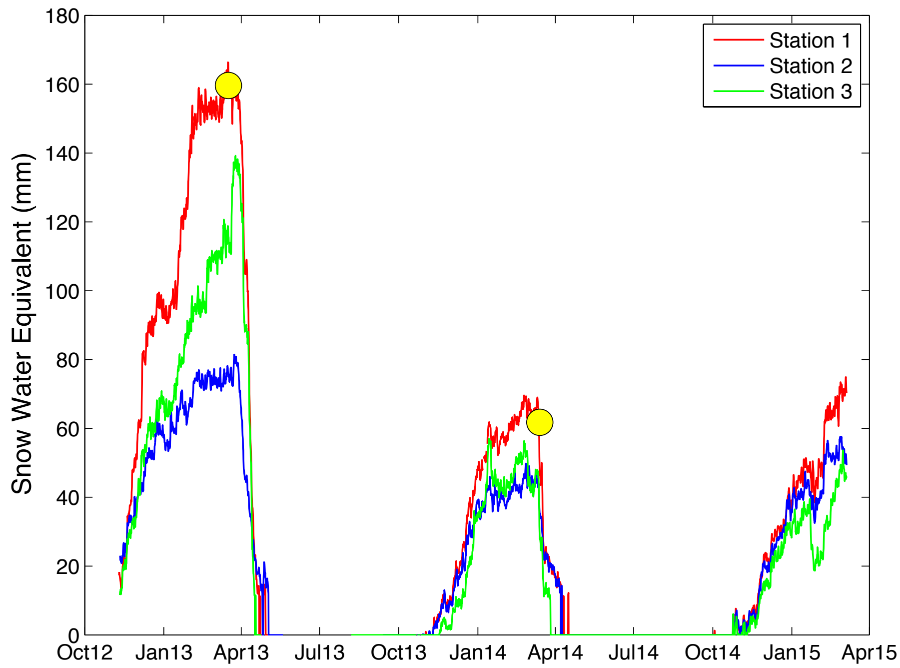

Figure 2.5. Snow water equivalent (SWE) measurements at 3 automated snow depth sensors from Sept 2012 until March 2015. Yellow dots denote the mean SWE during the snow survey conducted each year.

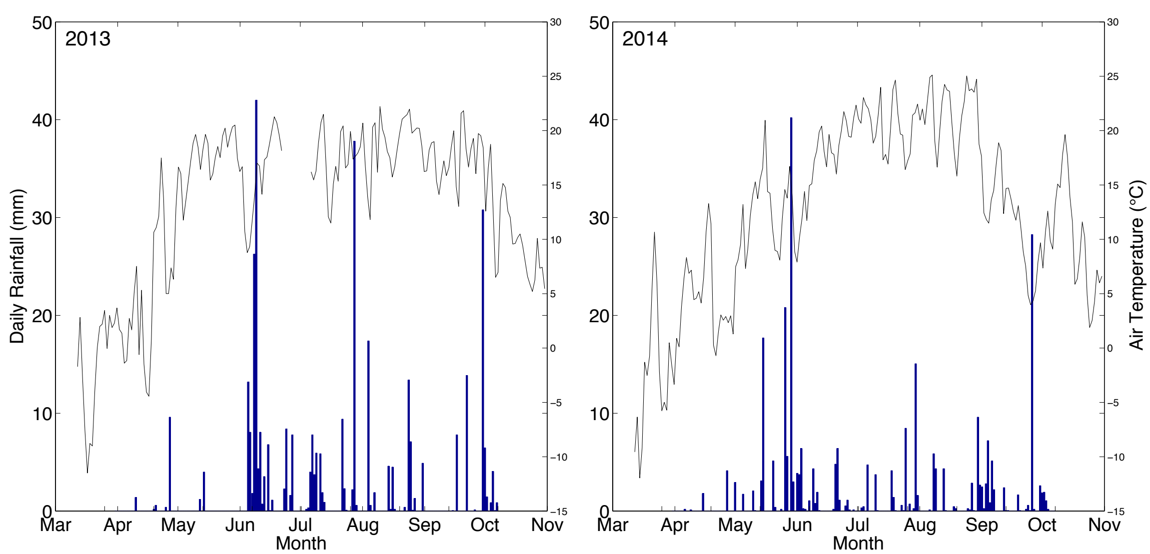

Figure 2.6: Precipitation (bars) and air temperature (lines) over the 2013 (left) and 2014 (right) snow free seasons, SFW, Fort McMurray, AB

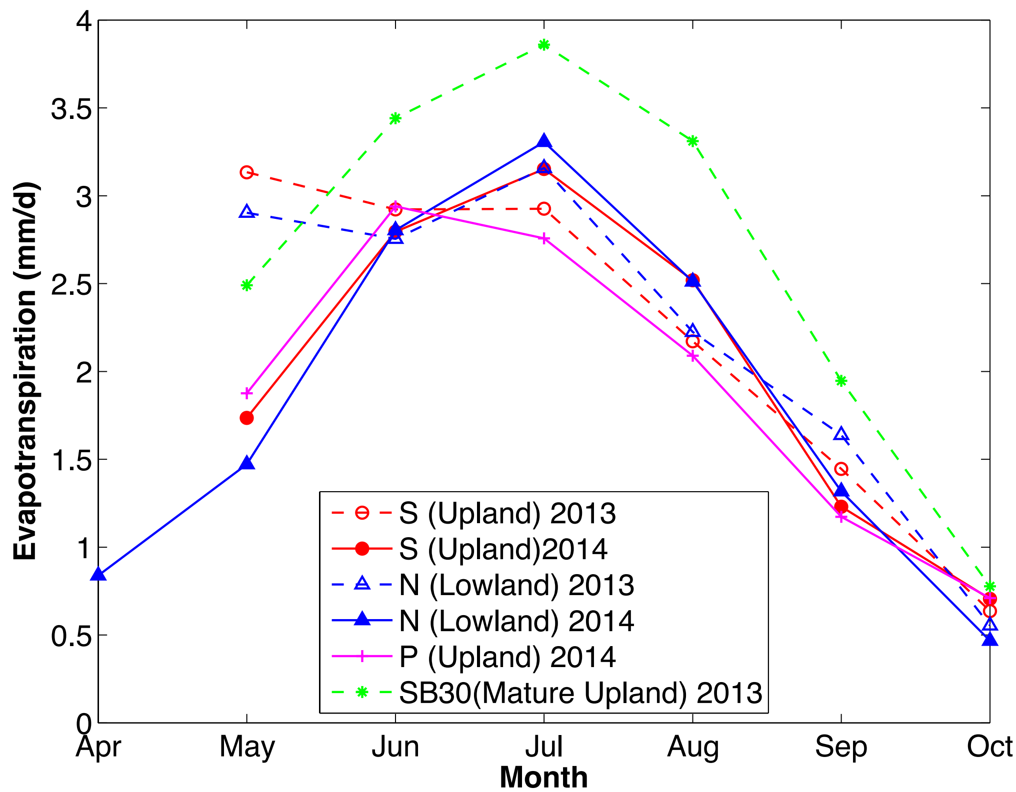

Figure 2.7. Mean monthly ET rates for the SFW and SB30, a forested reclaimed site constructed in 2002 at Syncrude Canada Ltd.

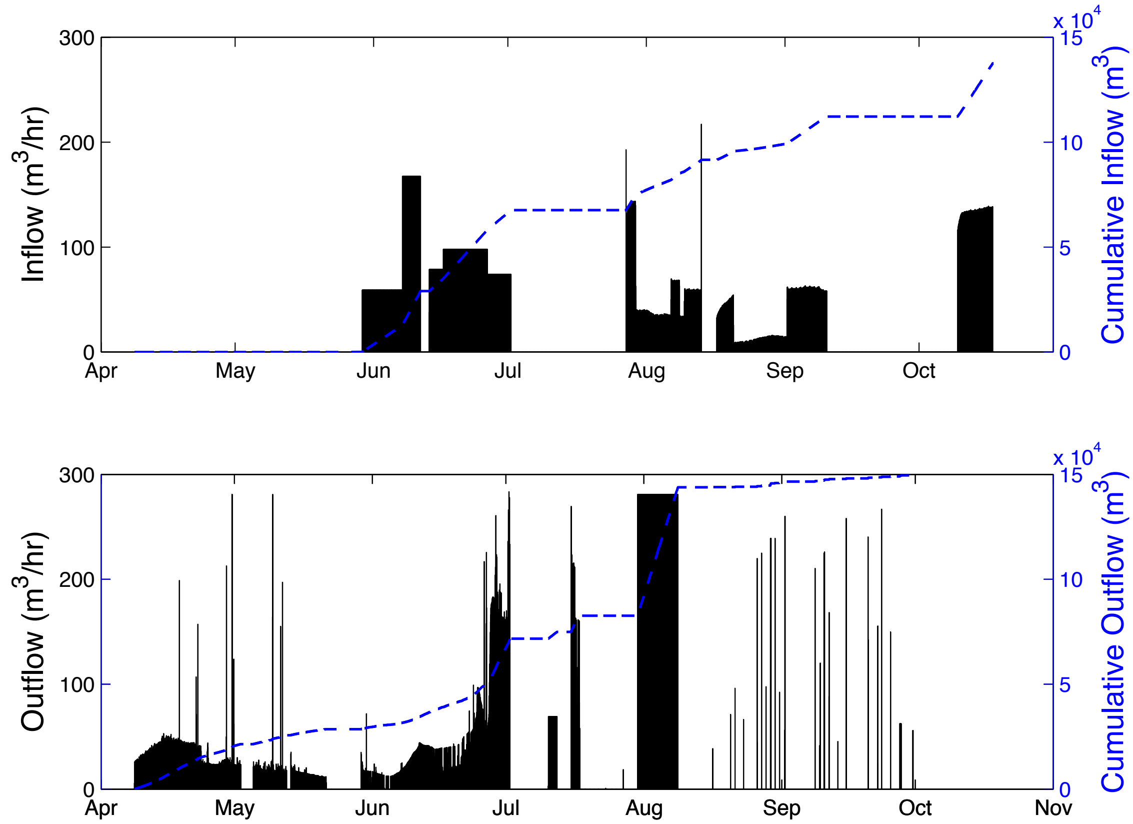

Figure 2.8. Total hourly (m^3/hour) and cumulative (m^3) inflow and outflow for the SFW in 2013.

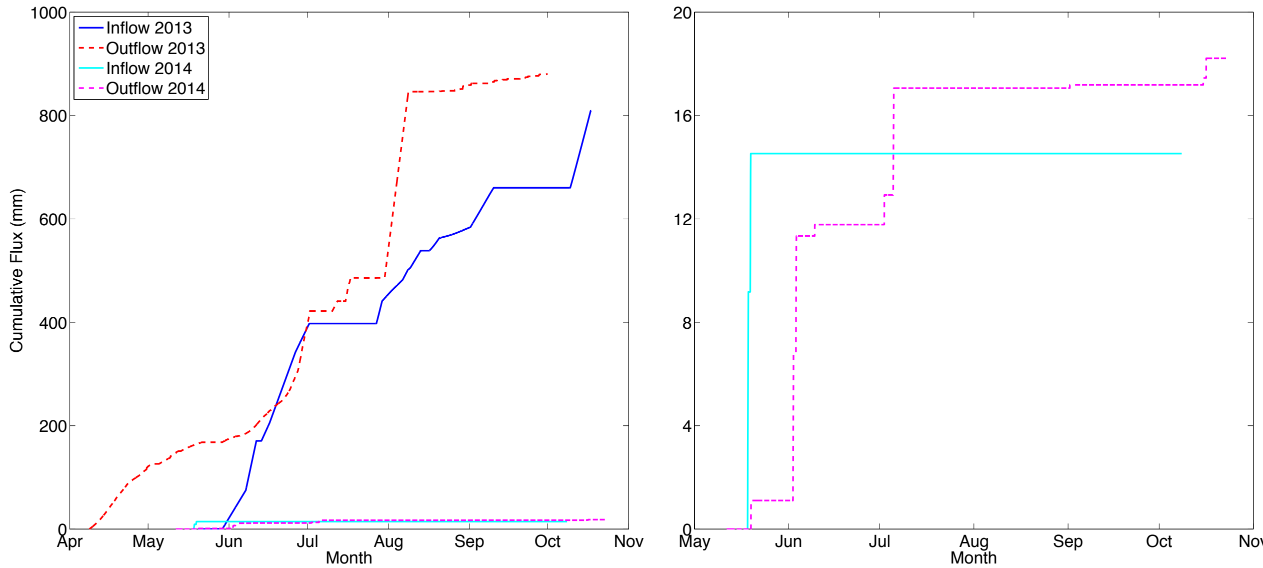

Figure 2.9. Cumulative inflow and outflow in mm (applied over 17 ha lowland) over the 2013 and 2014 season. Scale in 2014 (right) has been magnified to view pumping events.

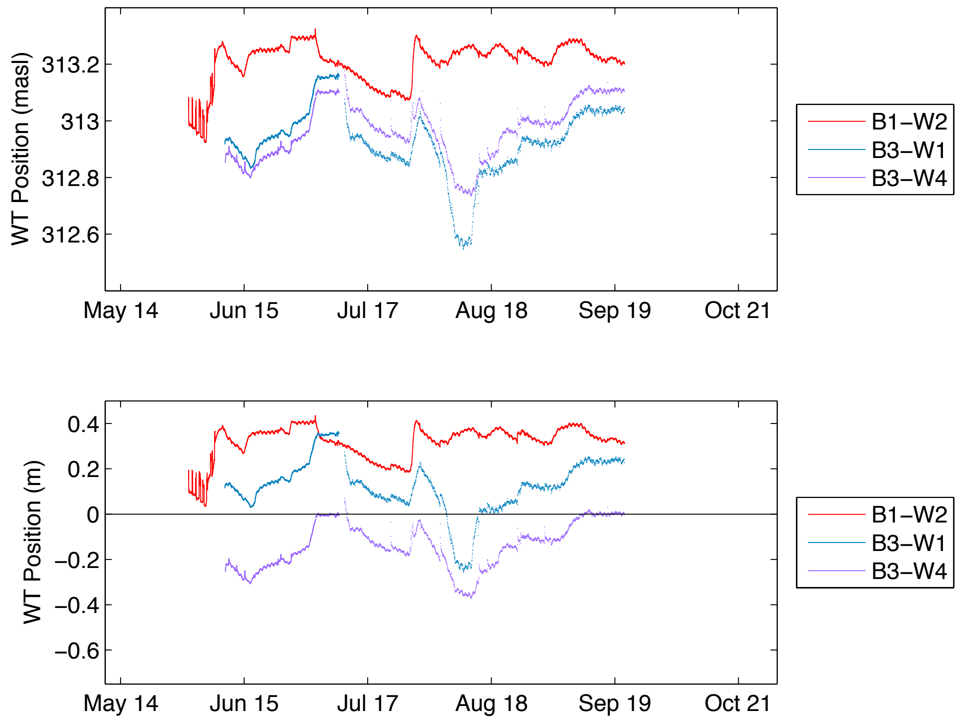

Figure 2.10. 2013 WT position for lowland transect in the SFW in masl (top) and with reference to the ground (bottom).

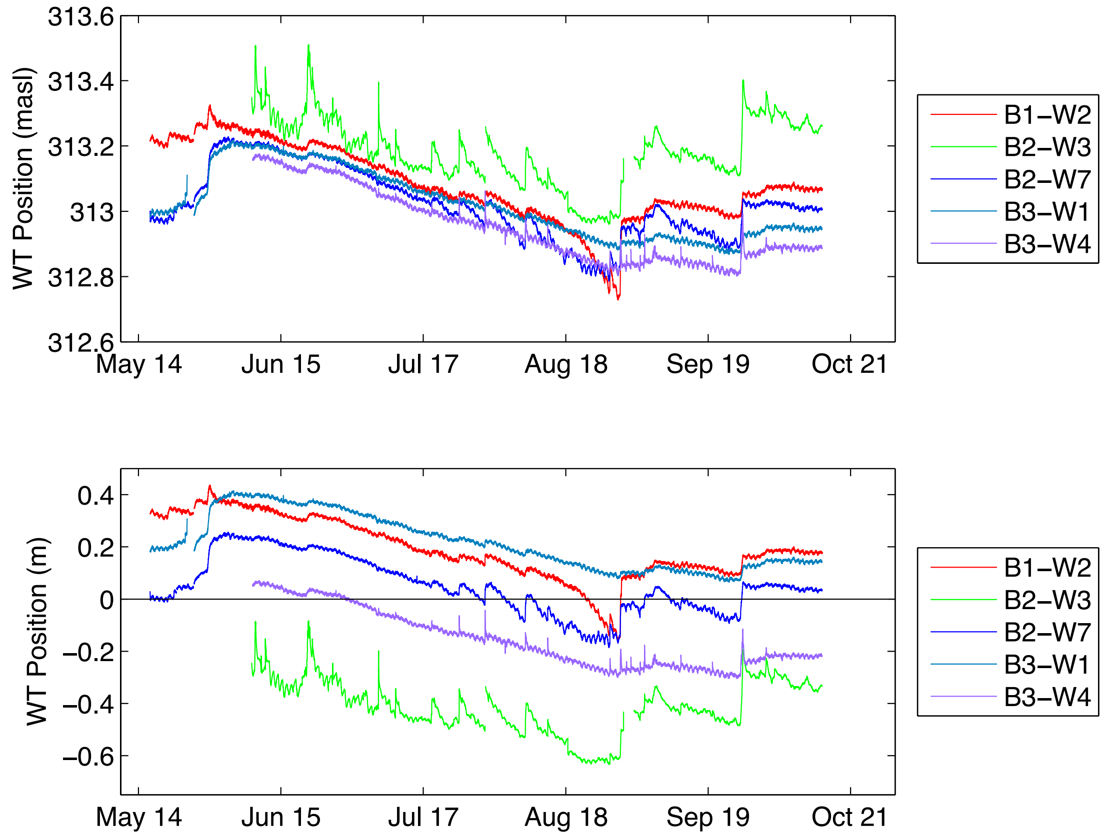

Figure 2.11. 2014 WT position for lowland transect in the SFW in masl (top) and with reference to the ground (bottom).

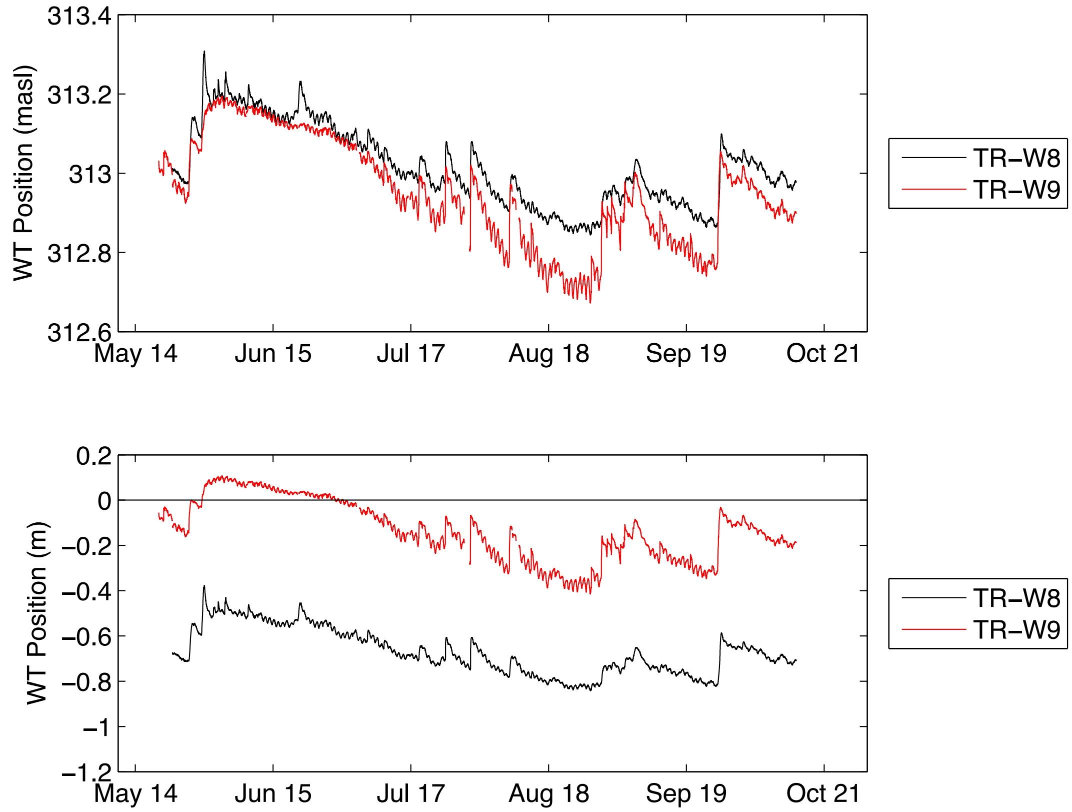

Figure 2.12. WT position for TR W8 and TR W9 in 2014 in masl (top) and with reference to the ground (bottom). TR W8 is located at the toe of a hummock, while TR W9 is positioned slightly further into the upland.

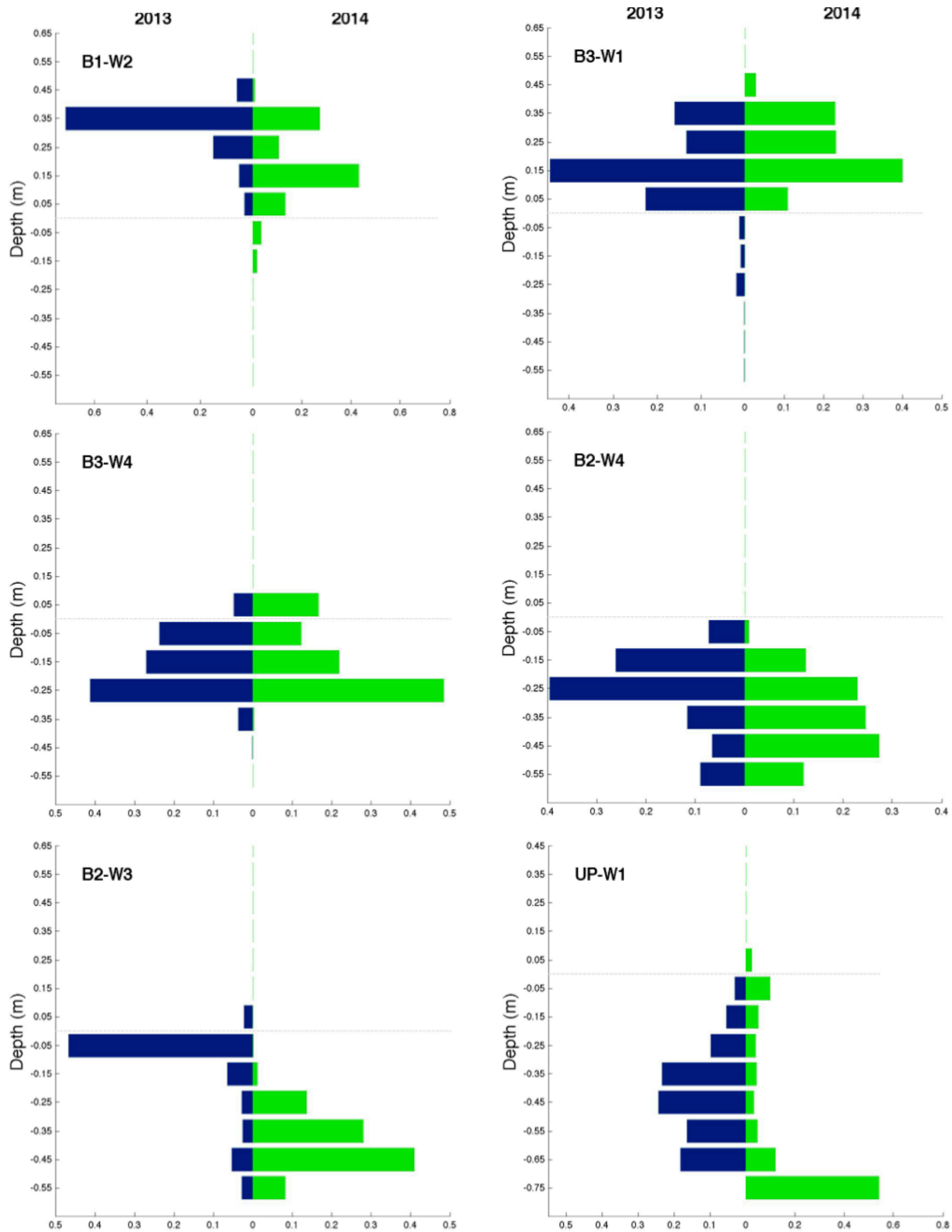

Figure 2.13. Comparison using proportions of time at various WT depths in wells during 2013 (left/blue) and 2014 (right/green).

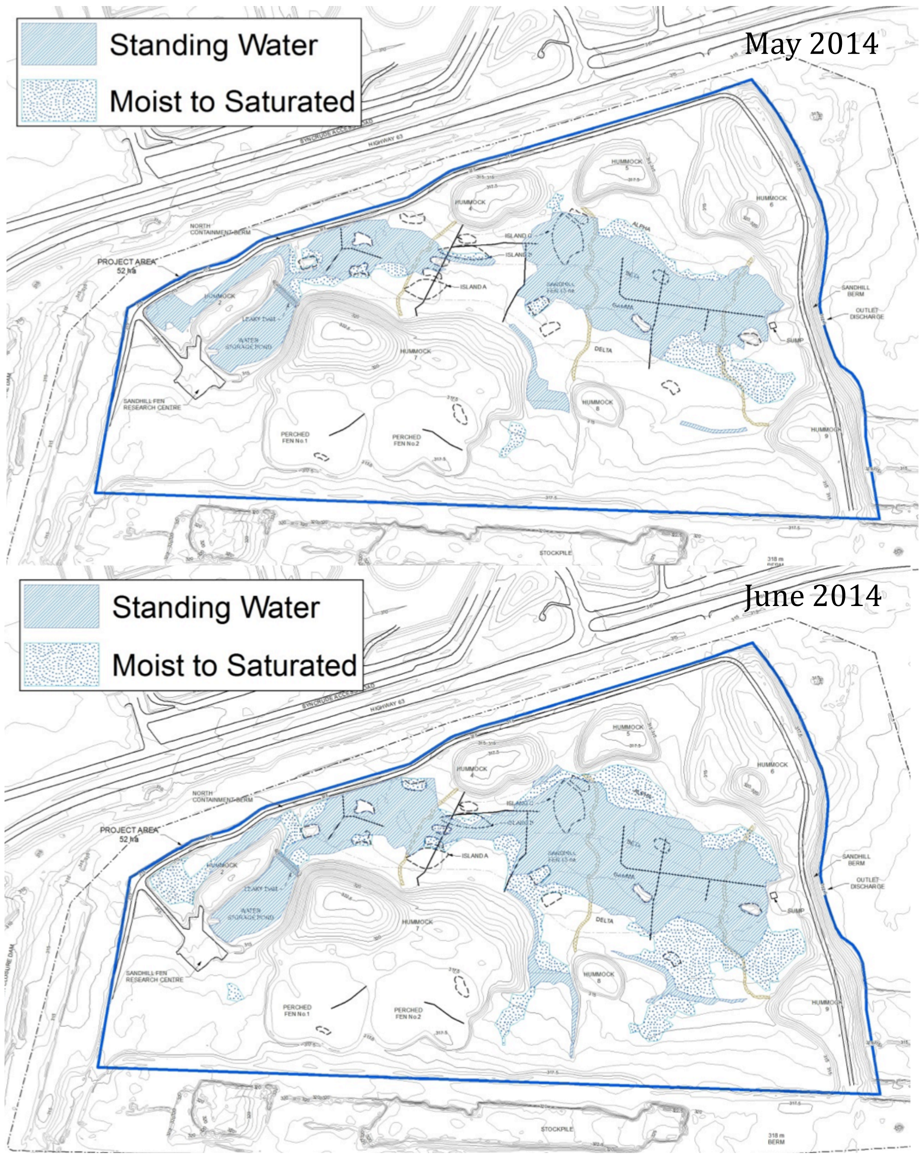

Figure 2.14. Saturation maps of the SFW in May and June of 2014 (top to bottom) provided by Carl Mendoza and BGC Engineering Inc.

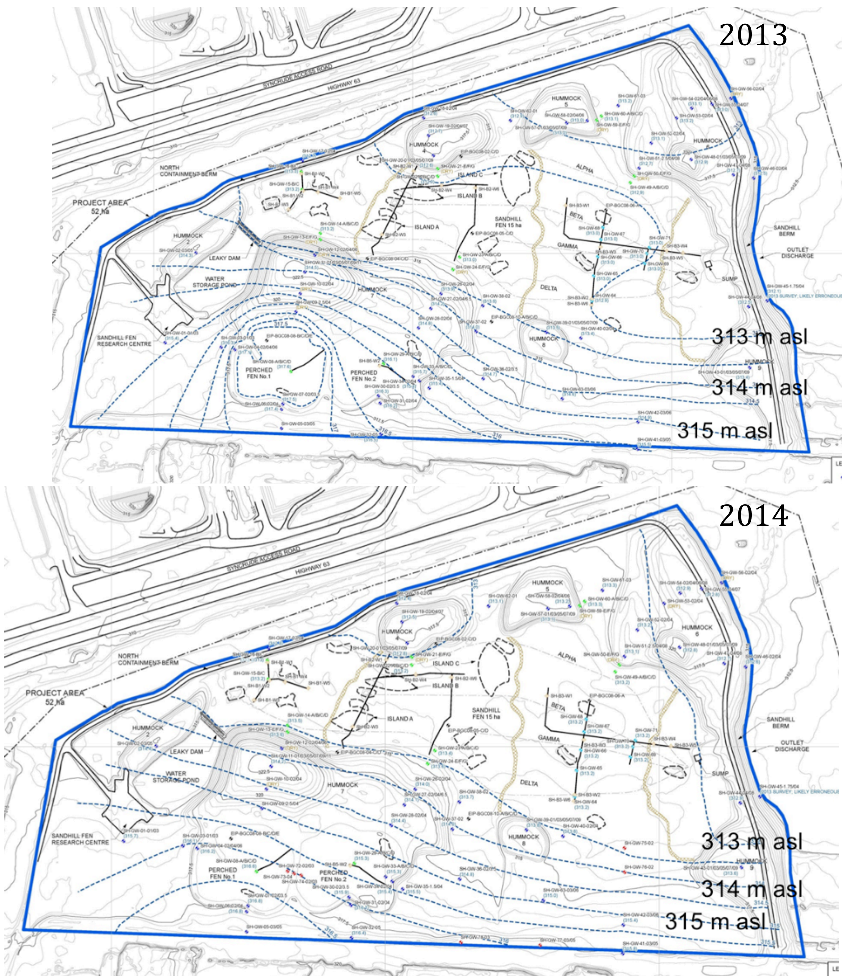

Figure 2.15. Groundwater maps on the SFW in 2013 and 2014, provided by Carl Mendoza and BGC Engineering Inc.

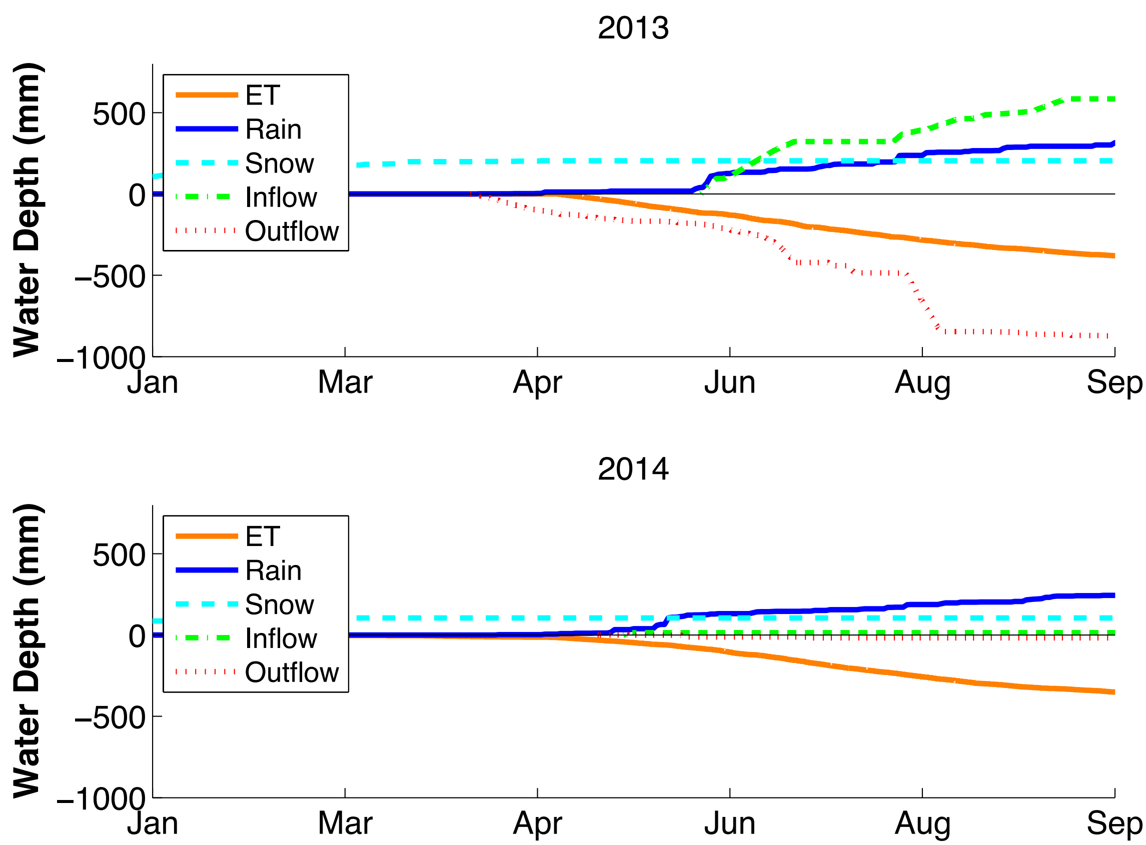

Figure 2.16: Water balance components of the SFW in 2013 (top) and 2014 (bottom).

2.9 Tables

Table 2.1: ET values for three eddy covariance towers on the SFW from 2012-2014. All values reported run from DOY 121-273 (May-Sept)

		2012			2013			2014	
	Max ET Rate (mm d^{-1})	Mean ET Rate (mm d^{-1})	Cumulative Growing Season ET (mm)	Max ET Rate (mm d^{-1})	Mean ET Rate (mm d^{-1})	Cumulative Growing Season ET (mm)	Max ET Rate (mm d^{-1})	Mean ET Rate (mm d^{-1})	Cumulative Growing Season ET (mm)
Fen S	5.91	2.22 (1.18)	339	5.26	2.52 (1.1)	386	4.65	2.29 (0.96)	350
Fen N	--	--	--	7.44	2.54 (1.19)	389	6.23	2.29 (1.21)	350
Fen P	--	--	--	--	--	--	4.50	2.17 (0.91)	332

Table 2.2. Growing season (May-Sept) water balance components for the SFW in 2013/2014

	P	ET	ET/P	Inflow	Outflow	**ΔS**
May 2013	5	95	19	22	55	-123
June 2013	136	86	0.63	369	221	198
July 2013	83	92	1.11	64	145	-90
August 2013	57	67	1.18	129	318	-199
September 2013	53	45	0.85	77	21	64
May 2014	103	51	0.50	15	1	66
June 2014	37	84	2.3	0	11	-58
July 2014	42	99	2.36	0	5	-62
August 2014	31	78	2.52	0	0	-47
September 2014	57	38	0.67	0	0	19

Table 2.3. Water balance for the SFW (in mm) over the 2012-2014 study periods

	Rain	Snow	ET	Inflow	Outflow	**ΔS**
Oct 1 (2012) – April 30 (2013)	15	160	--	0	123	--
May 1-Sept 30 (2013)	334	0	387	660	760	-228
Oct 1 (2013) – April 30 (2014)	27	62	72	149	0	+166
May 1 -Sept 30 (2014)	270	0	350	15	17	-82

Chapter 3: Evapotranspiration and surface energy balance of upland and lowland sites on a newly constructed watershed, Fort McMurray, Alberta

3.1 Abstract

In northern Alberta, oil sands mining has completely disturbed hundreds of square kilometers of natural boreal landscape. Reclamation strategies are currently focused on the reconstruction of wetlands and peatlands within this area. This is particularly challenging due to the long-term water deficit in this region, along with the ubiquitous presence of salts within the underlying tailings material. In 2012, Syncrude Canada Ltd. completed construction of the Sandhill Fen Watershed (SFW), a 52-ha upland-wetland system to evaluate wetland reclamation strategies. The watershed includes upland hummocks, vegetated swales, a fen wetland, an artificial pumping system, and underdrains. The success of the SFW is dependent on the sustainable supply and storage of water to promote wetland vegetation, peat accumulation and limit elevated salinity. The water balance in the Western Boreal Plain is primarily controlled by vertical fluxes, with evapotranspiration (ET) comprising the largest natural loss in this region. In this study, three eddy covariance towers were used to quantify ET and assess the controls on ET during the 2013 and 2014 growing seasons. Energy partitioning, total ET, and atmospheric and surface controls were compared inter-annually, between uplands and lowlands, and to natural boreal peatlands to contextualize this constructed system within the oil sands region. Both growing seasons received normal amounts of precipitation and were slightly warmer than the 30-year normal. Latent heat flux dominated energy partitioning throughout the growing season, with mean Bowen ratios between 0.31-0.45.

ET rates were similar between years and among tower locations, and average daily rates ranged from 2.41 – 2.52 mm d^{-1}. ET was primarily radiatively driven at all sites. Energy partitioning and total ET was similar to natural boreal peatlands, however ET within the upland area on the fen is expected to rise as LAI increases in coming years as vegetation develops. Long term monitoring and analysis of these controls is necessary to evaluate the influence of climate cycles and management strategies on the sustainability of reclamation ecosystems.

3.2 Introduction

The oil sands industry is one of Canada's most vital economic resources, containing the third largest oil reservoir in the world (Paskey, Steward and Williams, 2013). The mining process, classified as either in situ or surface mining, has caused significant disturbance to the natural boreal landscape. Disturbance caused by in situ mining is generally limited to infrastructure such as processing facilities, seismic lines, roads, and pipelines (Yeh et al., 2010). However, surface mining requires drainage and removal of vegetation and overburden up to depths of 100 m (Johnson and Miyanishi, 2008). This results in the natural mosaic of well-drained upland forests, lakes and wetlands to be stripped away, with the overburden stockpiled for later reclamation. The total oil sands area overlies an area over 142000 km^2, with more than 4800 km^2 available for surface mining, and almost 800 km^2 currently cleared or disturbed (Government of Alberta, 2013). According to the Government of Alberta's Environmental Protection and Enhancement Act, industry is responsible to reconstruct ecosystems to their previous land capability (OSWWG, 2000). With open pits, tailings and overburden piles left behind after mining, reclaiming this landscape requires complete reconstruction of ecosystems, rather than simple restoration. Construction of both uplands and wetlands is necessary and now mandatory for industry to receive reclamation certification and exonerate their liability (Vitt and Bhatti, 2012; Devito et al., 2012). Most reclamation techniques have focused on reclaiming upland ecosystems (Carey, 2008; Rowland et al., 2009; Lilles et al., 2010; Sorenson et al., 2011), while wetland reclamation strategies have only recently become a centre of focus (Raab and Bayley, 2011). Wetlands, and specifically peatlands make up approximately half the boreal landscape (Rooney et al., 2012; Price et al., 2010) and perform essential global and regional ecosystem services, such as water storage and transmission, carbon storage and biodiversity (Waddington et al., 2015). To fully reclaim the boreal environment, it is critical that peatlands be re-established in the post mining landscape (Government of Alberta, 2013).

Wetlands classification is based on hydrological and chemical gradients (Zoltai and Vitt, 1995). Mineral-type wetlands produce little or no peat, and include marsh, shallow water and some swamps, while peatlands are classified as areas accumulating peat exceeding 40 cm, and classifications include bogs, fens and some swamps (National Wetlands Working Group, 1997). Mineratrophic areas that receive water and nutrients from telluric or atmospheric inputs are classified as fens or swamps, while bogs are ombrotrophic and only receive inputs from precipitation (National Wetlands Working Group, 1997; Price and Waddington, 2000). Distinction between peatland types depends on chemical differences and variations in vegetation. Peatlands vary from acidic, *Sphagnum*-dominated bogs and poor fens to alkaline, brown moss-dominated rich fens

(Zoltai and Vitt, 1995). Carbon cycling, methane production and oxidation pathways in peat is due to the proximity of aerobic and anaerobic zones within the peat deposit, and therefore the water table position (Lee and Cheng, 2009). Non-peat forming wetlands do not develop extensive ground layer of bryophytes like fens and bogs, and commonly undergo severe seasonal water table fluctuations (Zoltai and Vitt, 1995). Marshes and shallow open water wetlands have been the focus of wetland reclamation projects as they may form extemporaneously in poorly drained areas (Alberta Environment, 2008; Raab and Bayley, 2012).

It is typically stated that reconstructing peatlands is particular challenging as they take thousands of years to form (Yeh et al., 2010). The process is further complicated by the sub-humid climate and long-term water deficit of the Western Boreal Plain (WBP), where annual potential evapotranspiration rates (PET) exceeds precipitation (P). Most of the precipitation also occurs during the summer, when evaporative demand is high, and little water is available for wetland development (Devito et al., 2005). Designing a sustainable watershed containing a peatland requires placing and contouring stockpiled peat in a way that sustains a basic wetness condition and limits salt movement to sustain wetland plant communities (Price et al., 2010). In the reclamation process, soil types of varying thickness and composition are used to cap overburden or tailings material, resulting in an ecosystem that may or may not have similar hydrology or atmospheric interactions as the previous boreal landscape (Huang et al., 2015). During the growing season, ET is typically the largest hydrological flux within the boreal region water balance (Barr et al., 2007; Devito et al, 2005) and therefore understanding the controls on the timing and magnitude of ET is critical to evaluating the long-term success of reclamation projects and in future planning of landscapes. Marshes that develop in surface depressions, or shallow ponds and lakes, experience high evaporative losses and may act as net water sinks, while areas with more vascular vegetation may minimize losses and act as net water sources to the landscape (Brown et al., 2010; Lafleur, 2008; Petrone et al., 2007), although complex feedback processes of water table depth fluctuations, peat deformation, aerodynamic roughness changes, vegetation type, and climatic cycles complicate these generalizations (Waddington et al., 2015). While water balance and ET dynamics studies have been performed on small plot-scale peatlands (Faubert and Carey, 2014), a full-scale wetland-containing watershed in a post-mining landscape has never been previously constructed (Price et al., 2010), the ideal proportions of wetland to forested upland are unknown, as are the quantities and major influences on ET in constructed systems. Varying patterns and ratios of uplands to wetlands will alter the dynamics of ET through changes due to sheltering and changes in surface roughness and atmospheric vapour demand (Petrone et al. 2007).

The general estimate of annual ET within a 50-70°N latitude zone is 300-400 mm yr^{-1} (Budyko, 1974), although this varies greatly between terrain units (Barr et al., 2009; Eaton et al., 2001). Long and short term variations in vegetative and atmospheric controls dictate ET trends and magnitude (Barr et al., 2009; Eaton et al., 2001). A varying rate of soil moisture depletion occurs depending on soil type and plant root characteristics (Petrone et al., 2015; Brown et al., 2010; Rouse, 2000). Within natural boreal systems, previous studies examining ET and energy partitioning from northern wetland systems have found that ET rates for natural fens are fairly low compared to marshes and swamps, while slightly higher than bogs (Brown et al., 2010; Lafleur, 2008). While these variations between wetland types do exist, Humphreys et al. (2006) studied mid-growing season ET dynamics on seven northern Canadian peatlands and found similar ET rates among all the sites, which included a wide range of bogs and fens. Wetland ET is primarily radiatively driven, with an effect of increasing stomatal control with increasing vapour pressure deficit (VPD) (Runkle et al., 2014; Brummer et al., 2012), particularly in the peatlands with vascular plants relative to peatlands with predominately moss-cover (Humphreys et al., 2006). Evaporation from moss-dominated peatlands tends to be below potential evaporation (Campbell and Williamson, 1997), while vascular vegetation tends to be relatively efficient in latent heat transfer (Lafleur et al., 19997). Effects of water table depth, atmospheric turbulence, canopy resistance and energy partitioning are understood within a natural context due to long term programs such as FLUXNET and BOREAS (Wu et al., 2010, Amiro et al., 2006; Barr et al., 2007; Baldocchi et al., 2001), and within restored peatlands in the eastern Boreal forest. However, the extent of these factors is not well understood for reclaimed systems (Wu et al., 2010, Carey, 2008). There is very little data quantifying and assessing these controls of ET from reconstructed wetland sites, as the first large scale projects have only recently completed construction.

Syncrude Canada Ltd. (SCL) finished constructing the Sandhill Fen Watershed (SFW) in 2012, one of the first instrumented wetland-containing watersheds built on soft tailings. The goal of this long-term research project on the SFW is to assess current reclamation strategies; design and management practices on the long-term functionality of constructed wetland ecosystems and compare this to natural boreal wetlands (Vitt and Bhatti, 2012). In this study, eddy covariance measurements of ET and the surface energy balance of upland and lowland locations on the SFW are reported. The measurements occurred over three growing seasons (2012-2014), representing the first three years after construction was completed. The objectives of this study are to: (1) document how growing season ET and energy partitioning vary inter-annually and between uplands and lowlands (2) evaluate the environmental and physiological factors influencing ET and 3) compare these values to natural boreal peatlands to contextualize this constructed watershed within the oil sands administrative area. As long term hydrological functions of the SFW depends primarily on the vertical water balance, this study provides baseline ET data for the first two years after construction and places the first large-scale peatland containing watershed construction project into the context of natural boreal peatlands. This data may be used to compare surface energy partitioning and water vapour fluxes in future years on the SFW, as well as provide a reference for design and management of future reclamation projects within the oil sands.

3.3 Methodology

3.3.1 Site Description

The SFW is located in northeastern Alberta, 40 km north of Fort McMurray (57°02' N 111°35' W). The area was mined from 1977-1999, and construction of the SFW occurred from 2008-2012, where the area was filled with 35 m of inter-bedded composite tailings, followed by a 10 m sand cap. Due to the presence of salts in the underlying layers, the fen area was capped with 0.5 m of fine-grained clay till to prevent the diffusion of tailings pore water into the fen. The lowland area, comprising 17 ha, was then topped with 0.5 m of salvaged peatland material. Sand islands were also placed in the lowland area. On the 35 ha of upland, well-drained hummocks were placed with harvested litter, fibric, humic (LFH) material, clay-till and peat-mineral mix. Freshwater is pumped in from a lake just north of the site, where it is held in a water storage pond, and released to the lowland fen through a leaky gravel berm (Figure 3.1). To further control elevated salinity, underdrains, constructed with perforated 9-inch high-density polyethylene pipes, were installed 1-3 m below the fen surface. Water collected in these pipes drain into a sump at the outlet of the SFW, where surface water flows through a weir, and the total discharge from the fen is pumped out of the watershed. Two perched fens totaling an area of 2.4 ha were designed in the southwest upland area and equipped with inflow pumps (Vitt and Bhatti, 2012).

Planting of wetland and upland vegetation is necessary to achieve reconstructed landscapes within a time frame reasonable for reclamation certification (Trites and Bayley, 2009). Upland vegetation was planted in early June of 2012 with varying proportions of trembling aspen (*Populus tremuloides),* jack pine (*Pinus banksiana),* black spruce (*Picea mariana*), and white spruce (*Picea glauca)*. Wetland species planted by seed include a variety of sedges (*Carex aqualtilis, C.diandra, C.paupercula, C.utriculata*), arrow grasses (*Triglochin maritima* and *T.palustre*), rushes (*Scirpus lacustris* and *S. cyperinus*) and slough grass (*Beckmannia syziagachne*) (Vitt and Bhatti, 2012). In August 2014, a vegetation survey revealed two distinct vegetation communities within the wetland, each associated with wet or dry areas (Dale Vitt, personal communication). Within the dry areas, *Calamagrostis canadensis* dominated, while *Carex aquatilis* dominated wet areas. Wetland species were reduced in dry areas, where weeds typically dominated (House et al., 2014).

3.3.2 Instrumentation

In order to better account for the spatial variability of ET between the upland and lowland areas, three eddy covariance towers measured continuous fluxes of energy, momentum and scalars throughout the growing season (May – October). The south tower (Fen S), located in the south upland, was constructed in May 2012. The north tower (Fen N) located within the east side of the wetland began data collection in June 2014, and lastly a tower was constructed in between the two-perched fens (Fen P) in May 2015 (Figure 3.1). Instrumentation details are provided in Table 3.1. Each tower was equipped with a 3-D sonic anemometer (Fen P and S: CSAT3; Campbell Scientific, USA, Fen N: R3-50, Li-Cor, USA) and a fine wire thermocouple situated in the center of the sonic head. Mass density of water vapour was measured using an open path infrared gas analyzer (LI-7500, Li-Cor, USA) (IRGA) at Fen P and Fen S, while Fen N used a closed-path IRGA (LI-7200, Li-Cor, USA) drawing air from directly below the sonic anemometer (tube length 1 m, diameter 9 mm). All gas concentration and wind speed measurements were collected at a frequency of 10 Hz.

Net all-wave radiation, as well as down and up-welling long- and short-wave radiation, was measured at Fen S using an NRLite net radiometer (Campbell Scientific, USA) and 2 SP Lite2 pyranometers (Kipp and Zonen, Netherlands). At Fen P an NRLite2 net radiometer was used (Kipp and Zonen, Netherlands) and at Fen N a CNR4 net radiometer (Kipp and Zonen, Netherlands) was installed. In addition, horizontal wind speed and direction at Fen P and Fen N was measured using a wind monitor Model 05103-10 (R.M. Young Co., USA) while horizontal wind speed was measured at Fen S using a 3-cup anemometer. ET over the entire watershed was computed as the product of LE fluxes for the uplands (mean of Fen S and P) and lowlands (Fen N) and the weighted area of each landscape unit.

Three tipping bucket rain gauges (Model CS700, Campbell Scientific, USA) measured precipitation at three meteorological towers. 22 near-surface wells continuously measured WT depth using Solinst Junior Edge leveloggers (Model 3001) (Figure 3.1).

3.3.3 Data Corrections and Gap Filling

EddyPro was used to apply spectral corrections for high and low frequency losses. Small gaps in fluxes of less than two half hour periods due to poor signal strength, technical malfunctions or rain events were filled using linear interpolation, while larger gaps were filled using the mean diurnal variation over specified windows of time. Net radiation data was run using 4, 5 then 14-day intervals. Q_E and Q_H were gap-filled by removing nighttime values when net radiation was less than 10 W/m^2. Values of Q_E and Q_H with absolute differences larger than 150 W/m^2 were removed. Q_E less than -50 W/m^2 and greater than 400 W/m^2 and Q_H values less than -100 W/m^2 were also removed.

3.3.4 Data Analysis

The energy balance for an extensive, homogenous surface, in the absence of advection is given by:

$$R_n = \lambda_v E + H + G + S \qquad (1)$$

Where R_n is net all wave radiation, $\lambda_v E$ is the latent, or evaporative, heat flux, H is sensible heat, G is ground heat flux, and S is storage (within the air column, standing water, vegetation) (Lafleur and Rouse, 1988). Positive R_n and S denote an energy gain by the study area, $\lambda_v E$ and H are positive when energy is upward, away from the surface, and G is positive for heat flux into the ground (Amiro and Wuschke, 1987).

Ground heat flux was calculated using soil heat flux plates buried at 2 and 5 cm below the ground. Two pairs of plates were installed at Fen N, and the mean flux at the surface was taken from the two 2-cm plates. At Fen S, a malfunctioning 5 cm plate led to using the 2 cm plate as surface heat flux, and to be consistent, the 2 cm flux plate was also used at Fen P. Heat storage in the soil above 2 cm was assumed to be negligible.

Heat storage within the column of standing water, J, was computed on a daily basis as the product of the average daytime temperature of the water column (measured every 10 cm), the density of water, and specific heat capacity of water, divided by time. Thermocouples were installed in late June 2014, and therefore changes in heat storage are calculated only from this date onwards.

The Penman-Monteith equation provides a framework to assess the primary atmospheric and biophysical factors controlling ET; available energy (R_n – G), vapour pressure deficit (VPD), aerodynamic resistance (r_a) and surface resistance (r_s). The equation describes the estimation of $\lambda_v E$ as:

$$\lambda_v \mathrm{E} = \frac{\Delta\ (R_n - \mathrm{G}) + \frac{\rho c_p (e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad (2)$$

Where Δ is the slope of the saturation vapour pressure curve versus temperature relationship, ρ a is the mean air density at constant pressure, c_p is the specific heat of the air, G is the ground heat flux, e_s is the saturation vapour pressure, e_a is the actual vapour pressure and r_a and r_s are the aerodynamic and bulk canopy resistances respectively (Oke, 1987). The measured values of latent heat using eddy covariance can be used to solve for r_s (Humphreys et al., 2003; Baldocchi et al., 2000) Surface resistance primarily refers to the bulk canopy resistance and therefore the stomata-mesophyll control, however the term encapsulates all resistances of a number of other pathways, including cuticula and ground resistance from the soil (Foken, 2008). Aerodynamic resistance, r_a, was calculated using Equation 3 to include excess boundary resistance to heat and water vapour transport, an approach commonly used in previous peatland studies. Surface and aerodynamic resistances are the inverse of the surface and aerodynamic conductance, which is also widely reported (Humphreys et al., 2006; Runkle et al., 2014; Kim and Verma, 1996).

$$r_a = \left(\frac{kB^{-1}}{ku_*} \left(\frac{d_h}{d_v} \right)^{2/3} + \frac{U}{u_*^2} \right) \qquad (3)$$

Within Equation (3), k is the von Karman's constant, U is the mean wind speed, u_* is the friction velocity, d_h/d_v is the ratio between thermal diffusivity (d_h) and molecular diffusivity to water vapour (d_v), and was set to 0.89 at 20°C. B^{-1} is a dimensionless parameter, and the term kB^{-1} is an estimate of the logarithmic ratio between the roughness length of momentum and the roughness length for mass and sensible heat fluxes (Owen and Thomson, 1963; Runkle et al., 2014). In order to compare r_a values to recent peatland studies (Runkle et al., 2014; Humphreys et al., 2006), a value of 2 was used for kB^{-1}, although values ranging from 1.6 to 2.3 have been used in previous peatland studies (Campbell and Williamson, 1997).

The Penman Monteith equation can also be utilized to evaluate the relationship between water availability and atmospheric demands. The degree of coupling between available energy and $\lambda_v E$ was determined using the Priestley-Taylor coefficient, α_{PT}, which is the ratio of measured $\lambda_v E$ to equilibrium $\lambda_v E$ ($\lambda_v E_{eq}$). $\lambda_v E_{eq}$ is the latent energy of a freely evaporating surface under a fully saturated atmosphere, or where surface resistance goes to zero and the aerodynamic term in the Penman equation is neglected (Priestley & Taylor, 1972; Jarvis & McNaughton, 1986)). α_{PT} is calculated as:

$$\alpha_{PT} = \lambda_v E / (\Delta R_a / (\Delta + \gamma)) \qquad (4)$$

where R_a is available energy (Priestley and Taylor, 1972), commonly calculated as $R_n - G$, α_{PT} values exceeding 1.0 indicate well-watered systems that are closely coupled to available energy. Commonly, a value of 1.26 is used to estimate non-water stressed crops. Lower values indicate dry, low productivity surfaces, where biotic controls greatly influence transpiration (Priestley & Taylor, 1972). Leaf area index (LAI) was measured at approximately once a month using a LAI-2200 (Li-Cor).

Finally, the decoupling coefficient, Ω, was used to quantify the degree of interaction between the evaporating surface and atmosphere, and therefore indicates the relative importance of the energy term. Ω is calculated as:

$$\Omega = \frac{\Delta/\gamma + 1}{\Delta/\gamma + 1 + r_s/r_a} \qquad (5)$$

The control of surface resistance, and therefore stomatal influence, increases as Ω approaches zero. Low values tend to occur in drier, water limited systems, with strong turbulent mixing, while values of 1 or high values close to 1 imply complete decoupling of latent energy and the atmospheric moisture budget and dominance of R_n in controlling ET (McNaughton & Jarvis, 1983; Jarvis & McNaughton, 1986).

The quality of eddy covariance flux measurements can be assessed using the energy balance closure, where the sum of available energy, net radiation minus soil heat flux, is compared to the sum of turbulent fluxes of latent and sensible heat. Energy balance closure values are reported in Table 3.1, and range from 0.48 to 0.62, which is considered low. Lack of closure is potentially due to loss of low frequency components of the flux, averaging procedures and a lack of precise accounting of storage terms (Meyers and Hollinger, 2004). Particularly at Fen N, where water was above the ground surface over 90% of the time in 2013 and 2014, heat storage was calculated using the mean daily change in temperature of the water column. Changes in heat storage accounted for ~23% of R_n over the 2014 season, and is expected to be similar in 2013, accounting for missing energy in the balance.

3.4 Results

3.4.1 Climate

There was a notable difference in rainfall (R) timing and magnitude between the study years (Figure 3.2; Table 3.2). The 2013 growing season (May-September) received 365 mm of rainfall, compared to 290 mm in 2014. The timing of these events varied between months; May 2013 was exceptionally dry, receiving only 5 mm of precipitation, while in May 2014, 111 mm of rainfall fell. Conversely, in 2013, June received 153 mm of rainfall, while only 40 mm fell in 2014. All other months in 2013 were similar to normal. Differences in rainfall timing can be attributed to the convective nature of storms in the region. Average precipitation events in 2013 and 2014 were 4.96 and 3.36 mm respectively. Both years received slightly more precipitation than the 30-year climate normal for Fort McMurray, AB, however, neither could be classified as an exceptionally wet or dry year. With respect to air temperature, 2013 was slightly warmer than 2014. Mean daily air temperatures on the SFW were 1.94°C and 1.32°C for 2013 and 2014 respectively, while average daily temperature (1981-2010) for the Fort McMurray Airport is 1.0°C (+/-1.3°C) (Environment Canada, 2014), which is located approximately 45 km south of the SFW. Both years were warmer compared to the 30-year climate normal for Fort McMurray Airport.

3.4.2 Water Management and WT Depth

The hydrology of the SFW in both study years was managed and controlled with an active pumping system. In 2013, the inflow and outflow pumps ran almost continuously from May-October, resulting in 809 mm pumped into the watershed, and 883 pumped out. In contrast, in 2014, the inflow and outflow were managed into events, with 14 mm pumped in between 19-20 May, and 18 mm pumped out throughout the summer in events lasting 1-4 hours (Figure 3.3).

Due to this pumping regime, water table (WT) depths fluctuated considerably in 2013, while in 2014 depths were more constant and experienced a steady drying throughout the season (Figure 3.4). WT at the lowland location was well above the surface for most of 2013 and all of 2014. At the upland location, WT was close to the surface in late May/early July, but fell below -0.5 m for periods of 2013 and majority of the summer months in 2014.

3.4.3 Surface Energy Balance

Partitioning of available energy varied between the sites and study years. In all years and months, mean monthly daily total of $\lambda_v E$ dominated energy partitioning (Figure 3.5). In mid-summer months (June-Aug), $\lambda_v E$ made up 55-74% of R_n at Fen S and 33-58% at Fen N. At both towers, average daily maximum $\lambda_v E$ increased from May and peaked in July of all years (Supplemental Data Table 5.1). Mean monthly $\lambda_v E$ was similar between towers, with differences ranging from 0.11 MJ m^{-2} day^{-1} to 1.01 MJ m^{-2} day^{-1}. Considering both years, mean seasonal (May – Sept) $\lambda_v E$ averaged 5.54 MJ m^{-2} day^{-1} at Fen S and 5.52 MJ m^{-2} day^{-1} at Fen N.

At Fen S in 2012, H was highest in June at 2.21 MJ m^{-2} day^{-1}, comprising 23% of net radiation, and decreased the rest of the season, while in 2013 and 2014, H peaked in July and June but was more consistent throughout growing season, ranging from 3-17% of R_n. At Fen N in 2013, H reached its maximum in June (14% of R_n), and decreased the rest of the season. In 2014, H peaked in May (13% of R_n), and decreased throughout the rest of the season, excluding a low H of 0.78 MJ m^{-2} day^{-1} in June, likely due to a high water table and a large amount of energy heating the standing water (Supplemental Data Table 5.1).

G was not measured at Fen S in 2012, however in 2013 and 2014, G ranged from 2-10% of R_n, and generally decreased throughout the season. G at Fen N showed a similar trends and magnitudes as Fen S, despite a much higher water table. A large amount of available energy was partitioned into the heating the standing water throughout the fen, averaging 23% of net radiation. Average seasonal (May – Sept) daytime G over both years at Fen S was 0.35 MJ m^{-2} $day^{-}$and 0.48 MJ m^{-2} day^{-1}at Fen N.

R_n followed the same general trend as λ_vE, with the highest average daily totals in June and July at both towers in all years. Fen S had slightly lower R_n values in 2013 and 2014. At the upland tower, net radiation (R_n) peaked in 2013 on DOY 182 at 15.11 MJ m^{-2} $day^{-1}$and averaged 7.87 MJ m^{-2} day^{-1} for 1 May – 30 Sept. In 2014, R_n peaked earlier on DOY 164 at 14.59 MJ m^{-2} day^{-1} and averaged 7.52 MJ m^{-2} day^{-1} (Figure 3.5). At the lowland tower, daily maximum R_n of 18.44 MJ m^{-2} day^{-1} was reached on DOY 167 in 2013. Slightly earlier, maximum R_n of 19.23 MJ m^{-2} day^{-1} was reached on DOY 151 in 2014. Lowland average daily daytime R_n values were 9.82 MJ m^{-2} day^{-1} in 2013 and 10.11 MJ m^{-2} day^{-1} in 2014.

Average diurnal patterns were similar at all sites, with maximum λ_vE at 15:00 at Fen N, 14:00 at Fen S (Figure 3.6) and 13:00 at Fen P (not shown). λ_vE at Fen N was lower than Fen S and P during morning hours and exhibited a more gradual rise, although reaches the same peak $\lambda_v E$ and falls gradually throughout the afternoon, later than the other towers. Fen S and Fen P both experienced a sharp increase in $\lambda_v E$ and a more gradual decrease throughout the afternoon. The gradual rise in $\lambda_v E$ at Fen N in the morning could also be due to partitioning of energy into heating of standing water in the lowland. At all towers, H peaked earlier, between 11:00-13:00, while G reached its maximum between 14:00-16:00.

With respect to incoming solar radiation, wetlands generally have a lower net radiation efficiency (ratio of net radiation to incoming shortwave radiation (K_{down})) compared to boreal forests due to their higher albedo (α) and colder and wetter surfaces. Lafleur et al. (1997) found a R_n/K_{down} ratio of 0.55 compared to ~0.73 for boreal forests (Sharratt, 1998). R_n/K_{down} was 0.44 at Fen S and 0.47 at Fen N during the study period. A higher seasonal mean R_n as well as midday maximum R_n was observed at Fen N (Figure 3.7; Supplemental Data Table 5.1), likely due to a lower albedo. Average albedo was calculated using values between 11:00-14:30 due to high variations in albedo with the angle of incident solar radiation. Average mid-day albedo from May-Sept at Fen N was 0.11 in 2014 similar to albedo found in a wetland tundra (0.13-0.14) by Rouse et al., Weick (1992) and typical mid-day open water values (0.03-0.1) (Oke, 1987). Albedo at Fen S was higher than Fen N, with values of 0.21 and 0.22 respectively; falling closer to values of drier peatland sites studied by Moore et al. (2013), and slightly above summer boreal wetland albedo values (α = 0.15-0.18) summarized by Baldocchi et al. (2000). Mean Bowen ratios (β) from May-Oct were similar between upland and lowland, with β equal to 0.35 and 0.42 at Fen N. Within the uplands, β of 0.31 and 0.45 at Fen S were observed in 2013 and 2014 respectively, which are low relative to mature boreal-forested sites (Arain et al., 2003).

3.4.3 Evapotranspiration

Total ET for the June – August 2013 and 2014 were similar between years and among towers (Figure 3.8a). Cumulative ET is also shown for South Bison Hill (SBH) , a reclaimed forested upland site, constructed in 2002 on an overburden pile at SCL and used here to illustrate ET and energy balance dynamics of an upland system ~13 years since reclamation (Figure 5.3 (Supplemental Information)) (Carey, 2008; Huang et al., 2015). Cumulative ET and daily ET rates were much higher for SBH than all fen locations, with a cumulative flux of 326 mm while all fen locations ranged from 245-264 mm over the three months. Mean daily ET ranged from 2.41 – 2.52 mm d^{-1} and the fen and 3.27 mm d^{-1} at SBH. Maximum mean monthly ET occurred in July each year (Table 3.4), excluding Fen P, which reached maximum ET in June 2014 (Figure 3.8b). ET rates on the fen, both upland and lowland, are within the range of rates found at boreal peatlands in previous studies (Humphreys et al., 2006; Lafleur et al., 2005; Campbell and Williamson, 1997). Mid-summer ET rates at Fen S have increased each year since construction and exhibited close ET rates to SBH shortly after construction, although partitioning to H was much larger at SBH in its early years than at Fen S (Carey, 2008).

3.4.4 Environmental Controls on ET

The Penman Monteith equation was used to evaluate the influence of available energy, atmospheric conditions, and vegetative control on ET. Assessment of these controls revealed that $\lambda_v E$ at both upland and lowland locations are primarily controlled by R_n and VPD (Figure 3.9). R^2 values are shown on correlations that were significant, with r and p values reported in Table 3.4. R_n was the strongest influence on latent heat, especially well correlated at Fen N, with the greatest coefficient of determination (R^2) on a regression of daily mean daytime (9:00-16:30) data. VPD also showed strong correlation, with R^2 values ranging from 0.33-0.78, although the strong temporal correlation between R_n and VPD ($r = 0.69$, $p < 0.001$) could interfere with determining the causal relationship with $\lambda_v E$. Relationship between r_a and $\lambda_v E$ was weak but significant in all years and sites except Fen S in 2013 (Figure 3.9; Table 3.3). Aerodynamic resistance was highest at Fen N, with a mean daytime average of 74 s/m (June – Aug 2013 and 2014) compared to 21 s/m at Fen S. SBH and Fen P also exhibited lower aerodynamic resistances which can be attributed to increased momentum absorption by tall vegetation. Overall, mean daily growing season r_s was greatest at Fen P (178 s/m), followed by Fen S (148 s/m and 157 s/m) and Fen N (150 s/m and 145 s/m).

Diurnally, large variation of ET controls existed among towers (Figure 3.10). Diurnal patterns of r_s for all towers were similar, lowering during the early morning, with a slight lag behind R_n, and increasing with increasing VPD in the afternoon. Values of June midday (11:00-12:30) r_s and VPD correlated well at Fen S in both years ($r = 0.69$, $p < 0.001$ and $r = 0.72$, $p < 0.001$) (Figure 3.11). Positive correlation is consistent with other wetland studies (Humphreys et al., 2006, Lafleur and Rouse, 1988). However, this correlation was not observed at Fen N. Surface resistance at Fen N remained relatively constant throughout the day, and correlation between VPD and r_s at Fen N was not significant in both years (r = -0.15, p = 0.20 (2013) and r = 0.04, p = 0.97 (2014)) The lack of correlation between VPD and r_s is also evident when examining wet and dry periods (Figure 3.12). In dry periods, there is little correlation between VPD and r_s below 1.0 kPa, however at VPD > 1.0 kPa, a positive relationship is observed at Fen S. After precipitation events, this relationship is weaker, as ET is no longer influenced by transpiration. A rapid mid-day increase in surface resistance in response to increasing VPD is common at forested Boreal sites (Arain et al., 2003). At Fen N, this relationship is not observed, especially during wet periods, which is attributed to the very high water table within the lowland. The young age of the site and lack of vegetation dominating this area suggest it is behaving similarly to an open water surface.

The WT at Fen N in 2014 was also the only year and tower to show a significant correlation with LE (r = 0.40, $p < 0.001$) (Figure 3.13). All other sites and years showed no correlation between WT and LE, an observation consistent with other wetland studies (Humphreys et al., 2006; Lafleur et al., 2005)

Examining the Priestley-Taylor coefficient, α_{PT}, revealed that ET was occurring at or above PET for most of the growing season season. Mean daily daytime (9:00-16:30) α_{PT} were calculated using H + $\lambda_v E$ as available energy rather than R_n - G due to poor energy balance closure. Values indicate both the upland and lowland were well-watered systems (Figure 3.14). Growing season α_{PT} averages for the upland towers, Fen S and Fen P, range from 1.01 to 1.11 in both years, with similar values of 1.1 and 1.14 at the lowland Fen N in 2013 and 2014 respectively. In both years, α_{PT} at Fen S decreased throughout the season, as vegetation developed in the uplands and stomatal influence on

ET increased. At Fen N in 2013, α_{PT} remained constant throughout the season at ~1.1, as increased vegetation growth and biotic control throughout the season was balanced by a rising water table and high standing water in the lowland. In 2013, both towers reached their maximum α_{PT} of ~1.8 after large rainfall events in early June. In 2014, the water table was also high, providing an almost open water surface for evaporation. α_{PT} of the lowland area was 1.14, similar to a value of 1.11 found by Petrone et al., (2007) for a pond within the Boreal forest. Although both the upland and lowland sites evaporated close to maximum potential, natural peatlands have shown mid-season α_{PT} below one (Humphreys et al., 2006; Runkle et al., 2014; Petrone et al., 2007). It is worth noting that when available energy is calculated as R_n-G, seasonal mean α_{PT} values do fall below one, and therefore an improved energy balance closure would be ideal to accurately assess these controls. Values may continue to lower as vegetation matures on both the upland and lowland sites and stomatal control or changing water table depths become more dominants influence on ET.

The decoupling coefficient, Ω, was used to quantify the degree of interaction between the atmosphere and vegetation. Seasonal mean daytime Ω was 0.27 at Fen S and 0.25 at Fen N. These values are slightly higher than those found in an Alberta peatland (Ω = 0.16) and a number of boreal forests, from coniferous to deciduous (Ω = 0.10 – 0.25) by Brummer et al. (2012). Moore et al. (2013) found higher values between 0.71-0.83 at a peatland disturbed by long-term water table manipulation and Runkle et al. (2014) reported monthly summer values ranging from 0.65-0.73 in a northern fen peatland. Diurnally, Ω was fairly constant for both towers, however Fen S exhibits a peak in late morning, followed by a gentle decline into the large afternoon, as VPD becomes a more dominate influence as the day progresses (Figure 3.15). Runkle et al. (2014) also observed this trend, along with a decrease in Bowen ratio throughout the day. At Fen N, while the Bowen ratio also declines in the afternoon Ω remains steady throughout all hours and months.

3.5 Discussion

3.5.1 ET Rates

The objective of assessing ET rates and controls on the SFW is to determine where the greatest losses of water are occurring, and what factors are controlling this loss. The ET rates observed in the first two years after commissioning show little inter-annual and spatial variation (Table 3.5). The range of annual mean daily ET rates on the SFW from May – September were between 2.2– 2.5 mm d^{-1} for both upland and lowland locations. Daily ET rates are similar to those reported in undisturbed peatlands within the boreal region (Lafleur et al., 2005; Brummer et al. 2012; Runkle et al., 2014). Humphreys et al. (2006) also found ET rates for peatlands in northern Alberta to fall between 2.0-2.5 mm d^{-1}. Values were slightly higher than growing season ET rates (~1.5 mm d^{-1} for fens of varying age after disturbance), studied by Barker et al. (2009). Over the growing season, the lowland tower exhibited slightly higher ET rates and lost 36 and 39 mm more than the upland sites in 2013 and 2014. This trend is contrary to results described in the literature, where typically ET is greater at upland areas by 11-20% during the growing season as opposed to lowland fen sites of the same age due to higher transpiration from greater tree biomass and leaf area (Barker et al., 2009). Brown et al. (2014) also found ET rates of 3.1 mm d^{-1} and 3.5 mm d^{-1} above an aspen-dominated boreal site in the Utikima region close to Fort McMurray, higher than the upland rates on the SFW. The study years of the SFW thus far represent the first two years after commissioning, and planted vegetation within the uplands is still immature. As uplands develop, it is likely the ET rate will approach values similar to SBH, a forested site reclaimed in 2001/2002 also on the SCL lease (Carey, 2008; Huang et al., 2015). SBH was planted with white spruce and aspen similar to the SFW uplands. Total ET from May-September in 2013 (10 years after completed construction) at SBH was 461 mm, 19% greater than both the upland and lowland on the SFW. This increased ET is due to the high LAI of SBH relative to the fen. In 2014, both uplands and lowlands began the season in late May with similar LAI values of 0.92 and 0.88 respectively. LAI increased and reached its maximum in mid-July at SBH. Maximum LAI values were reached later on in early August, with peak LAI of 2.28 in the upland and 1.93 in the lowland. These peak values are greater than LAI found at SBH in the first few years after construction, as Carey (2008) found peak LAI of 1.2 in late June 2003. Average seasonal LAI was 3.1 at SBH, 1.80 at the fen upland and 1.36 at the fen lowland. Therefore, while rates are similar between hydrologic units in the early development of the fen, ET in the uplands is expected to increase in the following years.

3.5.2 ET Controls

The high water table at the SFW and lack of mature vegetation resulted in ET flux being primarily driven by net radiation and atmospheric demand for moisture. High ET coupling to available energy and VPD is commonly found in moss-dominated peatlands

(Humphreys et al., 2006). However, Humphreys et al. (2006) observed a strong influence from canopy resistance in northern peatlands, causing ET to fall below potential values, a trend that is not yet evident on the SFW. Surface resistance was lower than values found in peatlands by Brummer et al. (2012). In the coming years on the SFW, it is likely WT drawdown will occur as pump management moves towards a more passive approach. This will lead to an increase in vascular and moss vegetation growth, which will increase surface resistance, alter aerodynamic regimes and cause a shift from the current energy balance partitioning. It is also important to note the areas denoted by 'upland' and 'wetland' are dynamic throughout the year (Figure 2.14).

3.5.3 Management Implications

In order for peatland-containing watersheds to be sustainable, a water surplus must be generated and held within the wetland area. The unique pumping regime on the SFW has provided an initial saturation of the lowland in the first few years of commissioning and resulted in very high water tables. In the long-term, these pumps will be turned off, and future designs for reclaimed watersheds will likely not include artificial in and outflow. Because of this, the ability of the SFW to maintain this moisture surplus depends on the vertical fluxes of water, ET and P. Both forests and wetlands each have their own evaporative rates and controls influencing water loss. Generally, ET from forests is greater than wetlands (Barker et al., 2009; Brummer et al., 2012). Within wetlands, ET generally depends on the amount of open water area compared to areas where the WT sits below the surface. In open water areas, long-term evaporation rates are high, and AET:P ratios tend to fall around 1.1 and a net loss to the atmosphere exists.

Areas with WT slightly below the surface promote cold, anoxic conditions that limit plant root extension. As a result, these areas have AET:P ratios of 0.8 (Devito et al., 2012). In the early years of reclamation, maintaining a high WT within the lowland through artificial pumping may actually increase ET rates and cause a net water sink.

The vertical water balance in growing season months of 2013 and 2014 show a net deficit during this season (Table 3.6). Without active pump management, consecutive dry years could lead to WT drawdown, although Lafleur et al. (2005) suggests effects of WT lowering on ET rates are minimized as decreased moss evaporation is initially offset by increased transpiration. It is the deviations from the long term mean precipitation that will provide the excess moisture needed to sustain a wetland system, and therefore continued monitoring of the water balance in the SFW is required.

The type of vegetation that eventually dominates within the watershed will have a large impact on energy partitioning, and therefore ET rates, along with changes in interception efficiency for both the upland and the wetland regions. Within the wetland, *Sphagnum* mosses show the highest ET rates relative to lichen, followed by feathermoss. This occurs despite the fact that *Sphagnum* mosses typically thrive in less saturated moisture regimes, as lack of ability to conserve water through stomatal closure increases the overall ET rate (Brown et al., 2010). The colonization of varying species also changes the systems ability to access water at varying depths (Humphreys et al., 2006). Resistance to water vapour in *Sphagnum* mosses has been found to be fairly insensitive to changes in WTD (Williams and Flanagan, 1996), while brown mosses show a greater change in canopy resistance with small fluctuations in WTD (Janssens et al., 1992). In contrast, physiological behavior of some vegetation may be resistant to changes in water level. House et al. (2013) reported at the leaf scale for wetland plants at the SFW that photosynthetic rate, transpiration rate, radiation use efficiency, and water use efficiency differed by no more than 33% between flooded, variable, perched and dry sites. Consecutive dry years or altered pump management on the fen may lead to a change in not only the type of vegetation cover, but also how that vegetation affects energy partitioning and ET. This is also the case within the upland areas; ET will vary significantly depending on dominant vegetation succession. Conifer forests in the boreal region evaporate at rates between 25-75% of equilibrium evaporation at rates of less than 2.5 mm day^{-1}, with high sensible heat exchange, while broad-leaved aspen stands approach equilibrium rates and may lose up to 6 mm day^{-1} (Baldocchi et al., 2000), similar to SBH. Aspens are known to colonize rapidly after disturbances, and their seasonal dynamics of leaf growth and high water use significantly alter energy and water partitioning. High ET rates after leaf development in aspen stands can rapidly lead to soil moisture deficits (Blanken et al., 2001). ET dynamics will change in response to the type of vegetation that succeeds, both within the uplands and lowlands, meaning long-term monitoring is necessary to compare early ET rates and controls presented in this study to future changes on the SFW.

3.6 Conclusion

Successfully reconstructing wetland-containing watersheds after mining disturbance requires the detailed understanding of the quantities and controlling factors influencing ET. Though characterized by a long-term water deficit, the deviations from the average precipitation patterns on seasonal, decadal and multi-scales combined with spatial disparity of ET rates among forests, wetlands and open water allow for hydrologic functionality to maintain forest and wetland ecosystems. Results indicate that on the first few years after construction of the SFW, ET rates were similar between upland and lowland areas and these rates were primarily controlled by net radiation and atmospheric demand for moisture. The partitioning of energy and main controls will evolve as vegetation matures on both the upland and wetland areas of this watershed, and therefore long term monitoring is required to determine proper hydrologic management of this unique system.

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3.8 Figures

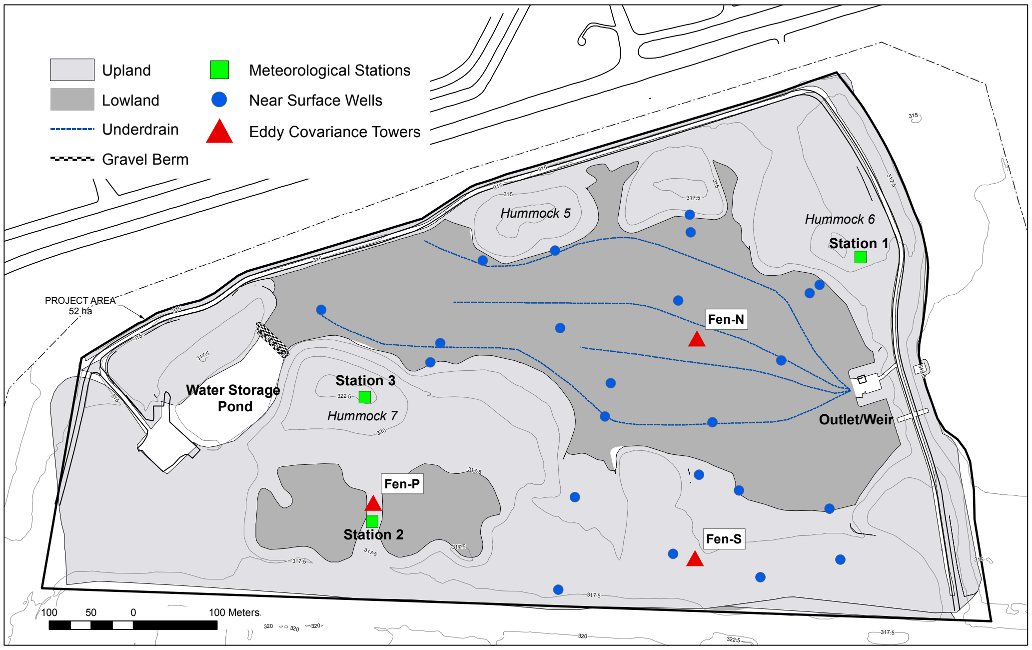


Figure 3.1. Instrumentation map of SFW. Eddy covariance towers Fen S and Fen P represent the upland (terrestrial) area, while Fen N represents the lowland (wetland) area. Fen S was constructed in 2012, Fen N in 2013 and Fen P in 2014.

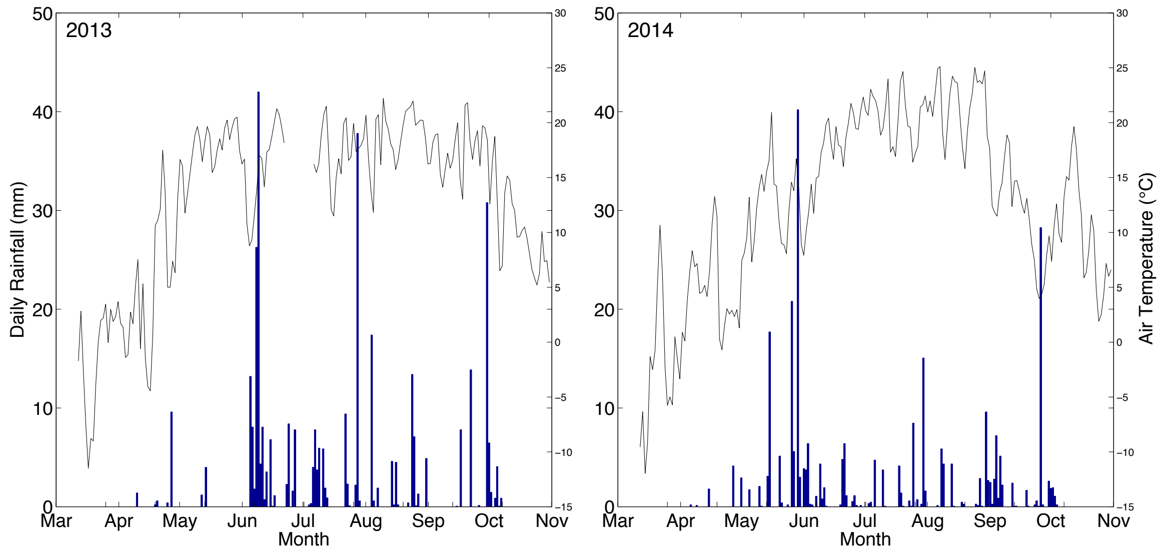


Figure 3.2: Precipitation (bars) and air temperature (lines) over the 2013 (left) and 2014 (right) snow free seasons, SFW, Fort McMurray, AB.

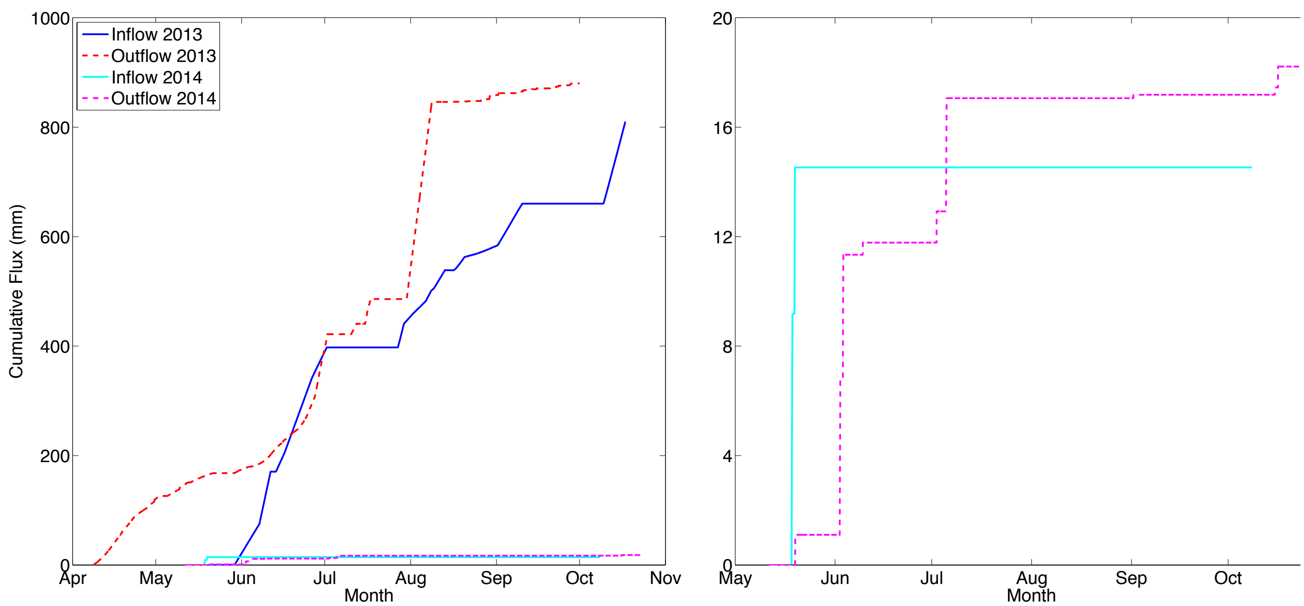


Figure 3.3. Cumulative inflow and outflow in the 2013 and 2014 season on the SFW.

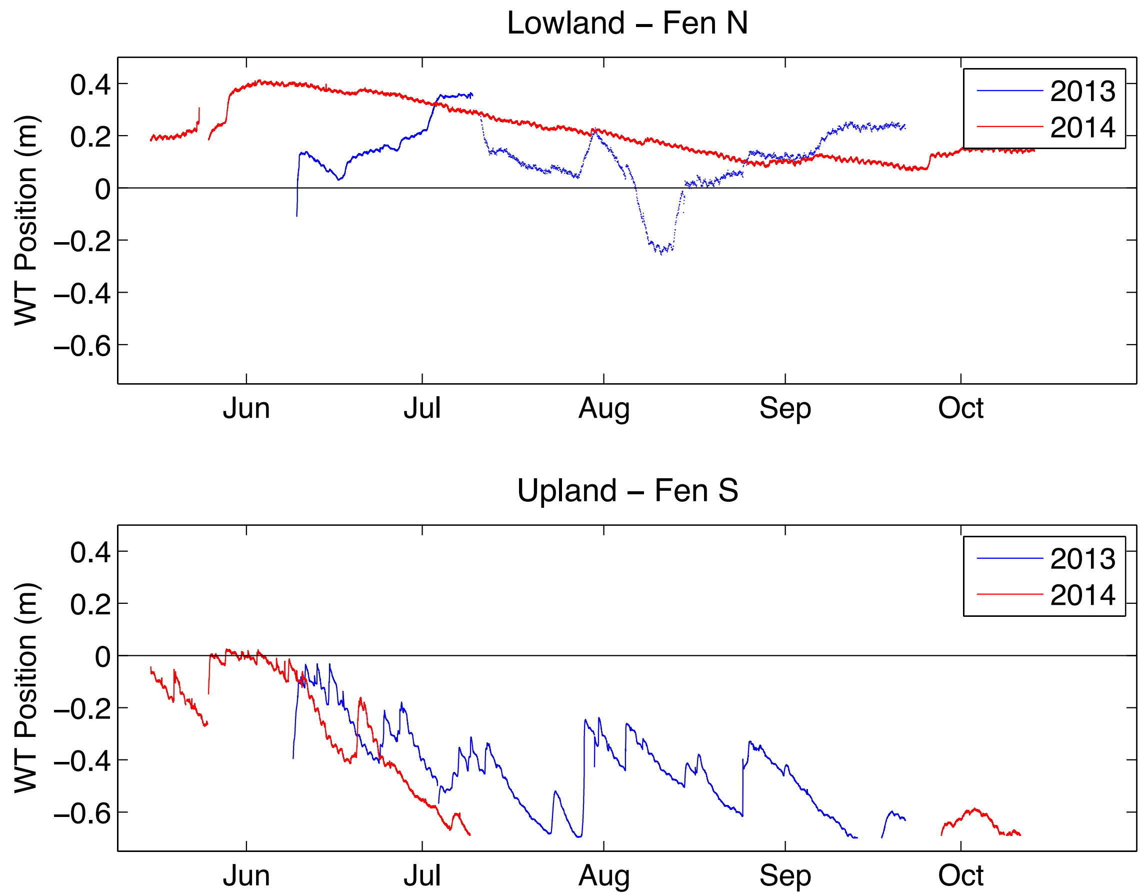


Figure 3.4: Water table depth with respect to ground for wells closest to the upland (Fen S) and lowland (Fen N) towers.

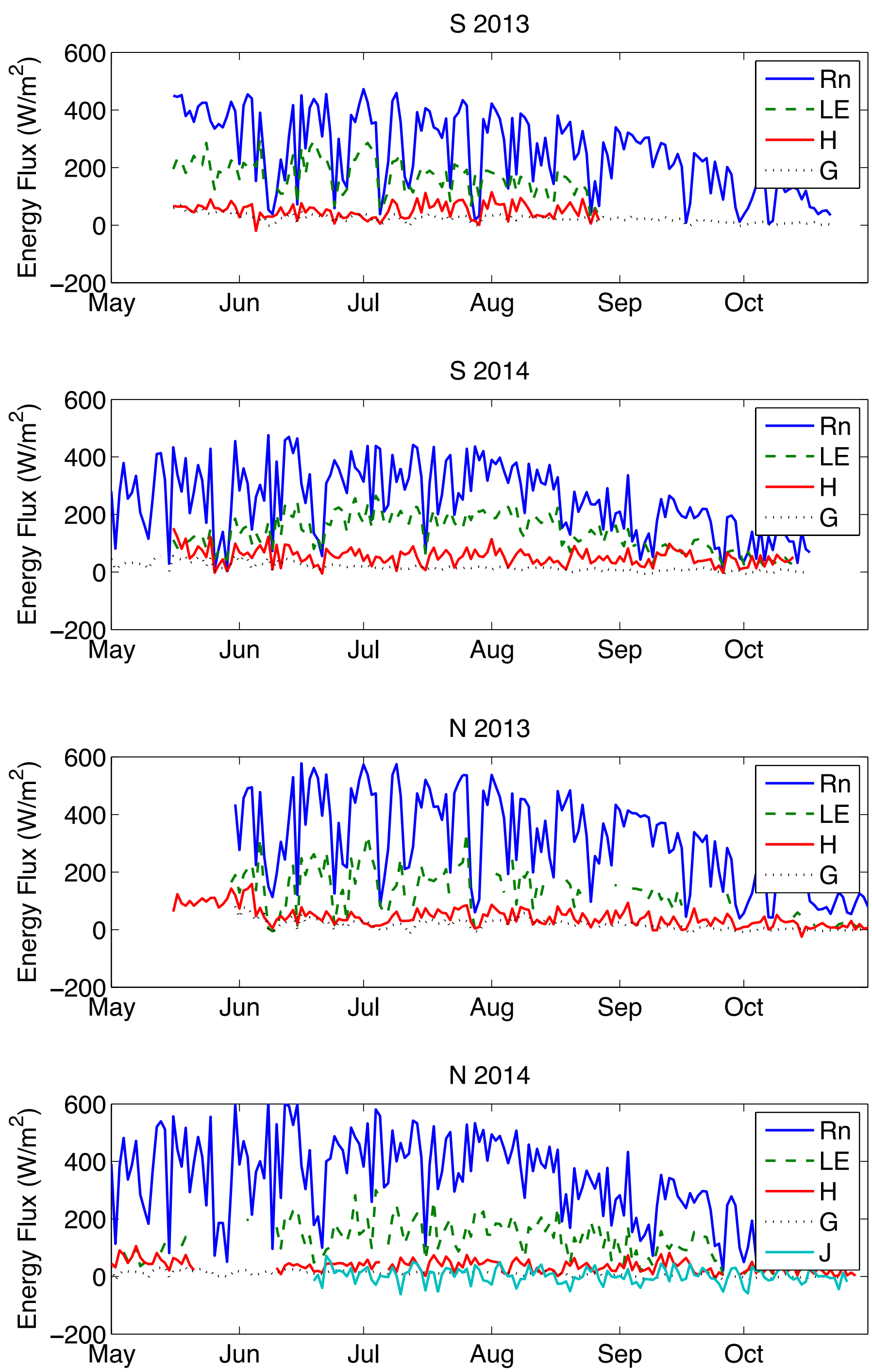


Figure 3.5. Mean daily daytime (9:00-16:30) energy fluxes for Fen S (upland) and Fen N (lowland) in 2013 and 2014.

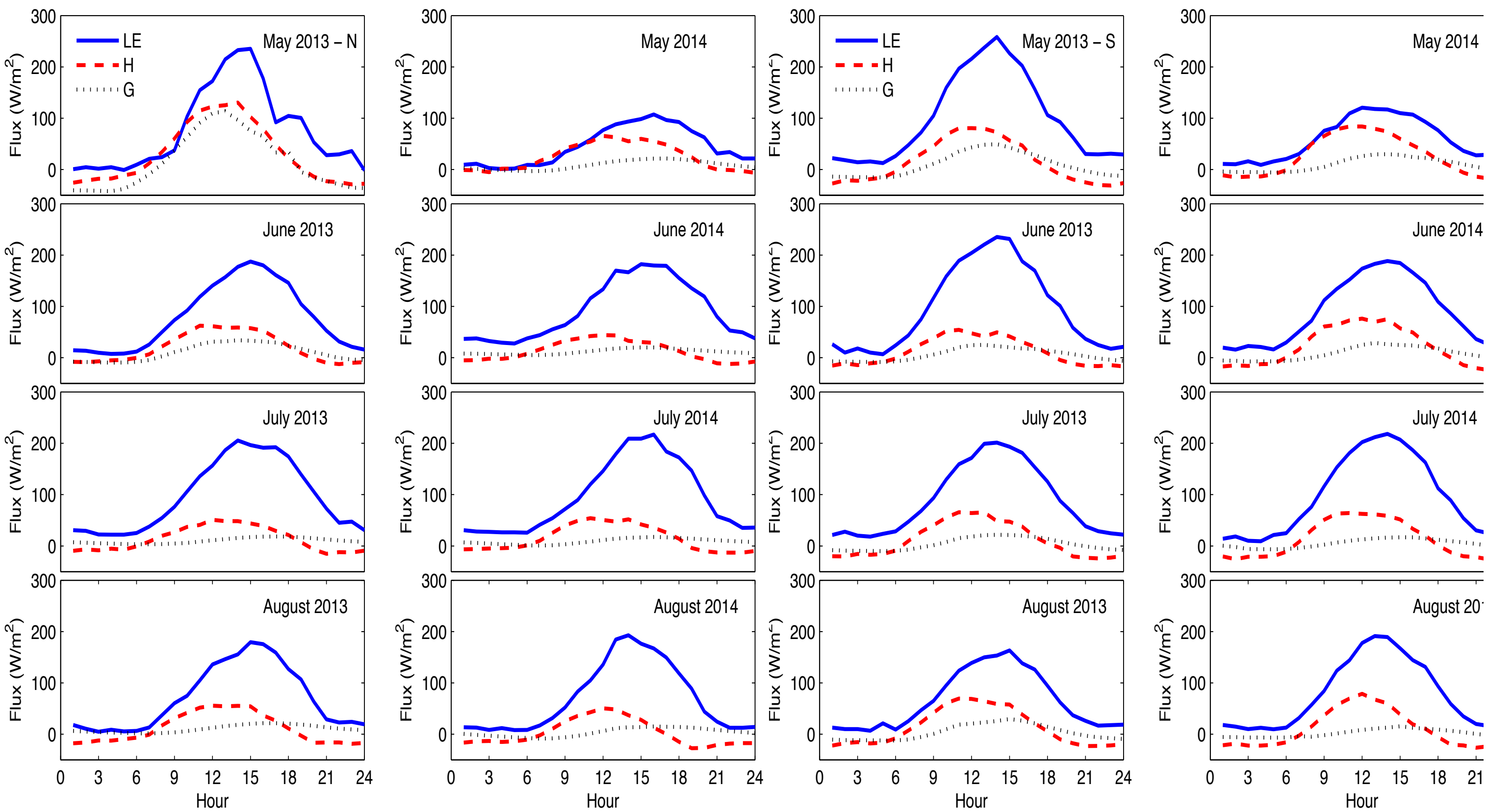


Figure 3.6. Monthly variation in the mean diurnal trends of latent ($\lambda_v E$), sensible (H) and ground (G) heat flux for Fen N (left) and Fen S (right).

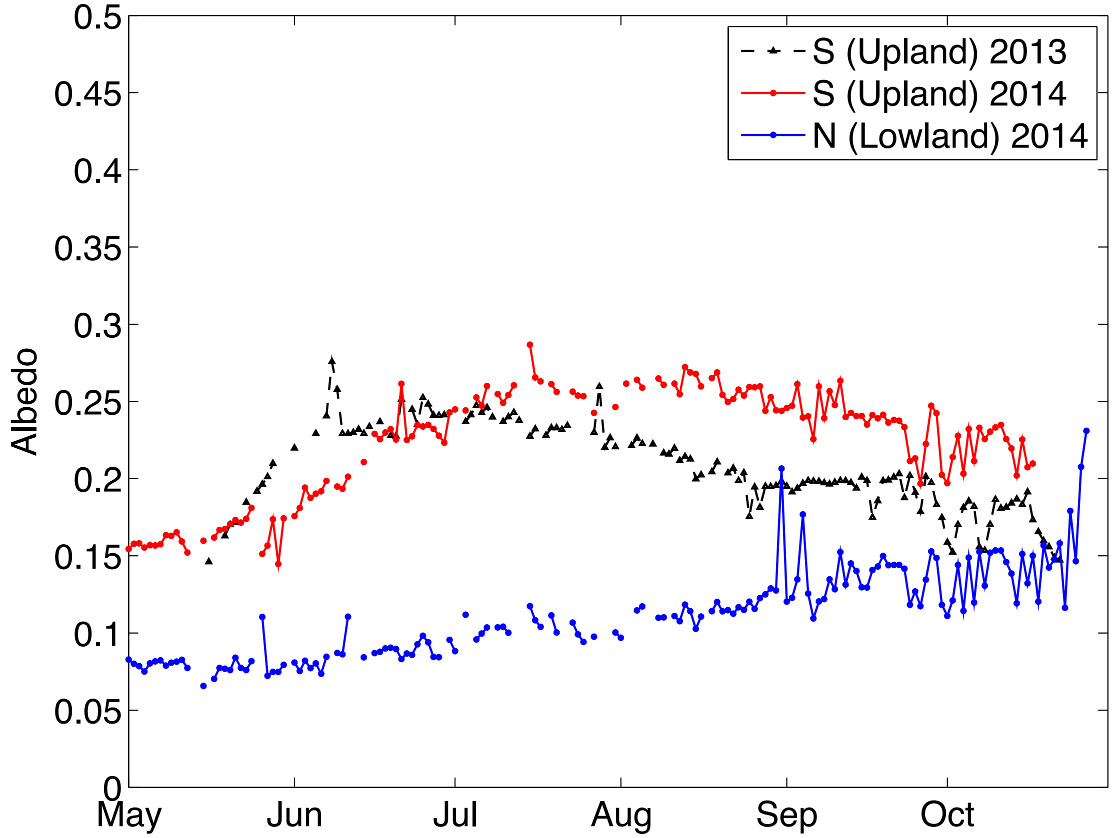


Figure 3.7. Mid-day (11:00-14:30) albedo at Fen S (2013-2014) and Fen N (2014).

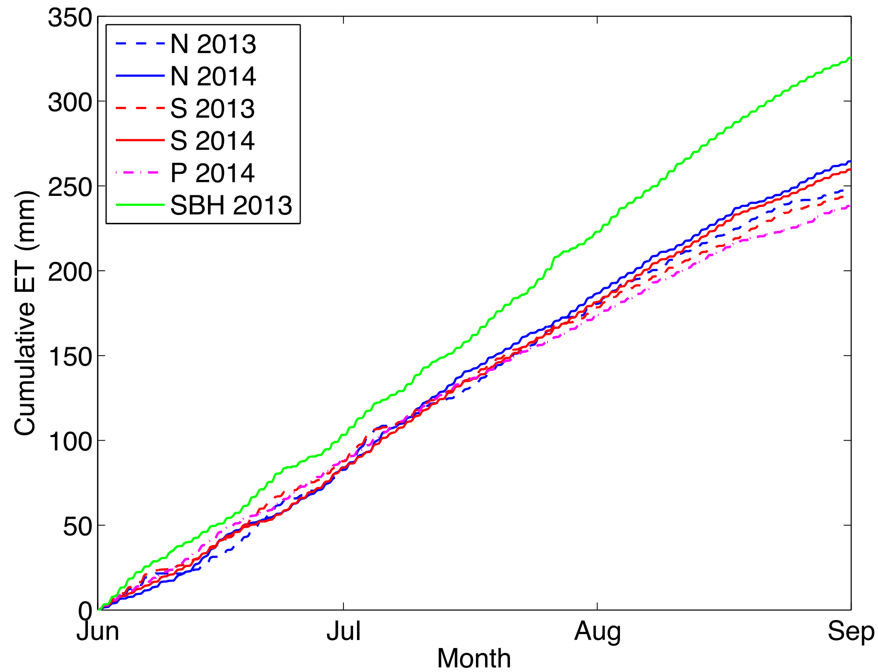


Figure 3.8a. June- August 2013 and 2014 cumulative ET (mm) for Fen S, Fen N, Fen P, and SB30, a nearby upland reclaimed forest constructed in 2002.

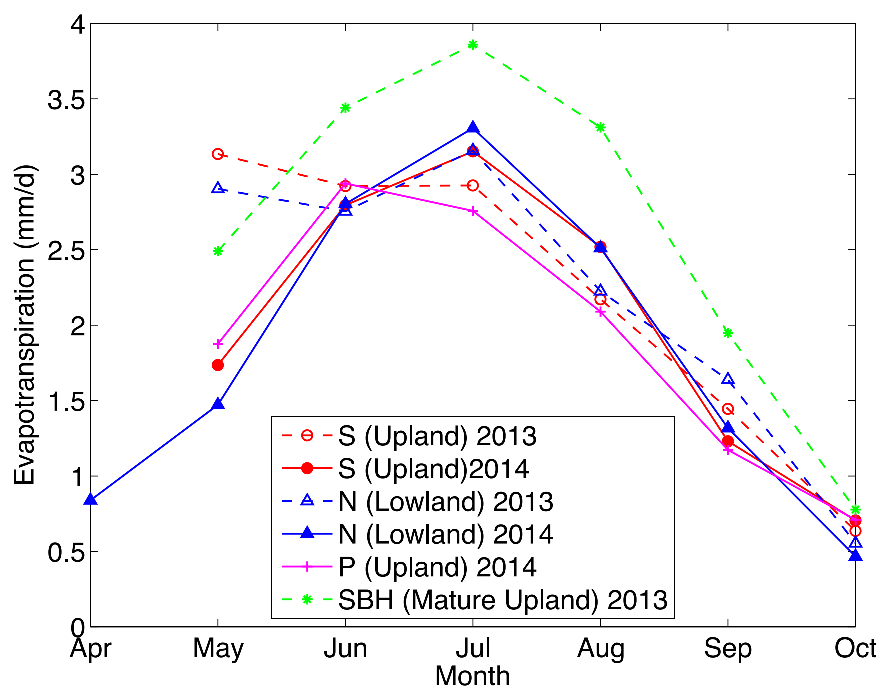


Figure 3.8b. Mean monthly ET rates for the SFW and SB30, a certified reclaimed forest that was planted in 2002 at Syncrude Canada Ltd.

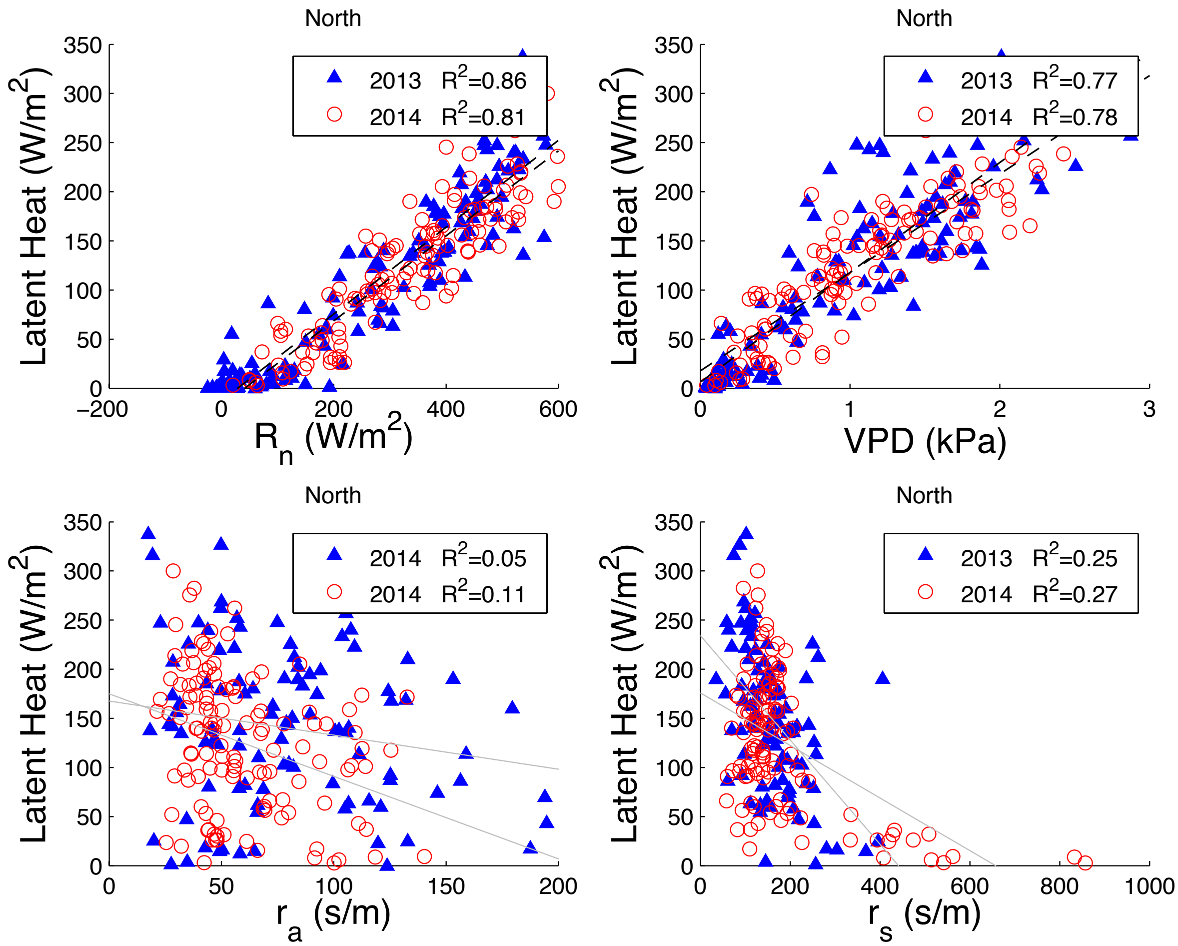


Figure 3.9a. The relation between mean daytime (9:00-16:30) latent heat and net radiation (R_n), vapour pressure deficit (VPD), aerodynamic resistance (r_a), and surface resistance (r_s) in 2013 and 2014 for Fen N.

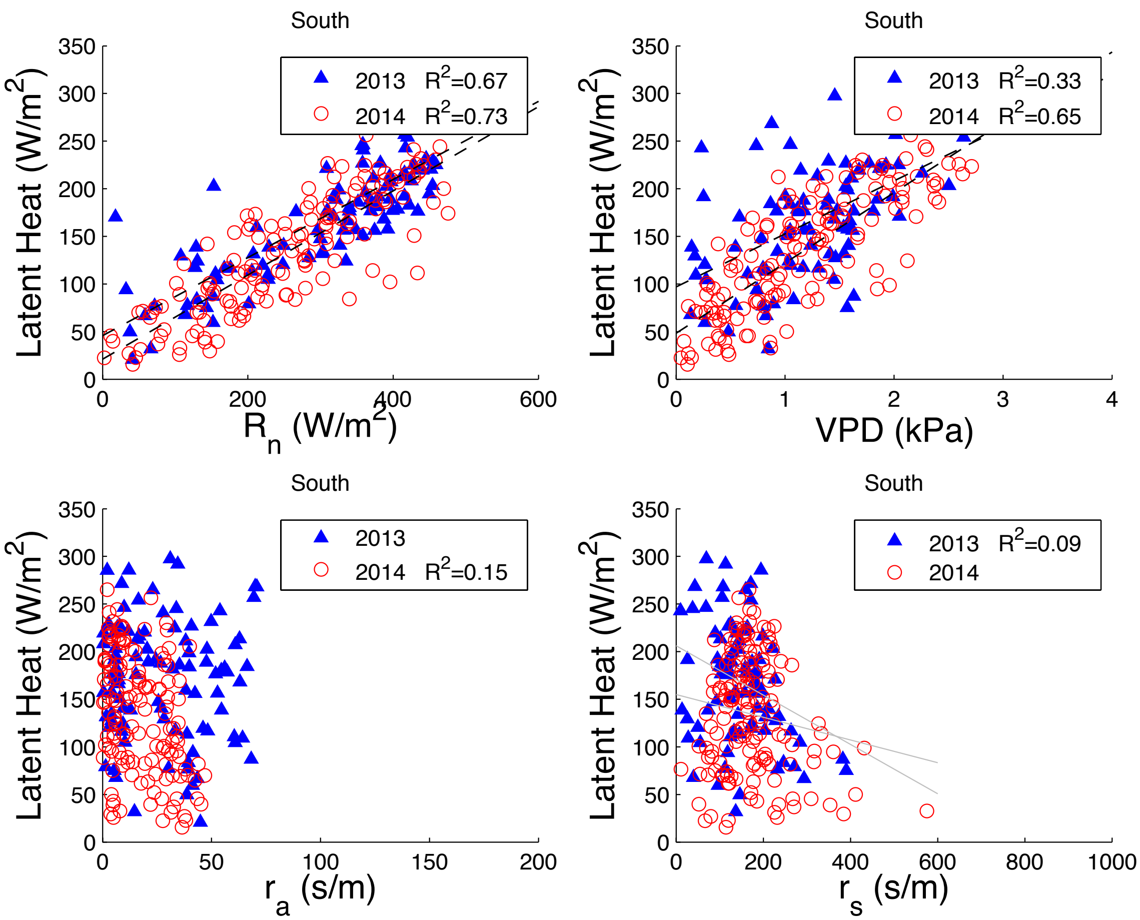


Figure 3.9b. The relation between mean daytime (9:00-16:30) latent heat and net radiation (R_n), vapour pressure deficit (VPD), aerodynamic resistance (r_a), and surface resistance (r_s) in 2013 and 2014 for Fen S.

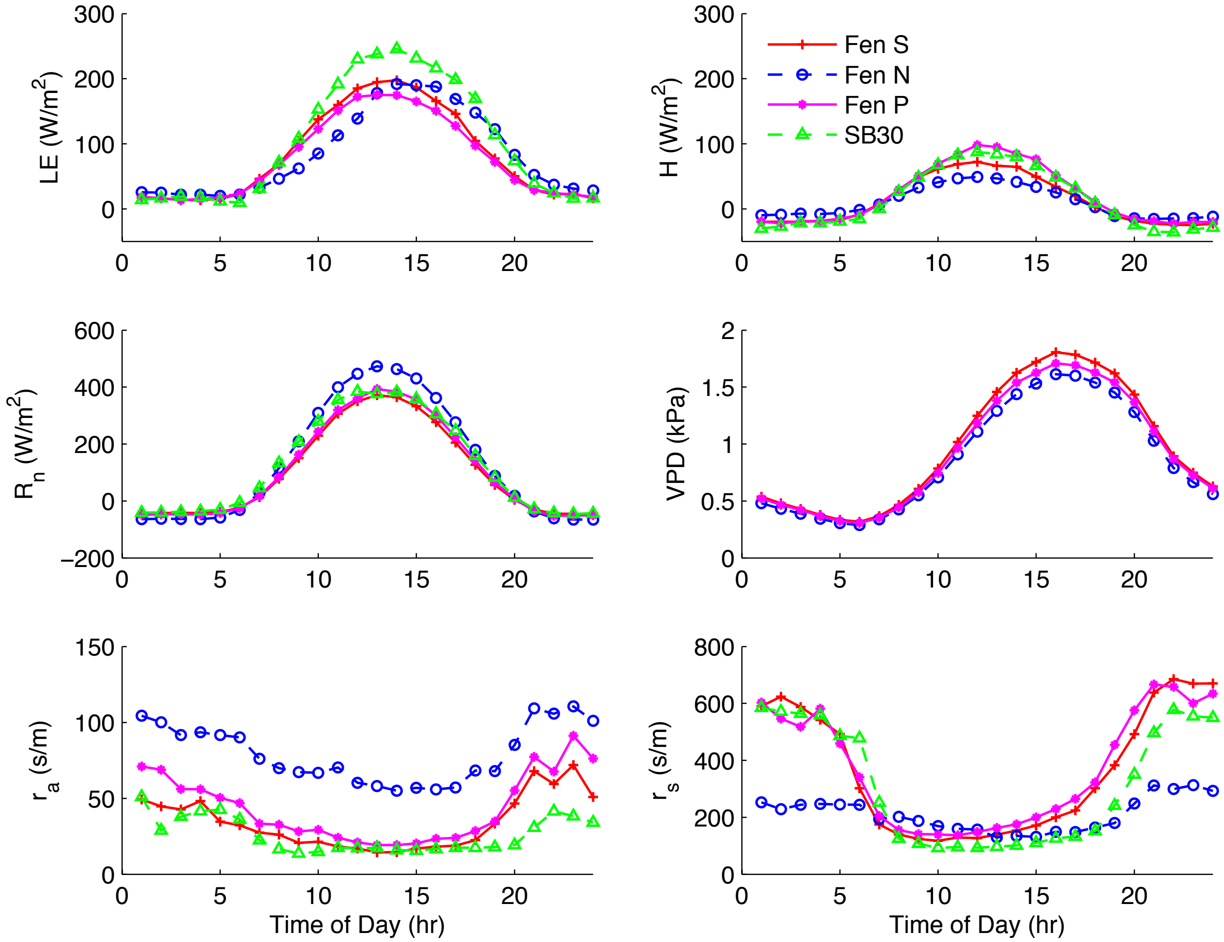


Figure 3.10. Diurnal patterns of latent heat ($\lambda_v E$), sensible heat (H), net radiation (R_n), vapour pressure deficit (VPD), aerodynamic resistance (r_a), and surface resistance (r_s). Values reported run from June 1 – August 31. Fen S, N, and P are reported values in 2014, while SB30 data is from 2013 due to more complete data in this year.

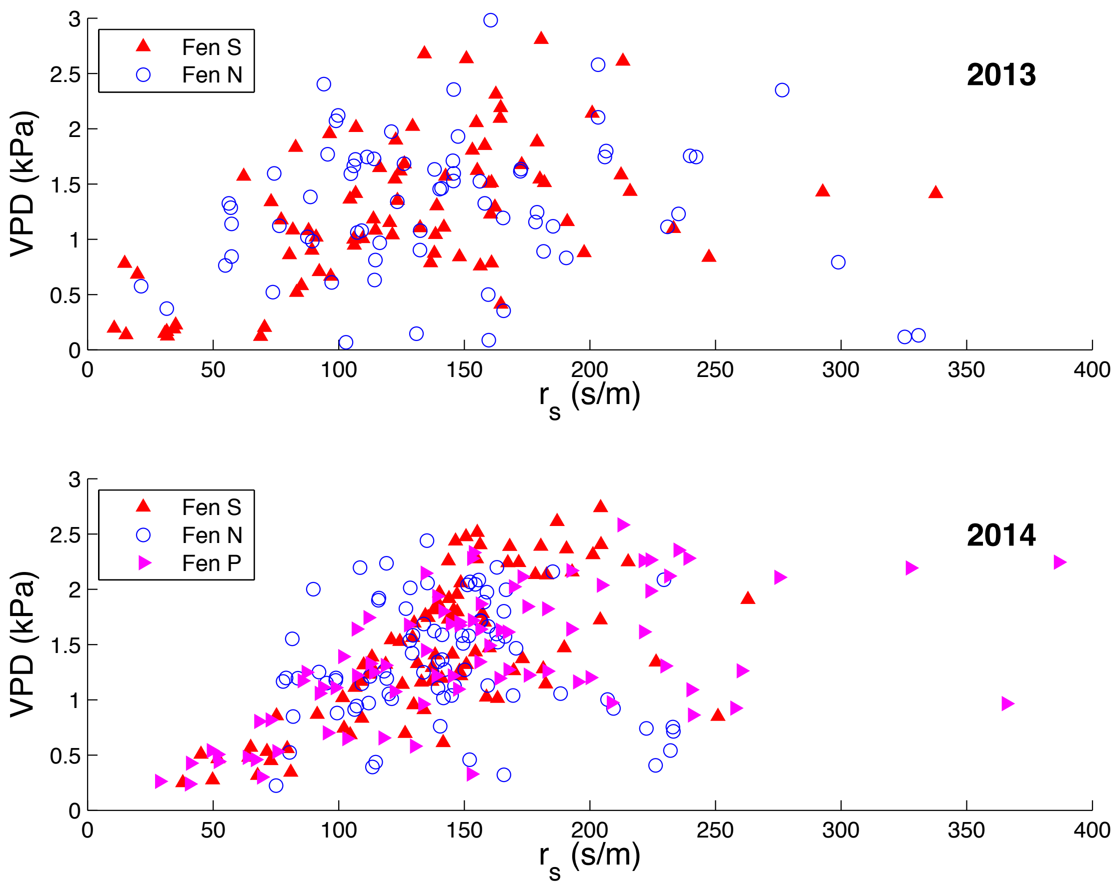


Figure 3.11. Midday (11:00-12:30) mean surface resistance (r_s) and vapour pressure deficit (VPD) for June - August for all towers and years on the SFW.

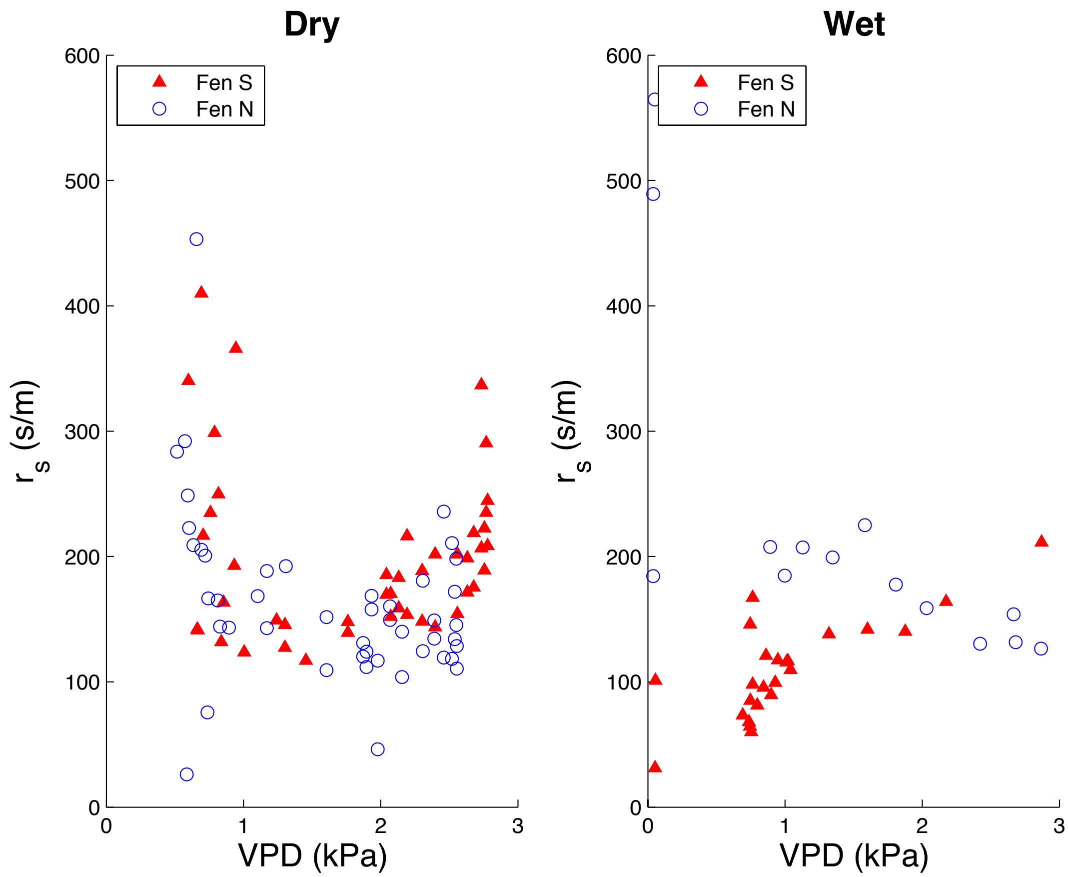


Figure 3.12. Daytime (9:00-16:30) half hour vapour pressure deficit (VPD) and surface resistance (r_s) during wet and dry days in 2014 at Fen S and Fen N. Dry days were 15 June, 16 July, and 4 August where there was no precipitation in at least two days prior. Wet days were 30 July and 26 September where precipitation exceeded at least 15 mm.

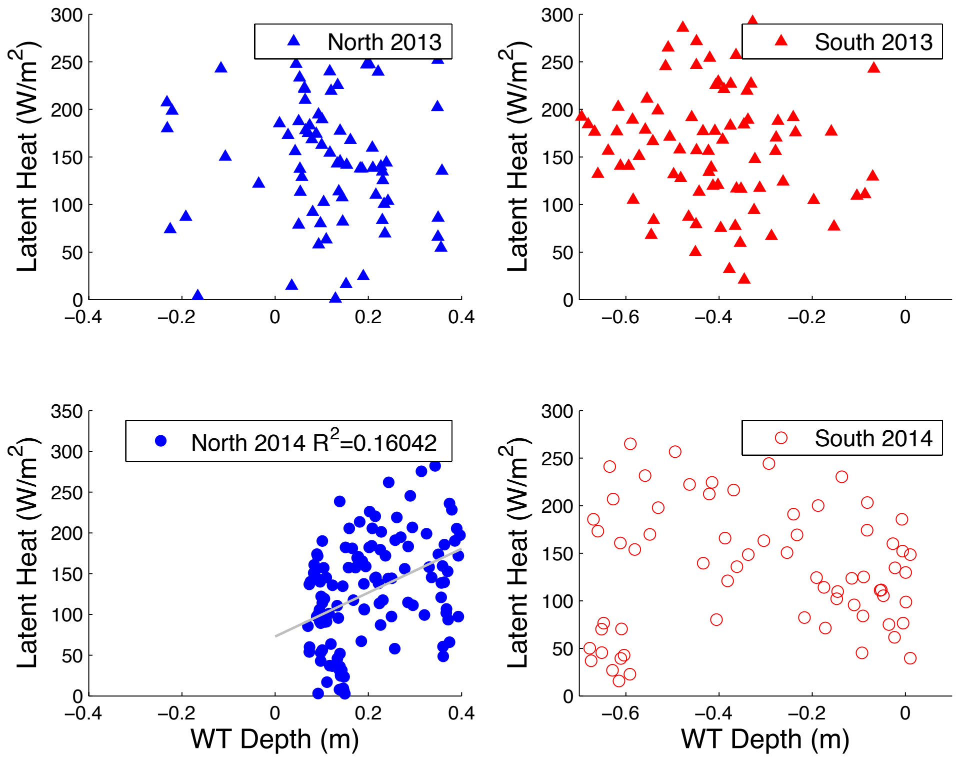
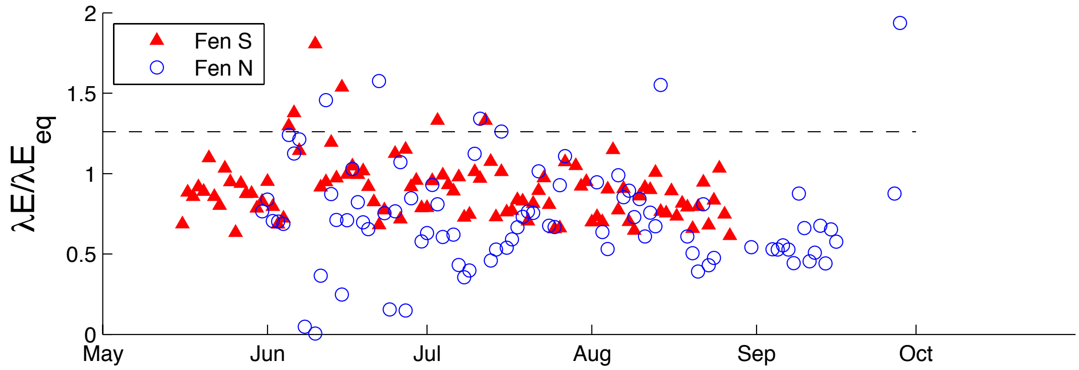


Figure 3.13. Relationship of water table (WT) depth with respect to the ground surface at Fen S and Fen N in 2013 and 2014.



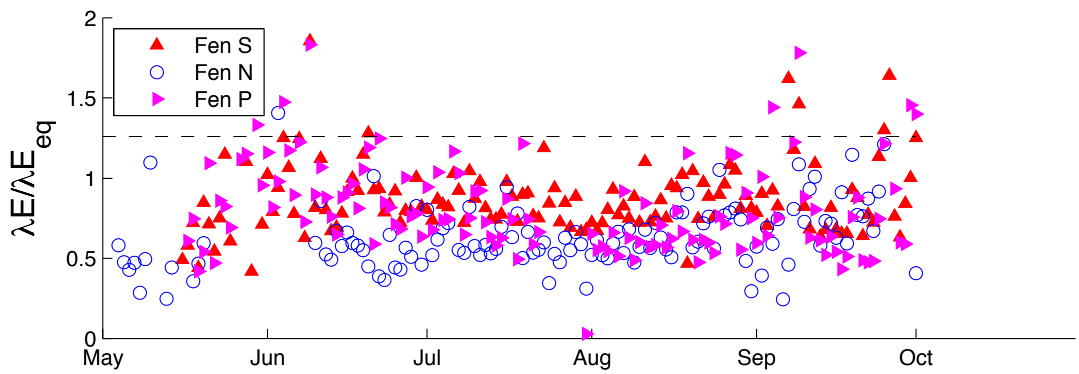


Figure 3.14. Daily mean daytime (9:00-16:30) α_{PT} (LE/LE$_{eq}$) for Fen S, Fen N, and Fen P during the growing season (May 1-Sept 30) 2013 and 2014 on the SFW. The dashed line represents α_{PT} of 1.26, a typical value for an extensive smooth, well-watered surface.

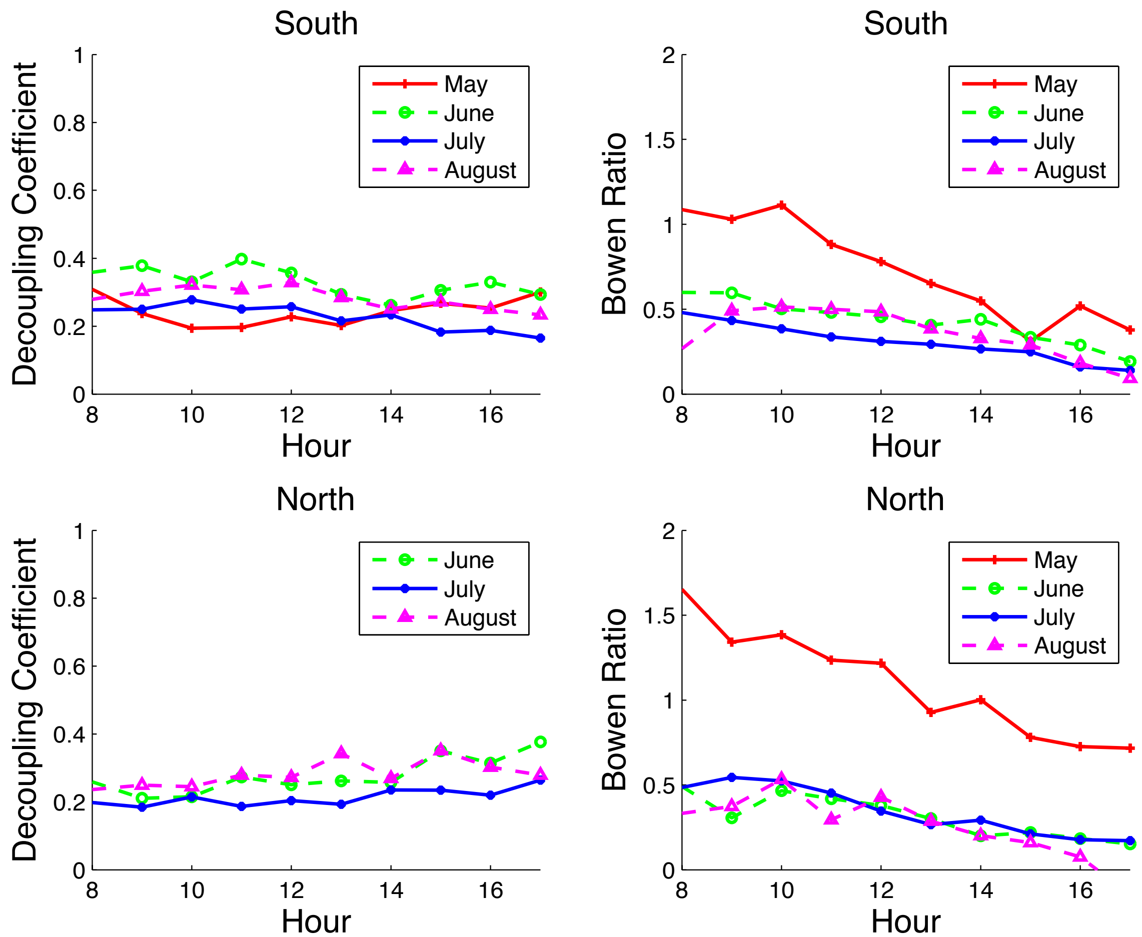


Figure 3.15. Monthly mean diurnal trends of the decoupling coefficient, Ω, and the Bowen ratio (H/ λ_vE) in 2014 for Fen S and Fen N towers.

3.9 Tables

Table 3.1: Instrumentation specifications and height above the ground for Fen S, N and P on the SFW from 2012-2014. Height above ground is represented in bold and in parentheses while manufacturing company is in italics.

Year/Tower	South	North	Perched
Sonic Anemometer (10Hz)	CSAT3 *Campbell Scientific, USA* **(2.6 m)**	R3-50 *Li-Cor, USA* **(3.05 m)**	CSAT3 *Campbell Scientific, USA* **(3.0 m)**
IRGA (10Hz)	LI-7500 *Li-Cor, USA* **(2.5 m)**	LI-7200 LI-7500 (June 3-August 2014) LI-7700 *Li-Cor, USA* **(3.05 m)**	LI-7500 *Li-Cor, USA* **(3.0 m)**
Wind Monitor	3 cup anemometer	Model RM (05103-10) *Young, USA* **(3.5 m)**	Model RM (05103-10) *Young, USA* **(2.8 m)**
Heat Flux Plates + Depths	2 Heat flux plates (HFT3-L) *Campbell Scientific, USA* **(2 and 5 cm)**	2 Heat flux plates (HFT3-L) *Campbell Scientific, USA* **(2 and 5 cm)**	2 Heat flux plates (HFT3-L) *Campbell Scientific, USA* **(2 and 5 cm)**
Humidity Probe	Model HC2-S3 in a radiation shield (Model 41303-5A) *Campbell Scientific, USA* **(2.0 m)**	Relative Humidity Sensor (Model STH-S331) with radiation shield (Model 43502) *Ace Tech Ltd., Papua New Guinea* **(3.0 m)**	Model HC2-S3 in a radiation shield (Model 41003-x) Tipping bucket Model CS700 *Campbell Scientific, USA* **(1.8 m)**
Net Radiometer	NR Lyte2 *Kipp and Zonen, Netherlands* **(1.9 m)**	CNR4 *Kipp and Zonen, Netherlands* **(3.0 m)**	NRLite2 *Kipp and Zonen, Netherlands* **(2.4 m)**
Pyranometers	SPLITE2 *Kipp and Zonan, Netherlands* **(1.9 m)**	2 PQS 1 PAR Quantum Sensors LI190SB-L Quantum Sensor (PPFD) *Kipp and Zonan, Netherlands* **(3.0 m)**	
Datalogger	CR3000 Micrologger *Campbell Scientific, USA*	CR3000 Micrologger *Campbell Scientific, USA*	CR3000 Micrologger *Campbell Scientific, USA*

Table 3.2. Energy balance closure for all towers on the SFW for daytime fluxes (9:00-16:30) from 2012-2014.

	Closure	Closure	Closure
	2012	2013	2014
South	0.62	0.54	0.57
North		0.5	0.48
Perched			0.62

Table 3.3: Monthly climatic averages for air temperature (T_{air}) and rainfall (R) for the two study years, averaged from three meteorological stations on the SFW in 2013 and 2014. CN is the 30-year climate normal (1981-2010).

Month	**T_{air} (°C)**			**P (mm)**		
	2013	2014	CN	2013	2014	CN
May	14.7	9.1	9.9	5.2	110.9	33.5
June	17.5	16.9	14.6	152.7	40.0	73.3
July	18.2	20.1	17.1	88.8	44.6	80.7
August	18.6	18.7	15.4	60.1	33.0	57.1
September	14.5	10.7	9.5	59.4	61.5	38.8
May-Sept Total	16.7	15.3	13.3	365	290.0	283.4

Table 3.4: Daily daytime (9:00-16:30) averages of ET controls (determined using the Penman Monteith Equation (Eq. 2) and $\lambda_v E$ during the growing season. Values are calculated using Pearson's correlation.

	r, *p*-value			
Site –Year	R_n - $\lambda_v E$	VPD - $\lambda_v E$	r_a - $\lambda_v E$	r_s - $\lambda_v E$
Fen S -2013	0.82, $p < 0.001$	0.58, $p < 0.001$	-0.02, $p = 0.81$	-0.3, $p < 0.005$
Fen S -2014	0.85, $p < 0.001$	0.8, $p < 0.001$	-0.4, $p < 0.001$	-0.15, $p = 0.07$
Fen N - 2013	0.92, $p < 0.001$	0.88, $p < 0.001$	-0.22, $p < 0.05$	-0.50, $p < 0.001$
Fen N - 2014	0.90, $p < 0.001$	0.88, $p < 0.001$	-0.32, $p < 0.001$	-0.52, $p < 0.001$
Fen P - 2014	0.76, $p < 0.001$	0.6, $p < 0.001$	-0.09, $p < 0.001$	-0.42, $p < 0.001$

Table 3.5. Monthly mean ET rates (mm/day) for all sites on the SFW. Values in parentheses are the standard error of the mean. *Denotes second half of month recorded

	Mean daily ET Rate (mm/day)				
Month	Fen S - 2013	Fen S - 2014	Fen N – 2013	Fen N-2014	Fen P - 2014
May	*3.13 (0.10)	1.74 (0.09)	n/a	1.47 (0.12)	1.88 (0.10)
June	2.92 (0.23)	2.80 (0.16)	2.75 (0.29)	2.80 (0.24)	2.94 (0.15)
July	2.93 (0.20)	3.15 (0.12)	3.15 (0.31)	3.31 (0.19)	2.76 (0.11)
August	2.17 (0.13)	2.52 (0.13)	2.22 (0.17)	2.51 (0.15)	2.09 (0.14)
September	1.44 (0.10)	1.23 (0.07)	1.64 (0.14)	1.32 (0.12)	1.17 (0.16)

Table 3.6: Vertical growing season (May-Sept) water balance components (in mm) for the SFW in 2013 and 2014 (over 17 ha lowland)

	P	AET	AET:P	Cum P	Cum AET	Cum AET:P
May 2013	5	95	19	5	95	19
June 2013	136	86	0.63	141	181	1.28
July 2013	83	92	1.11	224	273	1.22
August 2013	57	67	1.18	281	340	1.21
September 2013	53	45	0.85	334	385	1.15
May 2014	103	51	0.50	103	51	0.50
June 2014	37	84	2.3	140	135	0.96
July 2014	42	99	2.36	182	234	1.29
August 2014	31	78	2.52	213	312	1.46
September 2014	57	38	0.67	270	350	1.30

Chapter 4: Conclusions and Future Research

Research on wetland reclamation strategies within areas impacted by oil sands mining is only just beginning. This study presents the water balance dynamics in the early years of one of the first watershed-scale peatland construction projects on soft tailings. The sustainability of the SFW depends on the system's ability to maintain moisture levels appropriate for paludification, wetland vegetation growth and carbon sequestration. We found that artificial management can significantly affect the hydrology and cause water table fluctuations that may not be ideal for fen peatland sustainability. ET rates were similar between upland and lowland areas, and were primarily driven by net radiation. In coming years, vegetation development within the upland area, and possible moss growth in the lowlands may lead to a change in energy partitioning and ET rates. Additionally, natural peatlands within the boreal region exist due to variations from the long-term climatic mean, where a typically dry environment is punctuated with wet years where moisture surplus may be available for wetland development. Peatland development takes thousands of years, however the timeline of mine reclamation and closure planners requires construction of wetlands to begin immediately. The results presented in this thesis provide a useful baseline for hydrologic modeling and design planning for future reclamation sites. Long-term monitoring of the water balance and ET dynamics is necessary to capture the full evolution of this unique system.

Chapter 5: Supplemental Data

Figure 5.1. Fen S (upland) tower on 30 June 2012 (top) and 14 June 2014 (bottom).

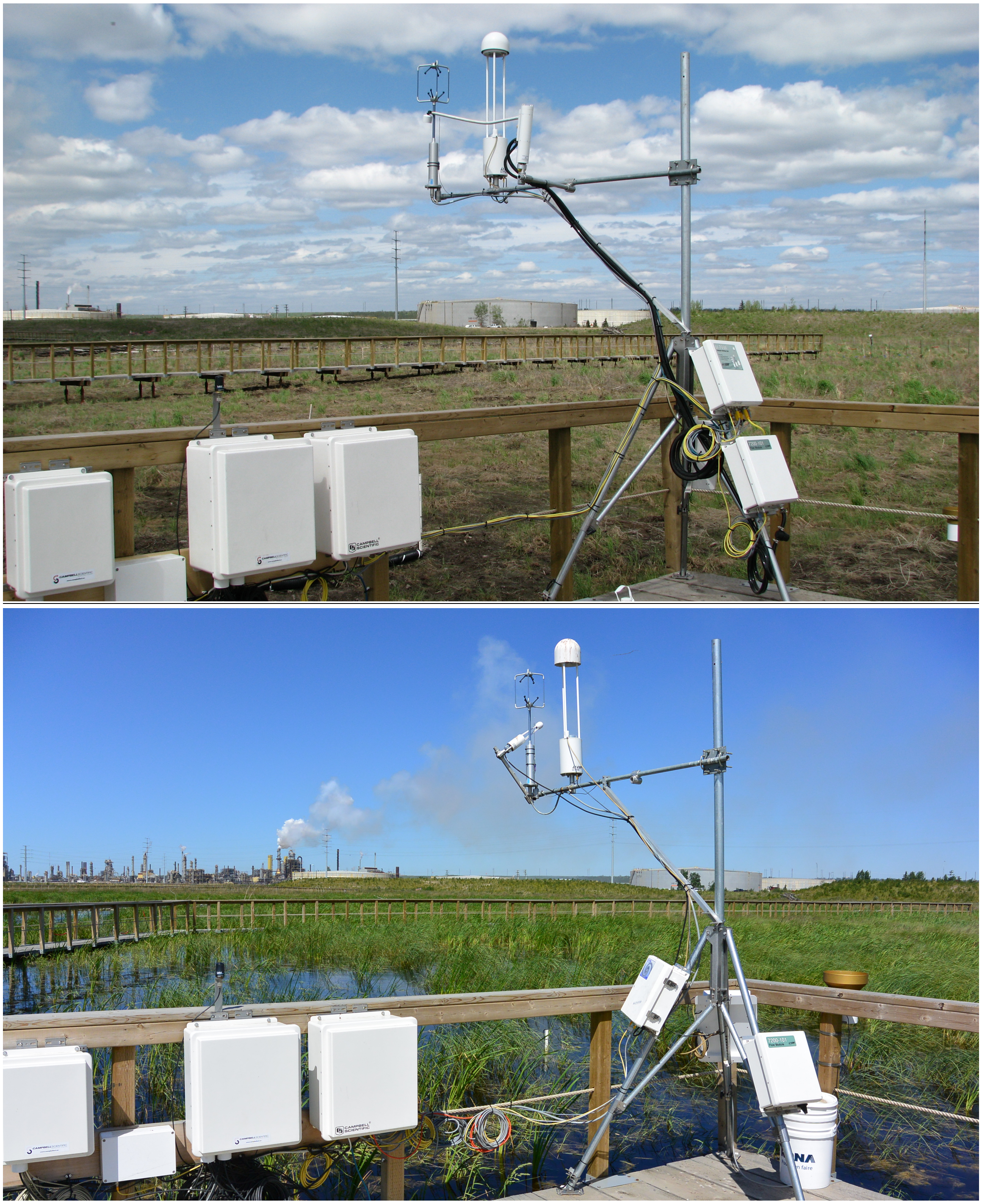


Figure 5.2. Fen N (lowland) tower on 25 May 2013 (top) and 14 June 2014 (bottom).

Figure 5.3. Photo of eddy covariance tower at South Bison Hill (SBH) on 1 August 2013. This site is an upland reclaimed forest at Syncrude Canada Ltd.'s Mildred Lake mine site. Construction was completed in 2002.

Supplemental Data Table 5.1. Mean energy budget terms for the growing season on Fen S and Fen N towers from 2012-2014.

	Month	Rn (MJ m^{-2} d^{-1})		$\lambda_v E$ (MJ m^{-2} d^{-1})		H (MJ m^{-2} d^{-1})		G (MJ m^{-2} d^{-1})		B ($H/\lambda_v E$)		$\lambda_v E/R_n$		H/R_n		G/R_n	
		North	South	North	South	North	South	North	South	North	South	North	South	North	South	North	South
2013	May	--	6.06	--	4.04	--	0.65	--	0.49	--	--	--	0.67	--	0.11	--	0.07
	Jun	11.89	8.92	6.19	5.93	1.63	0.95	0.84	0.57	0.26	0.16	0.52	0.66	0.14	0.11	0.07	0.06
	Jul	11.92	8.94	6.31	6.42	1.15	1.00	0.47	0.33	0.18	0.16	0.53	0.72	0.10	0.11	0.04	0.03
	Aug	9.58	7.2	3.18	3.96	0.94	0.88	0.47	0.30	0.30	0.22	0.33	0.55	0.10	0.12	0.05	0.04
	Sept	6.05	4.34	2.33	--	0.25	--	-0.07	-0.12	0.11	--	0.39	--	0.04	--	0.01	-0.02
2014	May	10.66	7.52	--	2.15	--	1.01	--	0.85	--	0.47	--	0.29	--	0.13	--	0.10
	Jun	12.46	9.36	5.29	6.3	0.78	1.59	1.01	0.67	0.15	0.25	0.42	0.67	0.06	0.17	0.08	0.07
	Jul	12.76	9.91	7.34	6.66	1.23	0.93	0.79	0.37	0.17	0.14	0.58	0.67	0.10	0.09	0.06	0.04
	Aug	9.64	7.44	5.2	5.33	0.23	0.68	0.31	0.08	0.04	0.13	0.54	0.72	0.02	0.09	0.03	0.02
	Sept	4.95	--	2.4	--	0.17	--	-0.21	-0.18	0.07	--	0.48	0.80	0.03	--	-0.04	--