# Implications of shallow groundwater and surface water connections for nitrogen movement in typical Boreal Plain landscapes

by

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B.Sc., University of Guelph, 2009

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# Supervisory Committee

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# Abstract

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This thesis examines both surface water and shallow groundwater connections in boreal watersheds at two study sites in the Athabasca Oil Sands Region using conventional hydrological techniques as well as stable water isotope techniques. Increased emissions due to oil sands development are expected to contribute significantly to acidifying airborne emissions. Specifically, nitrogen is forecasted to be deposited on the surrounding area within approximately 100 km of operations. The purpose of the research is to provide background information for predicting how individual terrain units such as fens, bogs, and uplands will respond to increased nitrogen loads, and to assess whether or not these units will act as sources or sinks of nitrogen under higher nitrogen deposition.

Two study sites situated within 100 km of Fort McMurray, Alberta were instrumented with a total of 30 nested piezometers, 26 water table wells, 4 micro-meteorological stations, and two gauging stations (weirs) at outflow points. Monitoring occurred during the open water season of 2011 and 2012. This study estimates evaporation through a simplified energy balance, documents hydraulic conductivity of shallow aquifers, utilizes stable isotopes of water to assist in mapping seasonal flow patterns, and calculates a vertical water balance for the sites. Bogs and fens were hydrologically connected, as bogs fed fens laterally at shallow depths within the acrotelm during wet years. Upland terrain units were found to have more variable connections. In spring, upland runoff recharged the wetlands at both sites. At JPH groundwater flowed towards the fen, whereas in ML limited connections were observed between the uplands and the fen. Also, no connections were seen to indicate that the wetlands recharged the uplands. A conceptual model is developed that emphasizes the role of connectivity in the boreal landscape. The main implication for nitrogen cycling is that it is difficult to quantify one landscape as a source or sink for additional nitrogen as its role may vary depending on seasonality and temporal scales. Further work is needed to identify if nitrogen loadings will have adverse affects on geochemistry of water at the sites.

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## 1.0: Introduction

### *1.1 Background in region*

The Athabasca Oil Sands Region (AOSR) is an industrial area situated in Northern Alberta's Boreal Plains surrounding the city of Fort McMurray (Figure 1.1). This area developed rapidly beginning in the 1970s because of its rich oil deposits, and increasing global demand for oil is expected to continue over the next few decades. Production has risen to approximately 1.8 million barrels of oil per day (Jasechko et al. 2012). Development of bitumen refining and expanding transportation demands in the AOSR has resulted in increased sulphur and nitrogen emissions. These oxides are deposited onto the landscape through wet and dry deposition (Allen 2004; Schlindler et al. 2006) and can vary spatially and temporally (Hazewinkel et al. 2008; Bytnerowicz et al. 2010). Elevated levels of nitrogen species from emissions are reported in the 30 km radius of industry (Proemse et al. 2013). Research suggests deposition of these oxides can contribute to acidification of terrain types and regional areas (Carou et al. 2008). Efforts to understand the impacts on the landscape are being examined, and nitrogen deposition onto the landscape from emissions is a key concern.

The Province of Alberta created a regional multi-stakeholder group known as the Cumulative Environmental Management Association (CEMA) to assess and manage environmental impacts of industry in the region of Fort McMurray. For characterization of acid deposition, CEMA concluded that higher resolution was needed in the AOSR for air, soils and lakes (CEMA 2004). Previous work completed by CEMA through the $NO_xSO_2$ Management Working Group (NSMWG) has outlined a framework for the management of nitrogen impacts (CEMA 2013). Management strategies were monitoring and modelling of air, soils, and lakes for regulatory decisions and the assessment of regional acidification risk (CEMA 2004). One of the management strategies used to assess the regional sensitivity to acid deposition was dynamic analyzes of critical loads of acidity that resulted in a variety of management actions (CEMA 2004).

To quantify critical loads of acidity for lakes, previous researchers used acid neutralizing capacity, water yields values on catchments, and base cation concentrations as noted below. This work was completed for lakes in the study region using the model of Steady State Water Chemistry (SSWC) and for forested uplands using the Model of Acidification of Groundwater in Catchments (MAGIC) (Curtis et al. 2010; Gibson et al. 2010a&b; Whitfield et al. 2010). General results revealed critical loads of acidity were not being reached in the region. Estimates were made for lakes and uplands; however, limited work has been completed that represents a more holistic approach that considers the mosaic of the landscape. Whitfield et al. (2010) suggests that understanding the biogeochemistry of components that comprise the landscape (i.e. uplands, bogs, fens, peat-pond complexes) may be important to develop a more complete picture of the effects of nitrogen loads on these individual terrain units and the potential transfer between them.

To further the understanding on the state of knowledge on setting critical loads of acidity to the region, a new multi-disciplinary research project was initiated and funded by CEMA to assess the overall response of two ecosystems consisting of jackpine uplands and wetlands (fens and/or bogs) to nitrogen deposition. The approach combines biogeochemical and ecological characterization of specific terrain units with hydrological assessments to better understand the potential for connectivity of the landscape. This approach uses an integrated watershed framework to examine the impact of nitrogen deposition on the overall ecosystem. The two major components of this project included fertilization experiments conducted at each of the terrain types where nitrogen was added and the plant response was studied in detail, as well as hydrological studies that looked at the movement of water and nutrients between different terrain types. This thesis focuses on the hydrological connectivity between different terrain units typical of boreal catchments in the AOSR. Examining these connections between different terrain units will help identify how the landscape may respond, process, store and/or utilize projected increases in nitrogen deposition.

The hydrological component of the research program commenced in 2011, led by researchers at the University of Victoria, and is organized into two sub-components. One of the sub-components is investigating the geochemistry of the ecosystems. The second sub-component, described herein, is focused on characterizing the hydrological connectivity between different terrain units within the study ecosystems. Understanding the connectivity between different terrain units gives insight into the movement and fate of nitrogen on and within the landscape.

### *1.2 Objective*

The aim of this study is to characterize and quantify the hydrological linkages between uplands, fens, and bogs typical of a mosaic landscape in the AOSR. The results of this study will help to refine the conceptual models of nitrogen fluxes and critical loadings of acidity for the region.

To measure the hydrological linkages between the terrain units of interest, this study combines traditional hydrological and hydrogeological methods with stable isotope tracers. This study has two objectives:

1. To identify potential surface and subsurface flowpaths between uplands, fens and bogs (described in Chapter 2). This is primarily accomplished through characterization of hydraulic conductivities, hydraulic gradients, and stable water isotope tracers.

2. To identify areas with the greatest potential to generate surface runoff (Chapter 3). This is completed using vertical water balance calculations combined with stable water isotope tracing.

*1.3 Experimental design*

This study uses data collected between 2011 and 2012 from two field sites located in the AOSR (Figure 1.1). The field sites were selected based on the presence of nutrient poor jack pine uplands, ombrotrophic bogs, and minerotrophic and nutrient poor fens. A single field site that contained a good representation of all of these units was not found so two sites had to be used. One of the sites, Jack Pine Hill (JPH), is situated north of Fort MacKay (57.12186°N, 111.44363°W) and the second, Mariana Lakes (ML), is situated south of Fort McMurray (55.89859N°, 122.08965°W). Both sites were selected to have minimal background exposure to excess nitrogen. JPH is an upland dominant site with a rich minerotrophic fen. ML is a peatland-dominated site comprised of an ombrotrophic bog and a poor fen. ML also has pockets of upland areas and islands. The study sites are described in more detail in Chapters 2 and 3.

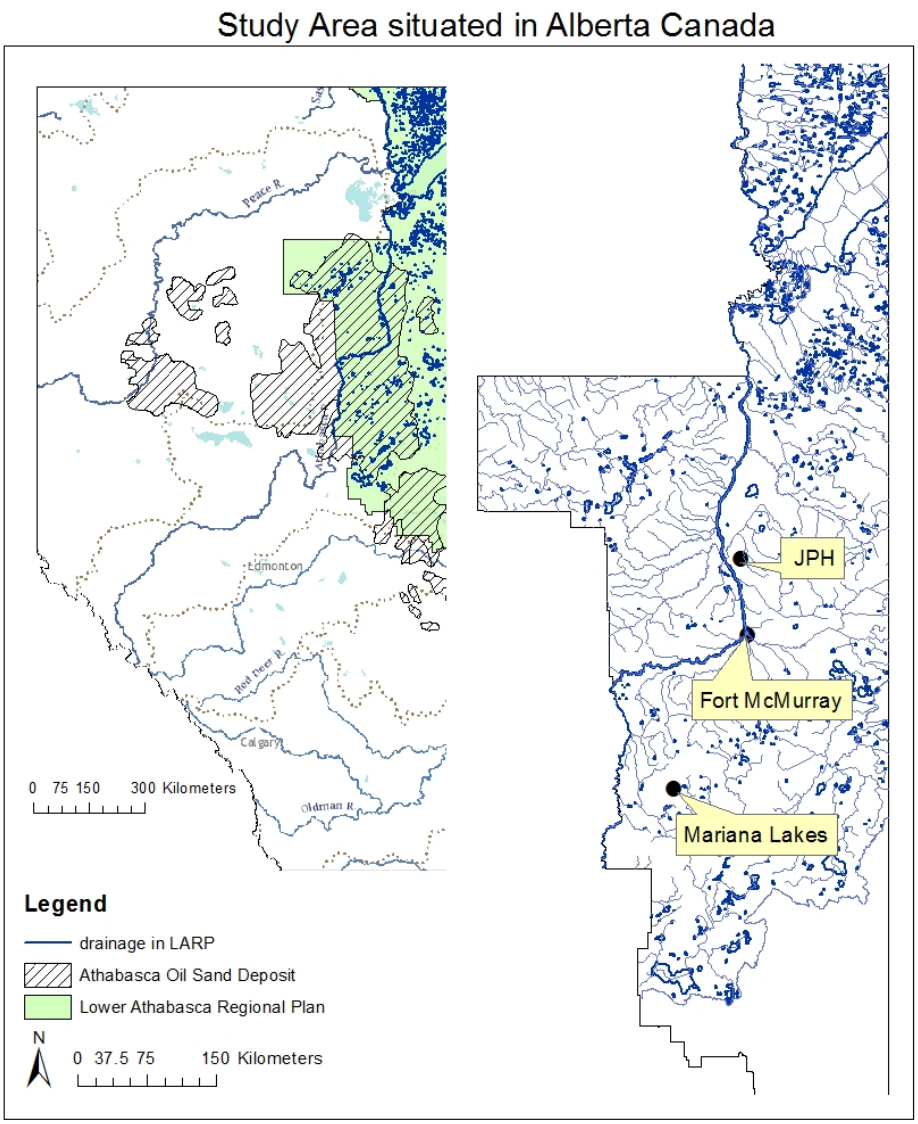


**Figure 1. 1 The two study sites are situated in Alberta, Canada, in the Boreal Plain region, coinciding with the Athabasca oil sands deposit and the Lower Athabasca Regional Plan (LARP) area. Study sites are: Mariana Lakes to the south and JPH to the north.**

Nitrogen amendment studies were conducted in plots located on each of the terrain units of interest. The hydrological monitoring focused on establishing sampling points for the measurement of hydraulic parameters and obtaining water samples from each of the terrain types, as well as measuring water and solute movement between terrain types. The hydrological monitoring was also established to complement the nitrogen amendment studies underway at plots nearby. The ML and JPH field sites were instrumented in the summer of 2011, and data was collected during the summers of 2011 and 2012. Site instrumentation details are provided in Chapters 2 and 3. Data sources included automated instruments, manual measurements, and water sampling.

*1.4 Study area*

AOSR is located in the Boreal Plains region consisting of a mosaic of uplands, wetlands, and aquatic ecosystems. This region is characterized as sub-humid, often experiencing more potential evapotranspiration than precipitation (Devito et al. 2005). The long term average annual precipitation recorded during 1971-2000 at the Fort McMurray airport is 445 mm, of which 155 mm fell as snow and 342 mm as rain. The daily average air temperature for July and January were 16.8 °C and -18.8 °C, respectively (Environment Canada 2012).

Climate and geology determine the catchment hydrology of the region (Devito et al. 2005). The only significant topographical features in the area are the Stony Mountains south of Fort McMurray and the Birch Mountains to the west of the city. The Athabasca and Clearwater Rivers are the dominant hydrological features on the landscape and have carved deep river valleys; and are fed by smaller tributaries, such as the Firebag and Muskeg Rivers to the north of Fort McMurray, as well as the Christina, Hangingstone and Horse Rivers to the south.

The geology of the Province of Alberta consists of three main regions: the Canadian Shield (to the north of Fort McMurray), the Rocky Mountains (to the west), and the

Interior Plains making up the majority of the landscape. The Interior Plains bedrock geology consists of Quaternary sediment overlying Cretaceous and Devonian formations consisting of shales, sandstones, and limestones (Barson et al. 2001). The Cretaceous deposit is a relic of marine life and is now bitumen. The McMurray formation, having a large abundance of bitumen, is located in a delta region of the prehistoric lake. This formation has surficial outcrops north of Fort McMurray and can be seen in river valley incisions near where the Clearwater and Athabasca Rivers meet, and increases in depth to the south and west.

The surficial geology from the Quaternary formations is defined by glaciofluvial and glaciolacustrine deposits that can exceed 300 m depth (Andriashek and Atkinson 2007; Fenton et al. 2013). These deposits are a mix of sands, silts, and tills deposited during the Wisconsin Glaciations period by the Laurentian ice sheet during its advances and retreats. As well, during the retreats river channels formed which are now abandoned, buried, and infilled. They are generally linear features defined by sands (Andriashek and Meeks 2001). The depositions of fine grain soils, in combination with the climate, have resulted in the abundant presence of wetlands, bogs and fens in this region. The surficial geology of both study sites is seen below in Figures 1.2 and 1.3.

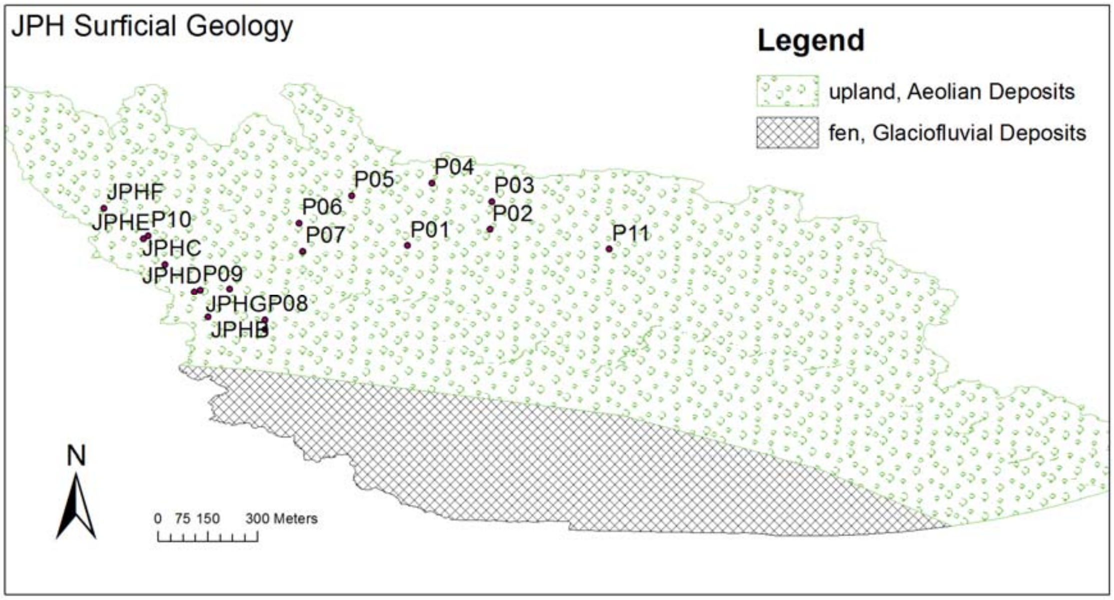


**Figure 1.2 The surficial geology at the JPH site (Alberta Research Council; Alberta Geological Survey; (Bayrock, 2006)).**

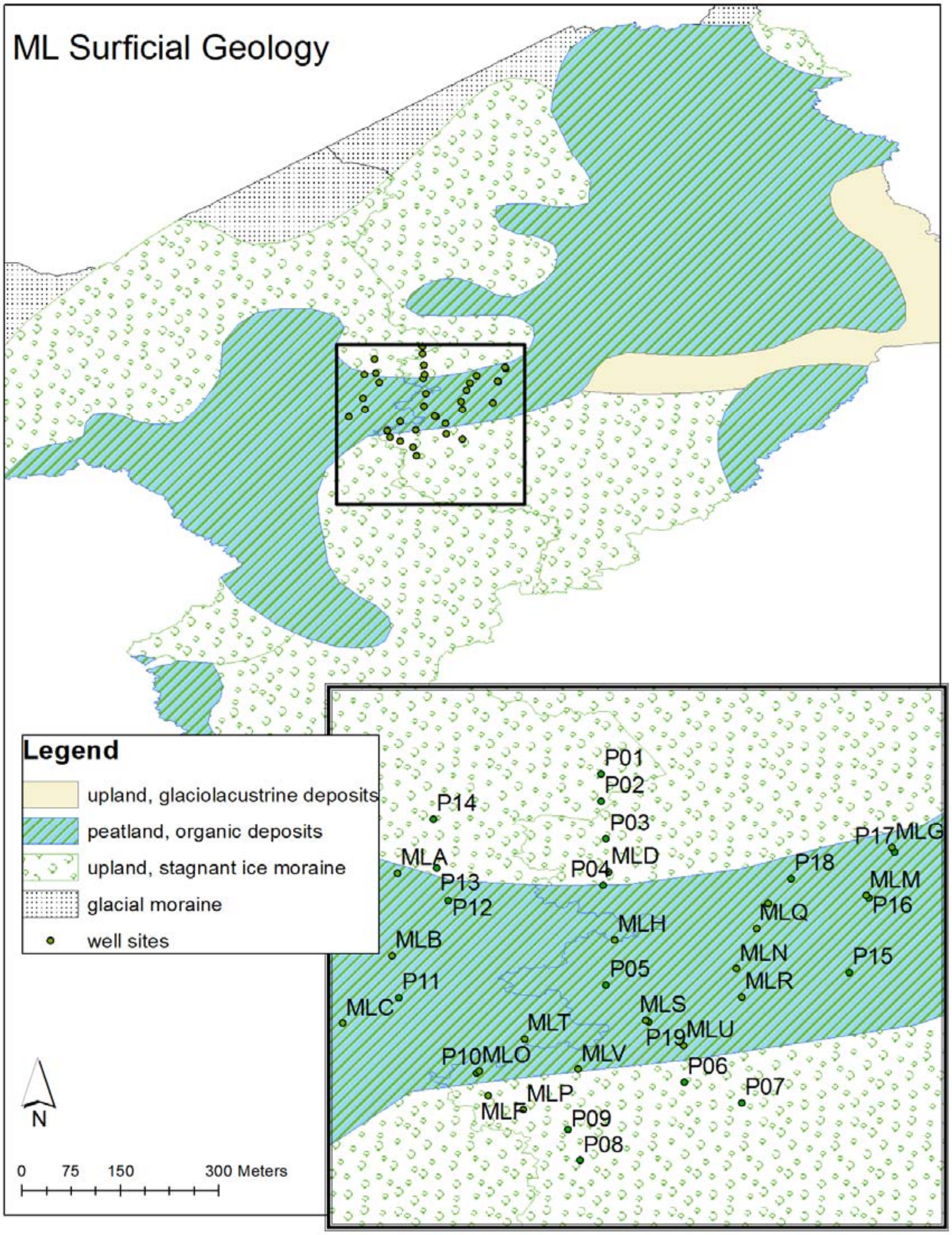


**Figure 1. 3 The surficial geology for ML site (Alberta Geological Survey; (Campbell et al., 2002)).**

## *1.5 Wetlands*

Wetlands are extremely important because of the large range of ecological (Schindler and Lee 2010) and hydrological (Turner et al. 2000) services they provide. As well as contributing to the dominant ecosystem type in the AOSR, these landscapes act as large carbon sequestration pools (Gorham 1991), and serve important biogeochemical functions (Bowden 1987; Prepas et al. 2006).

According to the National Wetlands Working Group (1997), wetlands are defined by a long term water presence that encourages hydrophilic plant growth. There are two main classes of wetlands: minerotrophic (lack peat accumulations < 40 cm and both groundwater and precipitation fed) and ombrotrophic (consisting of peat > 40 cm, and only precipitation fed). Further sub-classification of wetlands is defined by plant communities, nutrients, chemistry and water levels (Halsey et al. 2003).

Surficial topographic geology, consisting of poorly drained clay soils (Fenton et al. 2013) along with persistent high water tables, help to drive the accumulation of peat in this region (Zoltai and Vitt 1990). An additional driver is lower temperatures resulting in decreased rates of plant decomposition. Wetlands prevail in low lying areas and account for approximately half of the landscape in the AOSR (Vitt et al. 2001).

Vegetation found in ombrotrophic bogs is dominated by sphagnum mosses (*Sphagnum angustifolium, S. magellanicum, and S. fuscum*), and in nutrient poor fens, mosses (sphagnum and feather), and graminoid species (*Carex*) (Halsey et al. 2003). Common trees in these regions are tamarack (*Larix laricina*) and black spruce (*Picea mariana*). Slightly acidic conditions exist in these wetlands because of the decomposition of sphagnum species that cause organic acid to disassociate in the process (Siegel et al.

2006). Ombrotrophic bogs only receive atmospheric inputs (i.e. wet and dry atmospheric nitrogen), in comparison to fens, which receive inputs through atmosphere, through-flow of surface water, and groundwater (Bowden, 1987).

Numerous biological and hydrological factors influence the overall biogeochemistry of wetland systems. The vegetation and microbial communities can affect the transformation, cycling, and utilization of nutrients, including nitrogen. For example, the location of the water table is essential to the translocation of ammonium from within pore water in the moss mats upwards into sphagnum species (Aldous 2002).

A knowledge gap still exists about the importance of temporal variations in hydrology on the biogeochemistry of wetlands. Work in Europe has indicated that changing water levels in wetlands can result in changes in nutrient concentrations (Bougon et al. 2011). Nitrate concentrations were found to increase under wet hydrological regimes, and decrease during drier periods when water levels are drawn down. Bougon et al. (2011) found that the greater degree of connectivity in wetlands under wetter hydrological regimes resulted in increased fluxes of nitrogen because of increased oxygen from an adjacent stream. During the freshet, hydrological flowpaths have been shown to deliver increased dissolved organic nitrogen species, but not dissolved inorganic nitrogen; however, only a small portion was reported as exported out of the catchment (Petrone et al. 2007). This suggests that retention of nutrients occurred due to biogeochemical responses within the wetland.

Two hydrologic functions become important to the cycling of nitrogen in wetlands: 1) variations in water table level and 2) upland connections. The sinusoidal seasonal cycle for water tables in wetlands result in high fluxes of nitrogen species in the spring, followed by lower fluxes during summer in a dry cycle which is important for the overall natural abundance of nitrogen species present on a temporal scale (Cirmo and McDonnell 1997; Inamdar 2007). Fluctuations from high to low levels of the water table create different aerated locations within the wetland, which in turn can affect the biogeochemical processes that can occur. Aerobic conditions result in greater retention and transformation of nitrogen species (Cirmo and McDonald 1997; Pelster et al. 2008). Periodic rain events and the freshet can stimulate connections from the upland via overland flow which can add new sources of nitrogen into wetlands. Quantifying the overall fluxes of nitrogen within the boreal wetlands must consider overland flowpaths, groundwater connections, and site geomorphology (Price et al. 2005).

Along with hydrology, micro-topography and microclimate may also influence the movement and cycling of nutrients. Within peatlands, nitrogen cycling is dependent on the moisture conditions.  During wet conditions nutrients accumulate in the hollows; in contrast, high evaporation causes capillary uptake of nutrients into hummocks (Eppinga et al. 2010). As well, spatial distribution of nutrients may be associated with micro-topography because of hydrologic connections (Macrae et al. 2012).

*1.6 Uplands*

Upland portions of the AOSR are consistent with much of the Boreal forest of North America. Typical forests are dominated by jack pine (*Pinus banksiana*), an early successional species; however, other common trees found in this area are black spruce (*Picea mariana*), white spruce (*Picea glauca*), lodgepole pine (*Pinus contorta*) and birch (*Betulaceae betula*). Although not present at our study sites, aspen (*Populas tremuloides*) is found throughout the area. Fire is a common renewing factor for stands in the AOSR, resulting in monocultures of even aged stands of jack pine (Carroll and Bliss, 1982).

Ground vegetation in these Jack pine upland areas is minimal. The soil has a low moisture holding capacity due to a limited or absent clay content in glacial-fluvial and aeolian sands. In mature stands of jack pine it can be common to find exposed soil with no established vegetation (Carroll and Bliss et al. 1982). In addition, the generally nutrient poor soil of the boreal forest also results in limited forest floor vegetation. Specific to open jack pine stands, vegetation is strongly dominated by lichen (*Cladina*), labrador tea (*Rhododendron tomentosum*), and blueberry (*Vaccinium corymbosum)*. The main source of nitrogen inputs onto these landscapes is natural forest fires (Chanasyk et al. 2003). As well, nitrogen is the limiting nutrient in the carbon nitrogen soil ratio, and forest growth in the AOSR is related to nitrogen inputs (Yan et al. 2012).

The capability of nutrient retention in uplands forests and underlying soils is greater than wetlands (Pelster et al. 2008). Common soils of this region are Luvisols, with a greater presence of clays and tills, and Brunisols, dominated by sands (Ecological Stratification Working Group 1996). The sandy substrate typical of the upland areas has a low cation exchange capacity. The increased presence of clays and organic matter within the soil matrix will increase the buffering capacity of uplands for acid disposition (Whitfield et al. 2011). Finally, to maintain the soil's pH, a balance is needed between acid ($H^+$ and $Al^{3+}$) and basic ($Mg^{3+}$ and $Ca^{2+}$) cations.

Given the high hydraulic conductivity of the sandy sediments common in upland areas, flow from the surface of these uplands is largely vertical until either the water table is met or is intercepted by a slower hydraulically conductive substrate (Redding and Devito 2008). In both cases, the eventual result can be lateral flow. Therefore, hydrogeology and hydrology within these upland areas plays an important role in transport of nutrients between uplands areas and the adjacent wetlands.

Previous forestry-related research in the Boreal Plains, and specifically within the AOSR, has focused on the exchange of nutrients and phosphorus from upland areas into adjacent fens and waterways (e.g. Devito et al 2000). Yet, compared to other forested regions of North America, such as the eastern Boreal or western Cordillera, runoff between uplands and wetlands is much smaller in the Boreal Plains (Devito et al. 2005). This is mostly because of the sub-humid climate, limited relief and soil frost. Researchers have also noted that uplands and wetlands sometimes are often weakly connected due to infrequent episodes of runoff (Devito et al. 2012).

*1.7 Conceptual model of connectivity for uplands-fens-bogs in the Boreal Plains*

Based on what has been reported in the literature, a conceptual model was constructed for the study sites (Figure 1.4), to be used as the framework for the hydrological research component of the CEMA project. It identifies expected connections between uplands, fens and bogs. To identify the connection most likely to exist we have taken into account two prior models that identify connections in peatlands. The first is a surface model that assumes all inputs (such as water) are gained surficially into the system (Reeve 2000). This is based on the assumption of a decreasing hydrological conductivity with depth and minimal to no groundwater input. The second is defined as the dispersion model (Reeve 2001), which allows for mixing of waters at depths within large peatlands.

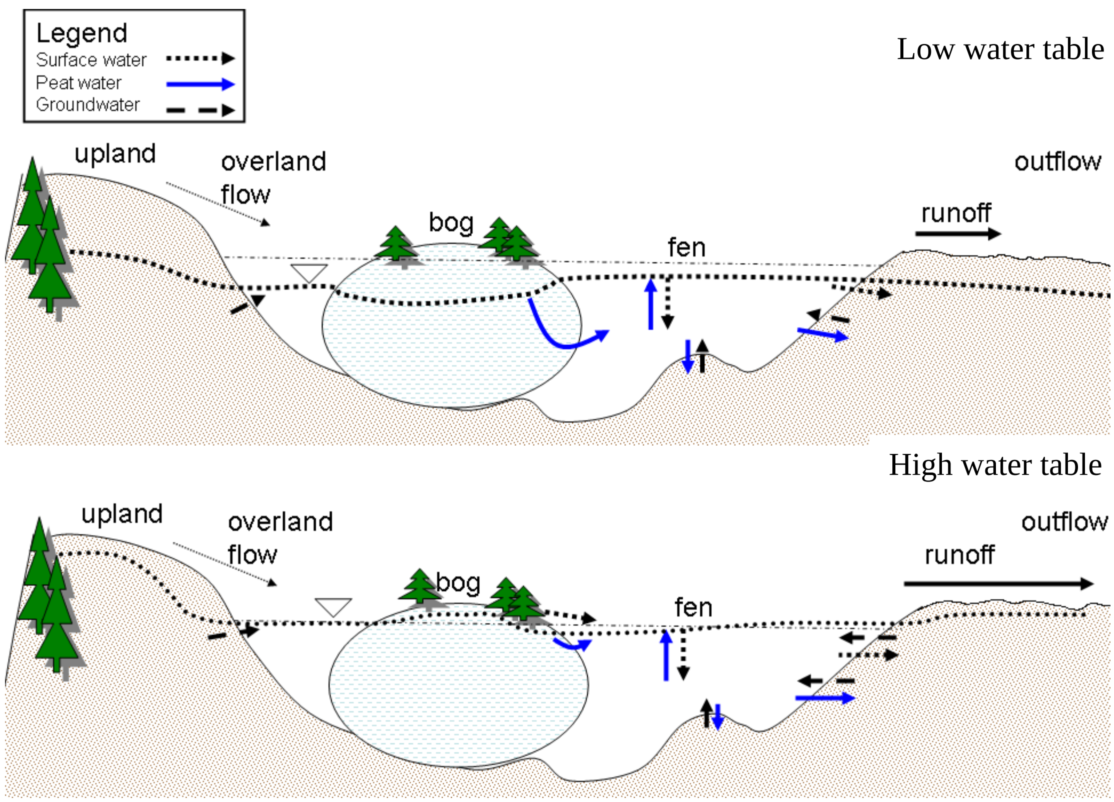


**Figure 1. 4 A Schematic of the conceptual model of our sites is shown. Connections and directions are indicated by arrows. The water table location is depicted by the triangle. Different arrow colors and patterns indicate different source of water for a connection.**

The basic assumptions of this conceptual model are that uplands are connected to wetlands through overland flow. This overland flow is dominated by snowmelt, as has been recorded by others (Petrone et al. 2007). As well, uplands may recharge wetlands in the spring in the shallow groundwater and vice versa in the fall (Hayashi et al. 1998).

Bog terrain units are defined as bathtub catchments that receive the only input from precipitation (snow and rain) with high rates of evaporation and continuous or episodic outflow (Gibson et al. 2000). Specifically, bogs have a larger storage capacity based on increase terrain roughness. In the past bogs have been considered to be hydrologically isolated, receiving only inputs from precipitation, but our conceptual model includes the potential outflows from these types of units. Flow away from bogs can occur when the recharge exceeds the storage threshold for water in the acrotelm (the living layer of peat), and may spill into the adjacent fens. We have also included a deeper flowpath of bog surface water into the fen water as was modelled by Reeve (2001).

Fens are characterized by receiving water through precipitation, surface through-flow, groundwater, and from adjacent uplands. Fens can also discharge water to uplands and groundwater via hotspots, which are heterogeneous areas within the peatland that have dissimilarities of thickness, porosity, and hydraulic conductivity allowing for a hydrological connection. *Hotspots* are recognized as exhibiting stronger connections via hydrological and biogeochemical functions (Morris et al. 2011). In addition, fens may undergo fluctuation in hydraulic gradients with upward gradients when evapotranspiration exceeds the precipitation in the summer, and downward hydraulic gradients when precipitation exceeds the evapotranspiration in the spring (Fraser et al. 2001).

Runoff water is assumed to be a mixture of surface water (water found in the acrotelm) and peat water (water found in the peat that is below the acrotelm). Evapotranspiration will occur across all terrains. The design of the study was to evaluate, and where possible, to quantify the hydrological properties and connectivity identified in this conceptual model, with the goal of understanding the potential transport of nitrogen between these terrain types.

Although not necessarily explicitly identified in the conceptual model, seasonality is an important factor that influences the hydrological connections between uplands, fens, and bogs in Boreal Plains, as it is highly variable and dynamic. To account for this factor the conceptual model identifies two different water table levels, high and low. We hypothesize that in the spring wetlands contribute to the surface flow regimes dominated with snowmelt runoff. As moisture depletes, wetlands play a greater role in subsurface flow as is identified in the low flow scenario. Researchers have found that as storage thresholds in wetlands deplete, the hydrological functions change from discharging to recharging (Ferone and Devito 2004). In addition, depending on the degree of saturation, wetlands may recharge in a dry year and discharge in wet years (van der Kamp and Hayashi 2009). As a result, the magnitude of runoff from catchments is variable in time.

This thesis is organized as follows. Based on the conceptual model (Figure 1.4), Chapter 2 examines potential movement of water within shallow groundwater (including peat water) in the bog and fen to the surrounding upland. Connections identified in the conceptual model are examined to assess if they are valid for the study sites. Chapter 3 focuses on surface water movement between terrain units. Both chapters also address the role antecedent moisture condition in water table fluctuations.

Each chapter is designed as a stand alone manuscript, resulting in some repetition in the site descriptions and methods. Overall this thesis contributes to the overarching goal of understanding the potential transport of nitrogen between these terrain types by focusing on characterization and better understanding of hydrological connections among key landscape components.

## 2.0 Shallow groundwater flow in the mosaic of terrains of the Boreal Plains

**Abstract**

Surface and groundwater flowpaths may act as conduits for the movement of dissolved nitrogen species in Boreal landscapes in the Athabasca Oil Sands Region (AOSR). This study combines traditional hydrological and hydrogeological methods, as well as stable isotopes of water to identify and characterize surface and groundwater flow. Two sites were instrumented with water table wells and shallow piezometers (< 8 m-depth) in the area of Fort McMurray, Alberta, and monitored during 2011 and 2012, to characterize the surface and subsurface flowpaths and connectivity between bogs, fens, and uplands typical of the Boreal Plains landscape.

Hydraulic conductivity had a large range at both sites, with a general decrease in hydraulic conductivity with depth in fen and bog units (averaging 2.3x $10^{-6}$ $ms^{-1}$) at both sites. Large vertical hydraulic gradients were found primarily to arise from very low hydraulic conductivity of compact peat at the base of the fens and bogs. Lateral hydraulic gradients showed the potential for groundwater flow from the uplands to the fens, and limited to negligible groundwater flow from the wetlands to the uplands. The connectivities between uplands, fens, and bogs differed between the two sites due to differences in hydraulic connectivity. Stable water isotopes indicate seasonal variations in the sources of water in shallow (<2 m) upper layers of fens and bogs, but below this depth the stable isotopic signature is more stable and representative of long-term weighted averages, especially in bogs. A few exceptions are noted for piezometers in the fen at ML (P17, P18). Spatial and temporal variability in the connectivity of adjacent

terrain units is a major feature of the landscape and makes it difficult to classify terrain units either as potential sources or sinks of nitrogen for the purposes of critical loads assessment.

### *2.1 Introduction*

The Boreal Plain is a region defined by its lack of topographic relief, which can make shallow groundwater flow difficult to characterize. In the absence of strong topographic gradients, many factors become important in defining shallow groundwater flow, including: geology, climate, and soil type (Devito et al. 2005).

The focus of this chapter is to test the potential hydrological connections between uplands, fens and bogs identified in the conceptual model (see Chapter 1) using a combination of hydrogeological and isotopic tools. Previous research examining hydrological connectivity using the combination of shallow groundwater flow and stable isotopes of water is limited in this Athabasca Oil Sands Region (AOSR) for the terrain units of interest. The objectives of this chapter are: 1) define the surficial flow, through a digital elevation model; 2) to define the shallow groundwater flow through traditional groundwater techniques; 3) and, where possible to verify the interactions of both through examination of the stable water isotopes.

Bedrock in the Fort McMurray region consists of Precambrian basement overlain by Devonian carbonates and a thick sequence of Cretaceous clastic rocks (Hackbarth and Natasa 1979). Quaternary sediments, including numerous buried channels up to 300 m-depth, overlie bedrock in the region (Andriashek and Atkinson 2007) and can strongly influence the regional groundwater flow paths.

This region is comprised of a heterogeneous landscape of low-lying wetlands, and subtle upland areas. Wetlands consisting of bogs, fens, and peat-pond complexes often derive most of their water storage from precipitation, which is in turn lost to evapotranspiration (Barr et al. 2012) or as drainage into rivers and lakes. Wetlands are found throughout the region with fluctuation in recharge, discharge, flow-through and storing states (van der Kamp and Hayashi 1998) varying based on differences in landscape positions (Winter 2001) and antecedent moisture conditions (Hayashi et al. 1998). Previous work has identified the importance of antecedent moisture conditions in determining the lateral transfers between uplands and the adjacent fens and bogs. Lateral transfer of stored water from uplands to wetlands was shown to be prevalent during wet periods and transfers from wetlands to uplands possible during dry periods (Hayashi et al. 1998; van der Kamp and Hayashi 2009). This is similarly seen outside of the region (Fraser et al. 2000). When the surface depression storage capacity of these terrain units is exceeded groundwater recharge or surface overland flow may occur. However, previous research in the AOSR has not extensively examined fens, bogs, and uplands. Research conducted under slightly different climatic regions such as ‘semi-arid’ may not have strong representativeness for this area. Therefore, there are still uncertainties about shallow groundwater flow across this mosaic landscape of the Boreal Plains.

Stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$) are particularly useful tracers for identifying different hydrological processes. Systematic variations in the isotopic labelling of precipitation arise because of temperature-dependent isotopic equilibrium fractionation that occurs during phase changes of water, and distinguishes differing sources of water within the hydrological cycle (Dansgaard 1964). As well, stable isotopes of water give insight to hydrological mechanisms such as seasonal flushing and evaporative losses in lakes and rivers based on isotopic enrichment and relative humidity (Gibson et al. 1993). Seasonal fluctuations in precipitations occur along the meteoric water line (MWL) defined by Craig (1961), with snow and winter processes being relatively depleted of heavier water molecules to lighter water molecules ($^{2}H^{18}O$ < $^{1}H^{2}H^{16}O$) and summer precipitation being relatively enriched in a ratio of heavy water molecules to light ($^{2}H^{18}O$ > $^{1}H^{2}H^{16}O$). In surface waters, evaporative enrichment occurs through both kinetic and equilibrium fractionation, resulting in a systematic offset from the MWL onto a local evaporative line (LEL) and is often seen in lake settings in this region (Bennett et al. 2008). The degree of offset from the MWL can be used to quantify the water balance of lakes (Gibson et al. 2011).

As precipitation recharges through the unsaturated zone to the water table, the seasonal variations in the isotopic composition of precipitation are gradually dampened, so that at depth the isotopic composition of groundwater should be similar to the amount weighted mean of precipitation (Fritz and Clark, 1997). Looking at variations in isotopic labelling of groundwater at depth can be used to identify a surface zone more influenced by seasonal variations (Fritz and Clark, 1997). At greater depth, the variability zone diminishes and a relatively stable background signature is present.

A few recent studies using stable isotopes of water have contributed important knowledge on flowpaths and connectivity of uplands, fens and bogs. In peatlands of northern Alberta, McEachern et al. (2006) found that discharge was dominantly from piston type flow rather than overland runoff, driven by the downward movement of recharging precipitation. A recent isotopic study by Levy et al. (2013) also revealed that seasonal recharge signals in a Minnesota peatland could be traced to depths greater than 3 m, challenging conceptual models that assumed vertical advection of recharge waters occurs only beneath the crest of large raised bogs.

Identifying the impacts of industrially derived atmospheric depositions in the AOSR is a primary goal of the CEMAs $NO_xSO_2$ management working group. Establishing relevant critical loads of sulphur and nitrogen for uplands, fens and bogs in the AOSR requires understanding of whether there are significant fluxes of these nutrients via hydrological connections. Understanding the potential for these transfers of nitrogen between terrain types requires better basic understanding of surface and groundwater interactions between wetlands and uplands, along with geochemical conditions that may influence the fate and transport of nitrogen and sulphur between these terrain types.

**2.2 Study sites**

Two study sites that lie within the north-eastern portion of the Boreal Plains of Alberta, coinciding with the AOSR (Figure 2.1) were examined. Sites were selected to be representative of a typical Boreal Plain landscape, and to include key terrains units:

upland, fen, and bog. Both sites were selected to represent natural undistributed hydrological conditions with minimal disturbances.

The first site is located 100 km south of Fort McMurray, near Mariana Lakes (ML) (Figure 2.1A). This site is a 23 $km^2$ peatland complex that includes jack pine (*Pinus banksiana*) islands and uplands, bordering a poor fen, and ombrotrophic bogs. *Sphagnum* mosses (*S. angustifolium, S. magellanicum, and S. fuscum)* dominate the peatlands. Other vegetation includes: sundews (*Drosera*), laurel (*Kalmia*), bog rosemary (*Andromeda glaucophylla*), and cranberries (*Vaccinium vitis-idaea*). Trees in the bogs are black spruce (*Picea mariana***),** and tamarack (*Larix laricina*).

The second site, Jack Pine Hill (JPH), is located 40 km north of Fort McMurray in an upland dominant area (Figure 2.1B). This site is approximately 7 $km^2$, and is dominated by nutrient poor sand soils at the surface. There is a uniform stand of jack pine (*Pinus banksiana*) trees and the forest floor vegetation is comprised of lichen (*Cladina*), labrador tea (*Rhododendron groenlandicum*), and blueberry (*Vaccinium corymbosum).* A rich minertrophic fen runs north through the western side of the site and vegetation includes: alders (*Alnus),* paper birch (*Betula papyrifera*), and sedge species (*Carex*).

The AOSR has a sub-humid climate with an average annual precipitation of 445 mm (measured at Fort McMurray airport, Environmental Canada, 2012) and evapotranspiration often exceeds the precipitation. Daily average temperatures are

-18.8 °C in January and 16.8 °C in July (Environmental Canada, 2012). Quaternary (surficial) geology in this region is a mix of glacial fluvial and lactrustrine deposits (Andriashek and Atkinson 2007).

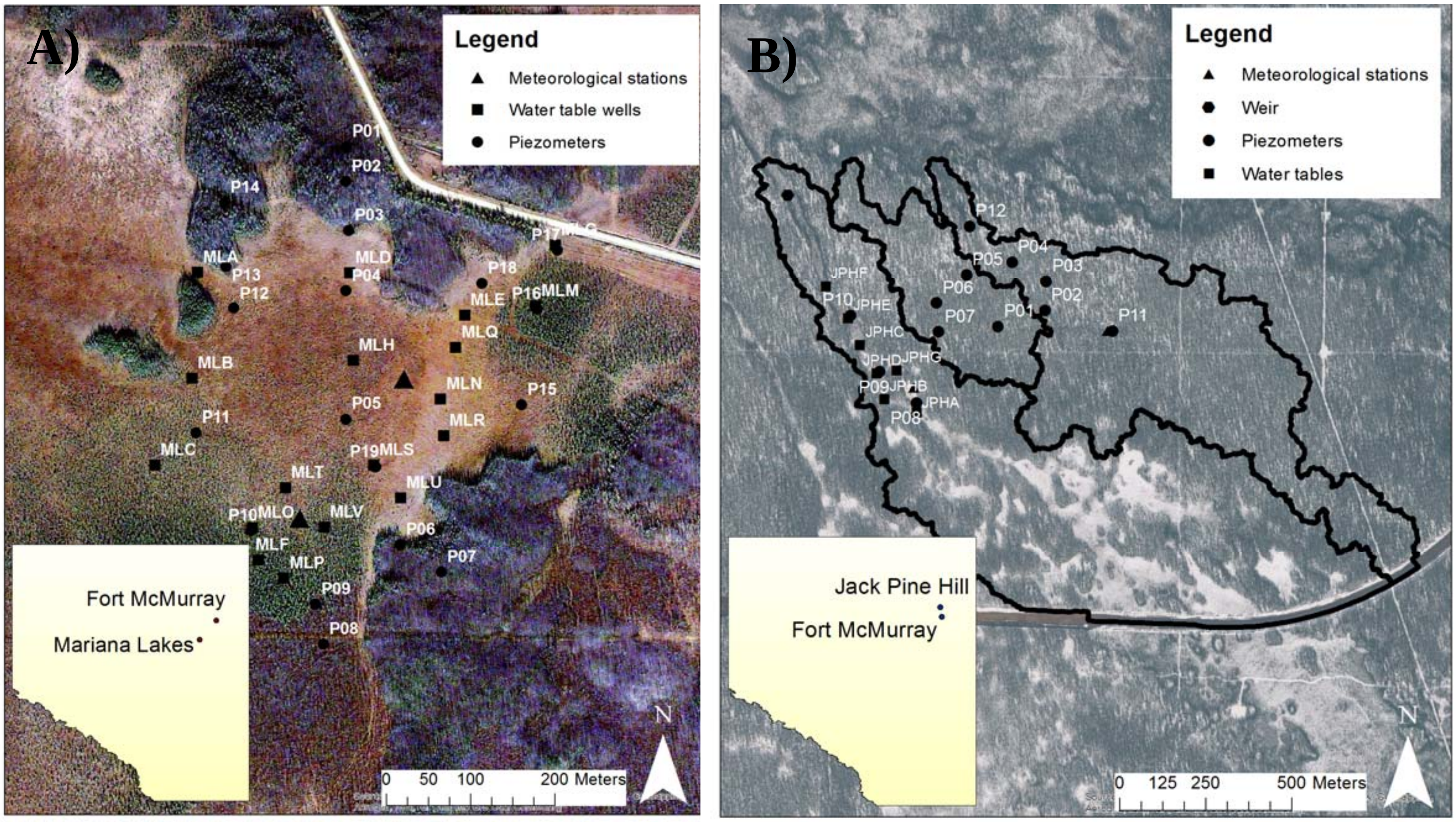


**Figure 2. 1 Study sites are situated in the province of Alberta (left), A is ML and B is JPH.**

## *2.3 Field methods*

### *2.3.1 LiDAR acquisition and DEM interpolation*

LiDAR surveys were flown for ML and JPH (June 22 2011 and June 23 2011 respectively) by DigitalWorld Mapping, Calgary AB. The total area surveyed for ML was 23 $km^2$ and 7 $km^2$ for JPH. The vertical accuracy of the survey was approximately 0.05 m and the resolution of the pixels was 1 $m^2$. Pixels were classified into ASCII files consisting of xyz locations with elevations for bare earth and first return layers interpreted into a digital elevation model (DEM). The DEM was completed using an algorithm through Arc GIS 10 (ESRI). The locations of potential surface flow paths were identified in the DEM grid as lowest elevation points for each 8 surrounding pixels and eventually linking to the outlet points. While these were not necessarily wet, they represent zones/pathways most likely to be wet during periods of overland flow events.

*2.3.2 Groundwater methods*

The two field sites were instrumented with nested piezometers (ML: 19 and JPH: 11 nests), water table wells (ML: 19 and JPH: 7 wells), micro-meteorological stations (ML: 2 and JPH: 2), and gauging stations (weirs) at outflow points for each site. Piezometers nests, ranging from 2 to 4 piezometers per nest were installed at depths ranging from approximately 1.5 to 7 m. Each piezometer was constructed from either PVC pipe or black iron pipe, threaded into a stainless steel Solinst™ model 615 drive-point screened piezometer tip. The polyethylene tubing (PET) was placed inside the PVC or steel piping and threaded directly into the piezometer tip. Piezometers were installed using a Pionjar™ percussion hammer. Water table wells were manually installed into the peat, and augured into the rich fen. They were constructed from slotted PVC pipe of approximately 1 m length, and covered with Nitex mesh to avoid sediment flow into wells. Some of the water table wells were installed alone and others were installed immediately adjacent to piezometer nests. At each piezometer nest, the deepest piezometers were installed into the lower permeability substrate underlying the peat (identified as the point of refusal for the drive point). To avoid fluctuations in water levels that might have been due to changes in elevations in the peat surface, all of the water table wells were anchored to rebar rods which were installed into underlying low permeable soils. In addition, the distance between the top of the well casing and the ground surface was measured yearly (within ~ 1 cm) to identify whether the surface of the peat had changed significantly. Wooden platforms were built around piezometer nests to try to reduce any peat compression that could occur during sampling or monitoring visits.

Three transects were used to examine the lateral hydraulic gradient at JPH (seen in Figure 2.2. The first transect (shown in red) runs east-west, and contains five wells P-11-2-1-7-10, the second (shown in yellow) runs southeast to northwest and contains five wells P-11-2-3-4-12, and finally, the third (shown in green) runs along the fen P8-9-10-F from southeast to northwest. The east-west transect (shown in red) consists of uplands wells (P11 through P7) and a well (P10) within the rich fen. Elevation is highest at P11, and the lowest at P10. The surface vegetation does not indicate any areas of standing water in the uplands, and the appearance of the fen represents an abrupt change to the landscape. For the southwest-northeast transect (shown in yellow) all wells are located in the uplands. The elevation is highest at P3 and lowest at P12. An increased presence of Labrador Tea and Black Spruce trees indicate a slight change in vegetation close to P12.The final transect (shown in green) runs the length of the studied fen with the highest elevation to the south and the lowest to the north. Note that there is limited direct evidence available on the composition of the shallow surficial deposits, and the only indications of changes in lithology at JPH are based on noticeable differences in properties of soil or refusal during installation of the drive-point piezometers. In general, during installation in the uplands in JPH, drive-point piezometers were installed at a consistent rate until a desired depth was met. This may suggest that the uplands are composed of fairly uniform sediments similar to what was observed at the surface, but it is possible that a lower conductivity layer may be present at depth.

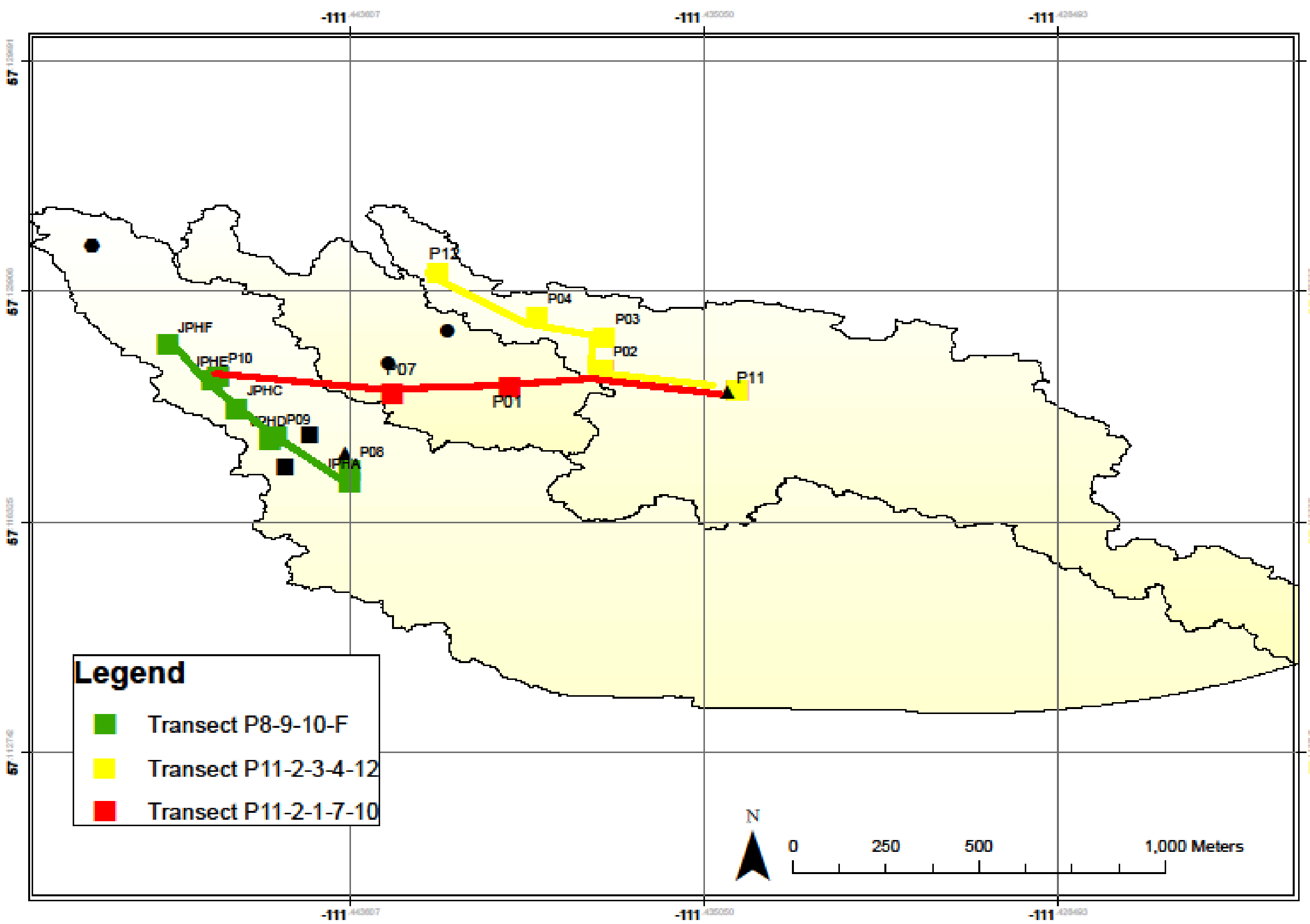


**Figure 2. 2 Transects used for flow nets at JPH site, one runs east-west in red transecting the uplands and the fen in red, another follows an upland flowpath southeast –northwest in yellow, and the final transect in green follows the rich fen running southeast to northwest.**

V-notch weirs and stilling wells were used to try to monitor the overall outflow of water from the basins at both sites. At JPH a weir was installed at the fen where seasonal surficial flow was observed during the initial site visit (2010). Outflow from ML was more difficult to identify. The fen complex at the ML site appeared to flow towards a culvert that had only periodic surface flow. The fen complex at ML fed a larger fen system that discharged via culvert at highway 63. Attempts to instrument the culvert closest to the main ML site were not successful, so our estimates of outflow are based on water table wells installed near the discharge point at ML and a weir located at the culvert at highway 63. Due to variable flow during the two years, attempts to gauge the outflows at both sites were unsuccessful.

During the open water season monthly to bimonthly measurements of hydraulic head (Fetter 2001 p.116), were made in 2011 and 2012. Elevations were determined from LiDAR surveys, and the pressure heads were recorded from water level readings. Water level measurements in the piezometers and water tables wells were made using a Solinst water level tape or a Heron little-dipper. Pressure head measurements were made at JPH and ML on: June 28 2011, Aug 7 2011, Aug 24 2011, Oct 4 2011, May 25 2012, June 6 2012, July 17 2012, Aug 3 2012, and Sept 8 2012. Potentiometric contour plots were created by kriging hydraulic head measurements using Surfer 8 (Golden Software Ltd). Hydraulic head was used to identify vertical hydraulic gradients and seepage fluxes, the following was applied:

$$dH/dL = VGH, \quad D = -(K)(VGH)(A) \qquad (1)$$

Where

dH = difference of hydraulic pressure head of two wells (m)
dL = distance between two wells screens (m)
VHG = vertical hydraulic gradient (unitless)
D = seepage flux ($ms^{-1}$)
K = hydraulic conductivity ($ms^{-1}$)

The Hvorslev (1951) method was used to calculate the hydraulic conductivities based on falling head tests conducted at all of the wells at JPH and wetland wells at ML. During the falling head tests, the initial water level of the well was recorded, followed by the removal of a slug of water using a peristaltic pump. An Odyssey Water Level Capacitance™ probe was used to obtain accurate falling head and time measured (every 5 s) in millimetres. The Hvorslev method accounts for the geometry of the piezometer and was applied as:

$$K = \frac{r^2 \ln(L_e/R)}{2L_e t_{37}} \quad (2)$$

where

K is the hydraulic conductivity ($cms^{-1}$)
r is the radius of the well casing (cm)
R is the radius of the well screen (cm)
$L_e$ is the length of the well screen (cm)
and $t_{37}$ is the time it takes for the water level to fall to 37 % the initial change (s)

(Fetter 2001:194p)

Falling head tests could not be conducted for the deep wells and uplands wells in ML because the water levels were too low and water was only present in the screened section of well. At JPH, the shallow upland wells also did not have water levels above the well screen. Due to the small diameter of the well screen, the Solinst water level tape did not fit into it nor did the Odyssey Water Level Capacitance™ probes; therefore no data was collected for these wells (P7, P4, and P1 at the 2 m depth).

### *2.3.3 Water sampling*

Water samples were collected from all water table wells, piezometers, at the outflow points (weirs) and for precipitation (event and bulk). Groundwater samples were collected after purging three well volumes of water from each well. Precipitation samples were collected after individual events and from bulk samples at the end of the field season. Snow samples were collected in 2012 using a Standard Federal snow sample corer and were used to characterize the isotopic composition of winter precipitation. Water samples for stable water isotopes were placed in 30 mL air tight high density polyethylene bottles with no head space to minimize the possibility of isotopic fractionation. Samples were analyzed by AITF Victoria using a Delta V Advantage mass spectrometer. Results were reported in per mil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW) with an analytical uncertainty of 0.1 ‰ for $^{18}O$, and 1 ‰ for $^{2}H$. The oxygen-18 and deuterium composition are reported as delta (δ) calculated using:

$$\boldsymbol{\delta}\,^{18}O \text{ or } \boldsymbol{\delta}\,^{2}H = [R_{sample}/R_{standard} - 1] * 10^{3}\text{ ‰}, \quad (3)$$

where $R_{sample} = {}^{18}O/{}^{16}O$ sample and $R_{standard} = {}^{18}O/{}^{16}O$ V-SMOW

$R_{sample} = {}^{2}H/{}^{1}H$ sample and $R_{standard} = {}^{2}H/{}^{1}H$ V-SMOW

## 2.4 Results and discussion

### *2.4.1 Surficial flow patterns from the Digital Elevation Model*

Elevation data were gathered from the LiDAR survey (seen in Figure 2.3). The elevation range at ML is around 4.0 m, with the highest areas being in upland sections at 703.1 m

(P2), and the lowest area (within the immediate study site) being 698.7 m (MLG) near the culvert at the access road. Elevations were slightly higher in the bog than the fen by about 0.3 m. At JPH, elevation differences are also about 4.0 m. The fen in the northwest is the lowest point with an elevation of 331.2 m (JPHF) and the highest area recorded is 335.2 m (P11).

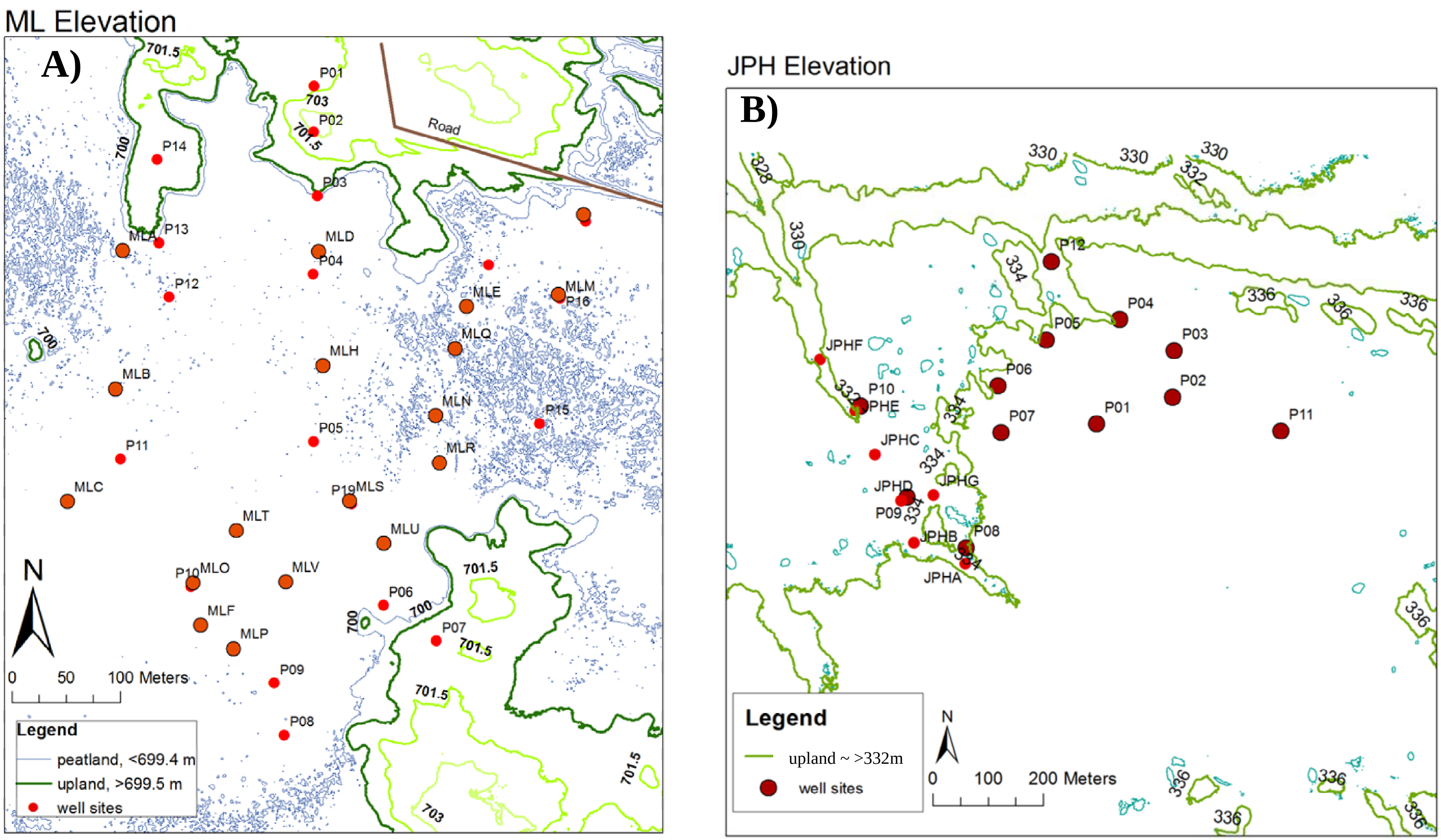


**Figure 2. 3 E Site elevations, A) ML elevations contoured at 1.5 m intervals, and B) JPH elevation contoured at 2m intervals.**

The Digital Elevation Model (DEM) developed from the LiDAR survey permits delineation of two sub-catchments in the ML study area. These sub-catchments divide the fen and bog terrain at the ML site and potentially indicates a surface water divide (seen in inset of Figure 2.4). The catchment to the west is 3.32 $km^2$ and the catchment to the east is 3.82 $km^2$. From the DEM it is evident that the construction of the AltaGas road has altered the natural flowpaths exiting the instrumented site (near MLG), as natural flowpaths have been diverted into three culverts. In addition, in areas of minimal relief, building new infrastructure can dramatically alter the surficial flow through the creation or reduction of hummocks (Lee and Boutin 2006). The some of the surficial flow tracks predicted by the DEM closely resemble the observed water tracks (lighter fen areas) as seen from satellite imagery for this site (see Figure 2.1).

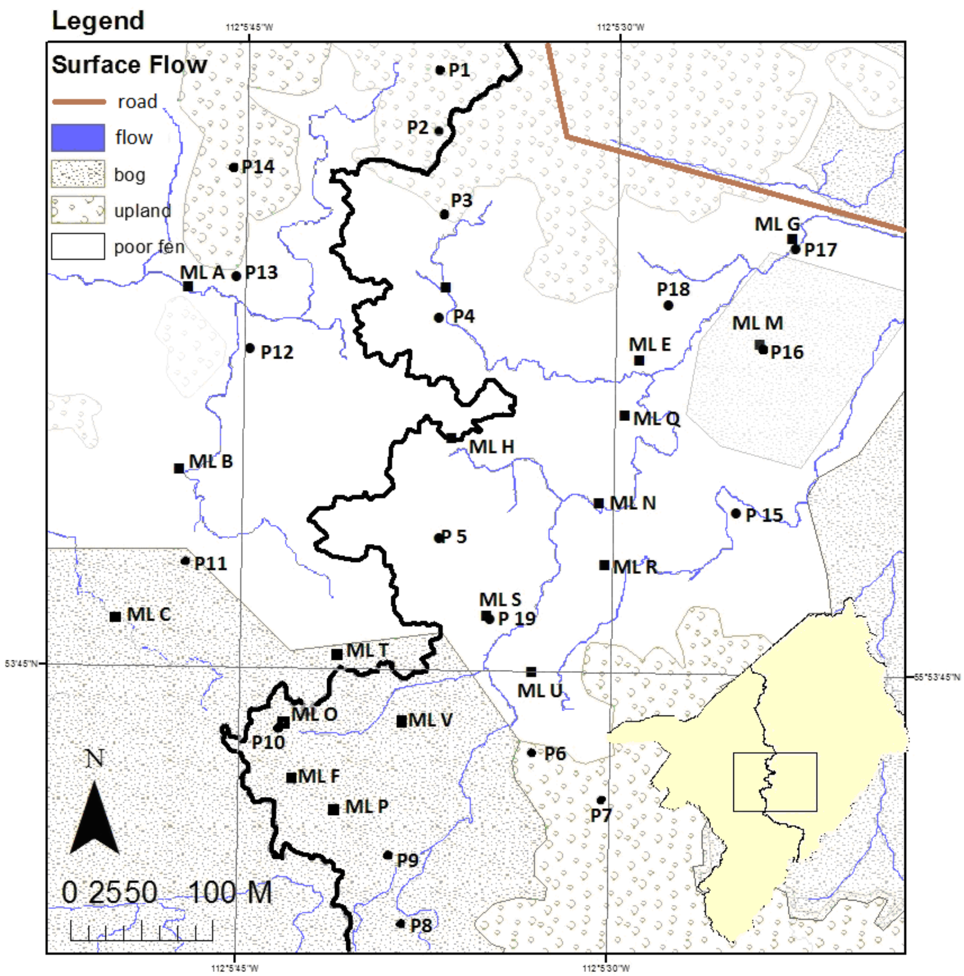


**Figure 2. 4 ML watershed with hypothetical surficial flow tracks (blue lines) delineated from LiDAR. Black line indicates a watershed divide between two sub-catchments seen in the inset of the full catchment. Locations of piezometers are in circles and water table wells in squares.**

The DEM at the JPH site (Figure 2.5) reveals several sub-catchments as well as many predicted water tracks. The predicted water tracks situated in the fen were the only ones ever observed to be saturated and periodically flowing, whereas the potential water tracks identified in the upland areas were dry throughout the study. Three sub-catchments were delineated at this site: A, to the west (0.82 $km^2$); B, central (0.17 $km^2$); and C, to the east (0.5 $km^2$). All of the sub-catchment water tracks flow northwest. The results of the DEM analysis suggest that surface water flow from the central and east sub-catchments would not likely be directed towards the fen, and the only potential hydrological connection between these sub-catchments and the fen would be via groundwater flow.

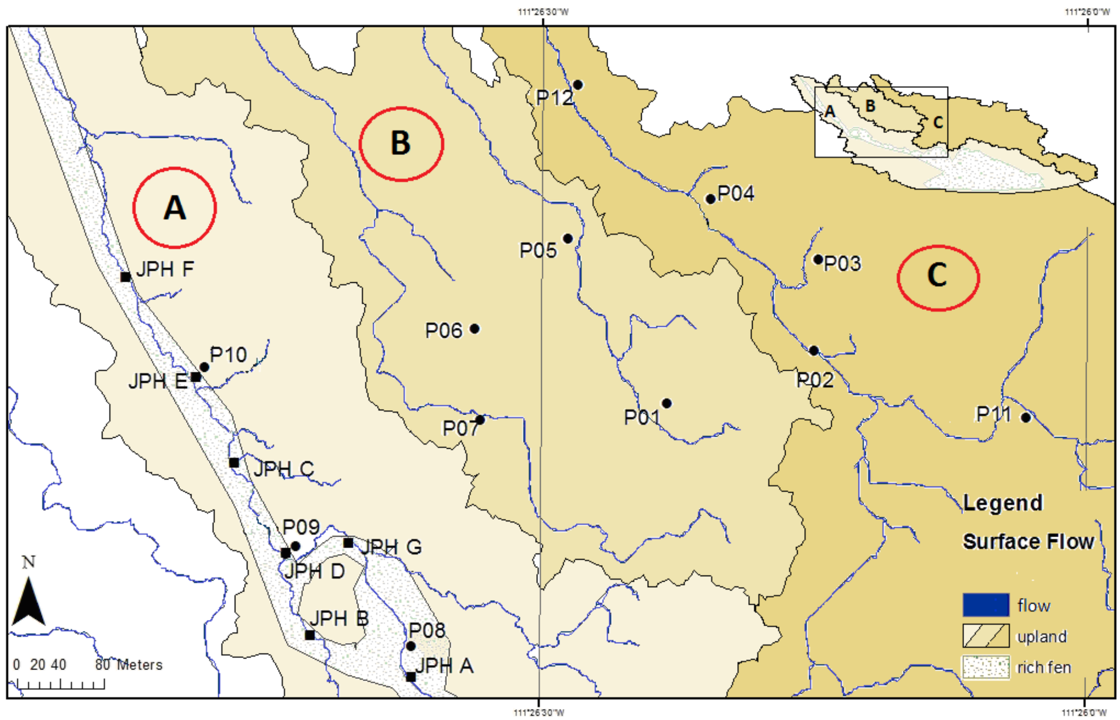


**Figure 2.5 JPH watershed with sub-catchments (A, B and C) and potential surficial flow tracks Black line indicates a watershed divides between the sub-catchments seen in the inset of the area. Sub-catchments are labelled A, B, and C from west to east, respectively. Locations of piezometers are in circles and water table wells in squares.**

*2.4.2 Hydraulic conductivities*

The range of hydraulic conductivity estimates vary between sites and years (Figure 2.6). Overall, the hydraulic conductivity estimates at JPH are higher than those at ML with an order of magnitude less variability. The hydraulic conductivities obtained from the JPH site are consistent with sand deposits, similar to the sandy soil observed near the surface. A soil pit was dug near P1 to a depth of 1 m. Sandy soil was uniform throughout the depth of the pit and there were no colour changes to indicate changes in redox conditions. The piezometers installed in the rich fen at JPH show higher hydraulic conductivities in the surface layer of the peat, and lower hydraulic conductivities at depth in the fen (Figure 2.7a), as is expected for peatland soils.

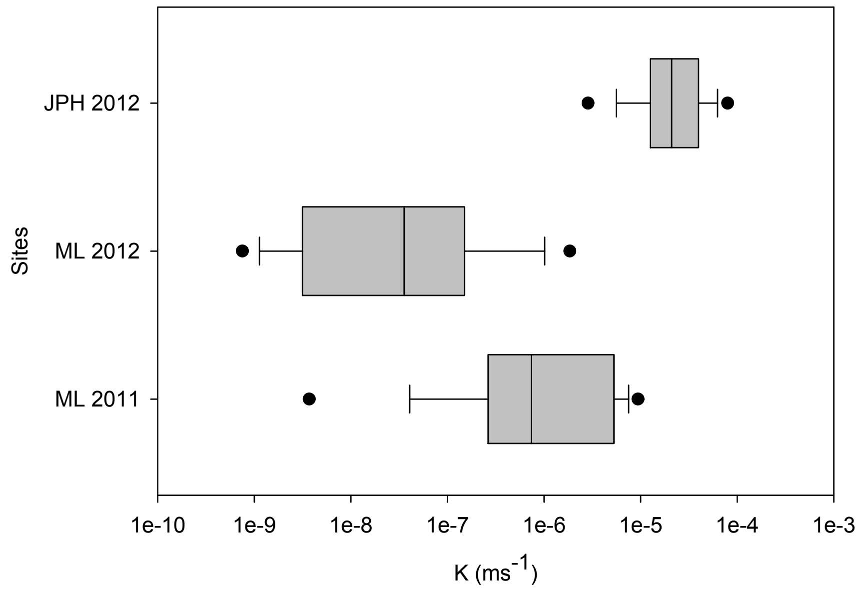


**Figure 2. 6 Summary of hydraulic conductivities recorded at ML in 2011 and 2012, and JPH in 2012.**

The large overall range of hydraulic conductivities at ML (Figure 2.6) shows the greater variability in hydraulic properties in the sediments present at this site. There were also significant differences in the hydraulic conductivities observed at ML over the two year study period (Figure 2.7b). Differences in values measured for 2011 and 2012 may be due to variation in the method used to conduct the test. In 2011, a slug of water was injected into piezometers (falling head tests), while in 2012 a slug of water was removed (rising head test). The later procedure was adopted in 2012 to avoid introducing foreign water into the subsurface which could damage the isotopic and geochemical composition of groundwater. Surridge et al. (2005) found a slight increase in hydraulic conductivity values with the rising head tests, suggesting it could be related to a well film. In addition, the slug of water that was injected was deionised water, possible resulting in a flushing of smaller particles away from the well. Baird et al. (2004) noted a similar effect of increased hydraulic conductivity by adding "clean water" to piezometers in peat.

Hydraulic conductivity differences may not be solely due to the methodology used, but they may also reflect interannual differences in the water table position. Large ranges in values of hydraulic conductivity in peat can be associated with water table position resulting in varying pore formation within the structure of peat (Price 2003). Previous workers examining drained peatlands in Europe have noted that desiccation cracks can form after a significant drawdown of the water table (Holden et al. 2004). Peatlands have also been observed displaying hydrophobicitiy closer to the surface, resulting in an increased responsiveness of a deeper groundwater table (Schwäerze et al. 2002). This could possibly lead to increased movement of water in macropores at depth in peat and thus increased hydraulic conductivity. Finally, seasonal changes in gas content of peat have been noted to change the hydraulic conductivity by over two orders of magnitude (Kettridge et al. 2013).

The piezometers located at the edge of the upland (6A and 6B) had the lowest calculated hydraulic conductivities. ML 6A (7.5x $10^{-10}$ $ms^{-1}$) and 6B (1.51x $10^{-9}$ $ms^{-1}$) values fall within the range of a clay sediment 1x $10^{-10}$ –1x $10^{-7}$ $ms^{-1}$ based on Fetter (2001 p 85). Deeper peat had lower hydraulic conductivities ranging from 1.5x $10^{-9}$ to 9.4x $10^{-6}$ $ms^{-1}$ and averaging 2.3x $10^{-6}$ $ms^{-1}$, whereas shallow peat had higher values ranging from 4.6x $10^{-8}$ to 5.3x $10^{-6}$ $ms^{-1}$ and averaging 9.0x$10^{-7}$ $ms^{-1}$. These findings for

2012 are consistent with previous studies of peat where hydraulic conductivity was evaluated at several depths (Quinton et al. 2008; Morris et al. 2011).

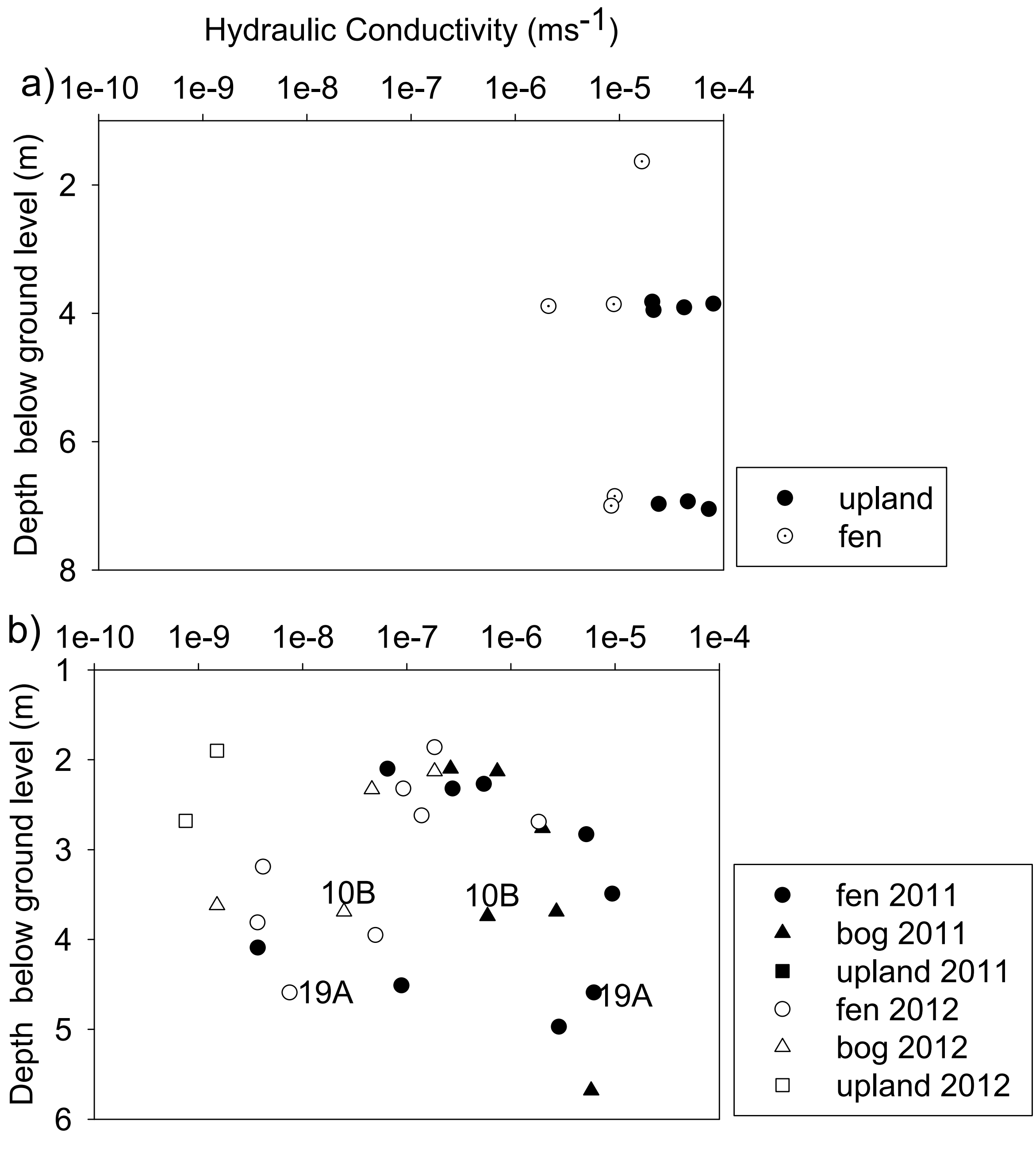


**Figure 2. 7 a) Hydraulic conductivities of JPH with respect to depth for 2012. b) ML hydraulic conductivities with respect to depth for both 2011 and 2012 with terrain units.**

### *2.4.3 Groundwater hydraulic gradients*

Potentiometric surface maps were constructed from the hydraulic head data to illustrate lateral and vertical flow direction at surface, shallow and intermediate depths during spring, summer and early fall of both years of study for both sites. These results are described below by site.

Lateral contoured hydraulic head gradients for JPH (Figure 2.8 and 2.9), show groundwater predominantly flowing north and northwest following the surface topography at the site. During spring of 2011 (June 28), for intermediate wells, groundwater moves towards the fen from the uplands, and piezometer P9, located in the fen, displays an upward (discharging) vertical hydraulic gradient. This trend is not seen in 2012. Shallow wells in the fen display the largest vertical flow potential, primarily recharging shallow groundwater, except for a periodic shift to a discharging gradient seen at P8. The shallow wells in the uplands were dry during Oct. 3, 2011 (Figure 2.8) and so hydraulic head was not recorded. At P4, the piezometer with the lowest elevation within the uplands, we find a discharging hydraulic gradient at shallow depth. In general, minor differences are seen in the groundwater flow in shallow and intermediate wells at JPH. In the drier year, 2011, the potential flow is generally to the west towards the rich fen; whereas, in 2012 the path was found to be somewhat more northerly.

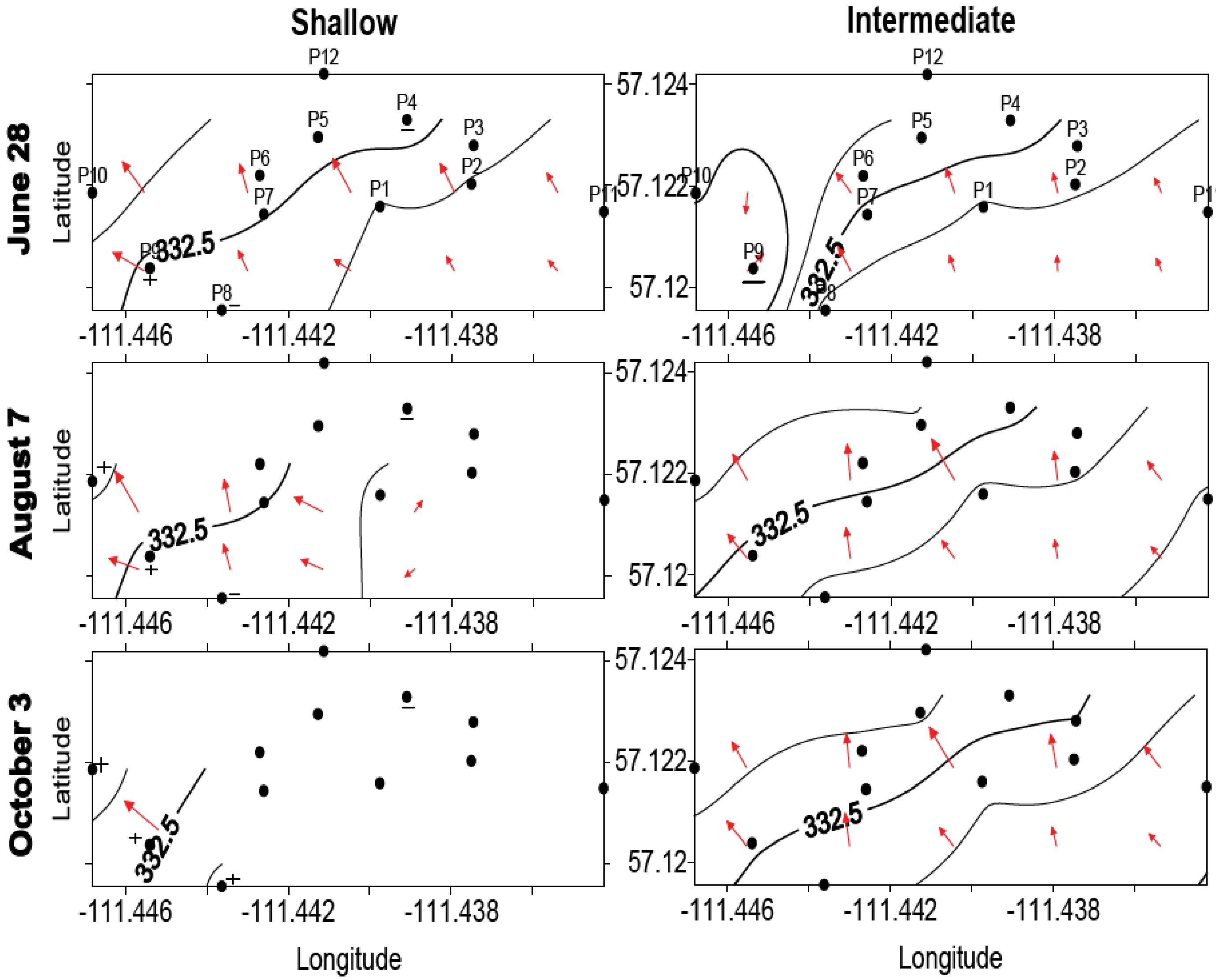


**Figure 2.8 Map views showing groundwater flow interpretation at JPH for 2011 using potentiometric contours with flow arrows at 0.5 m for shallow (~ < 2 meters below the surface) and intermediate ( ~ 4 m below the surface) wells. Seasons represented here are spring (June) summer (August) and fall (October). Vertical hydraulic gradients directions are indicated by (+) for recharging conditions and (-) for discharging conditions.**

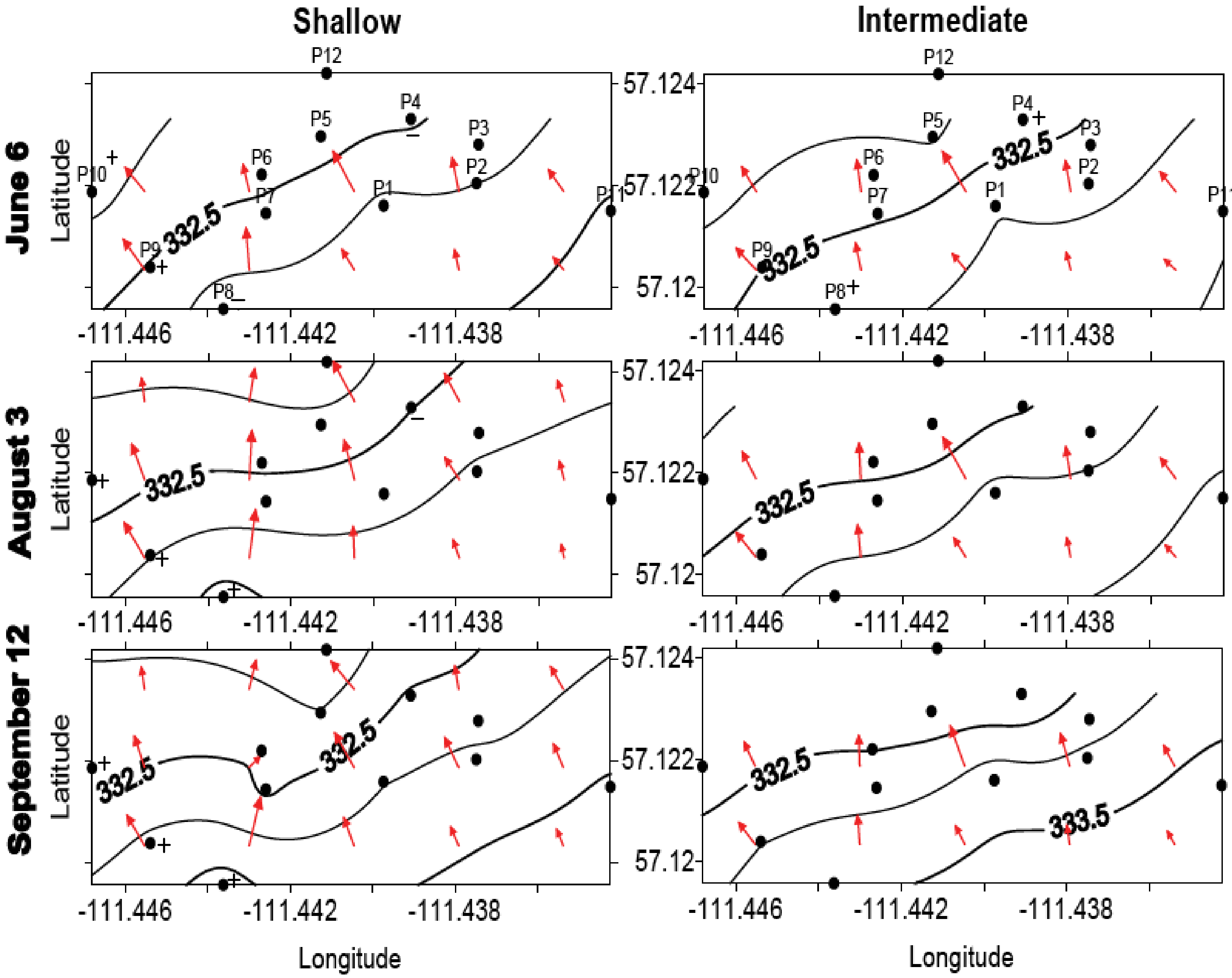


**Figure 2.9 Map views showing groundwater flow interpretation for 2012 at JPH using potentiometric contours with flow arrows at 0.5 m for shallow (~ < 2 meters below the surface) and intermediate ( ~ 4 m below the surface) wells. Seasons represented here are spring (June) summer (August) and fall (September). Vertical hydraulic gradients directions are indicated by (+) for recharging conditions and (-) for discharging conditions.**

Lateral hydraulic gradients are contoured for the ML site for 2011 and 2012 in Figure 2.10 and 2.11 for surface, shallow and intermediate depths. Overall, there is large variability in the groundwater flow potential. However, surface water in the peatland always appears to diverge from the bog towards the fen in both years. Surface water follows the water tracks identified in the DEM with a downward (recharging) gradient present for the majority of the study period. MLA (Aug. 3, 2012) is an exception as the well shows a slight upward (discharging) gradient. Shallow wells illustrate differences in flow potential during 2011 and 2012. In the spring of 2011 (June 28, 2011) shallow groundwater flow was northeast-ward converging with a recharging gradient present at P18. While in the summer (Aug. 7, 2011) and fall (Oct. 4, 2011) flow is northeast-ward as well as northwest-ward towards P13 and P12 (and both reveal a recharging gradient). More variability of shallow groundwater in the fen occurs during 2012 (Figure 2.11). Throughout the spring (June 7, 2012) shallow groundwater converges towards P19 showing a recharging vertical gradient. In the summer (Aug. 3, 2012) lateral flow appears similar to October of the prior year, moving both northwest and northeast-ward, with recharging gradients present at both P12 and P18. Finally, in the fall (Sept. 9, 2012) shallow groundwater follows the surface water tracks with recharging conditions at both P4 and P18. Changes in groundwater flow potential are most likely due to temporal changes in antecedent moisture conditions. In 2011, the peatlands were the wettest in the spring and flowed towards P18. During 2012, the peatlands were the wettest during the fall and also flowed toward P18 at this time.

In the intermediate wells minimal lateral groundwater flow potential is seen at ML, rather it appears to be localized and differs to that of the shallow wells. These contrasting results for shallow and intermediate groundwater are likely a function of hydraulic conductivity, as variability in hydraulic conductivity can have a strong influence on where water moves laterally (Ferone and Devito 2004; van der Kamp and Hayashi, 2009). During the summer of 2011 (Aug. 7, 2011) vertical hydraulic gradients are mostly discharging between intermediate and deep wells; this may permit groundwater to transfer water upward near the mineral soil into peat waters of the fen. Then during the fall of 2011 (Oct. 4, 2011) groundwater flow is towards P6 with downward (recharging) gradients occurring throughout the study area. During the following spring (June 7, 2012) groundwater moves towards P18, with the largest lateral gradient. A vertical recharging gradient was mainly occurring during 2012 across the site. In addition, at ML, we found minimal water in the shallow upland piezometers and little to no water in the intermediate upland piezometers (P1, 2, 3, and 14) for the duration of the study. This variability in upland conditions is difficult to interpret, but may suggest that there are areas where lateral recharge to the wetlands could be possible, hydraulic conductivity permitting. This situation would involve a perched water table with much deeper groundwater flowpaths below.

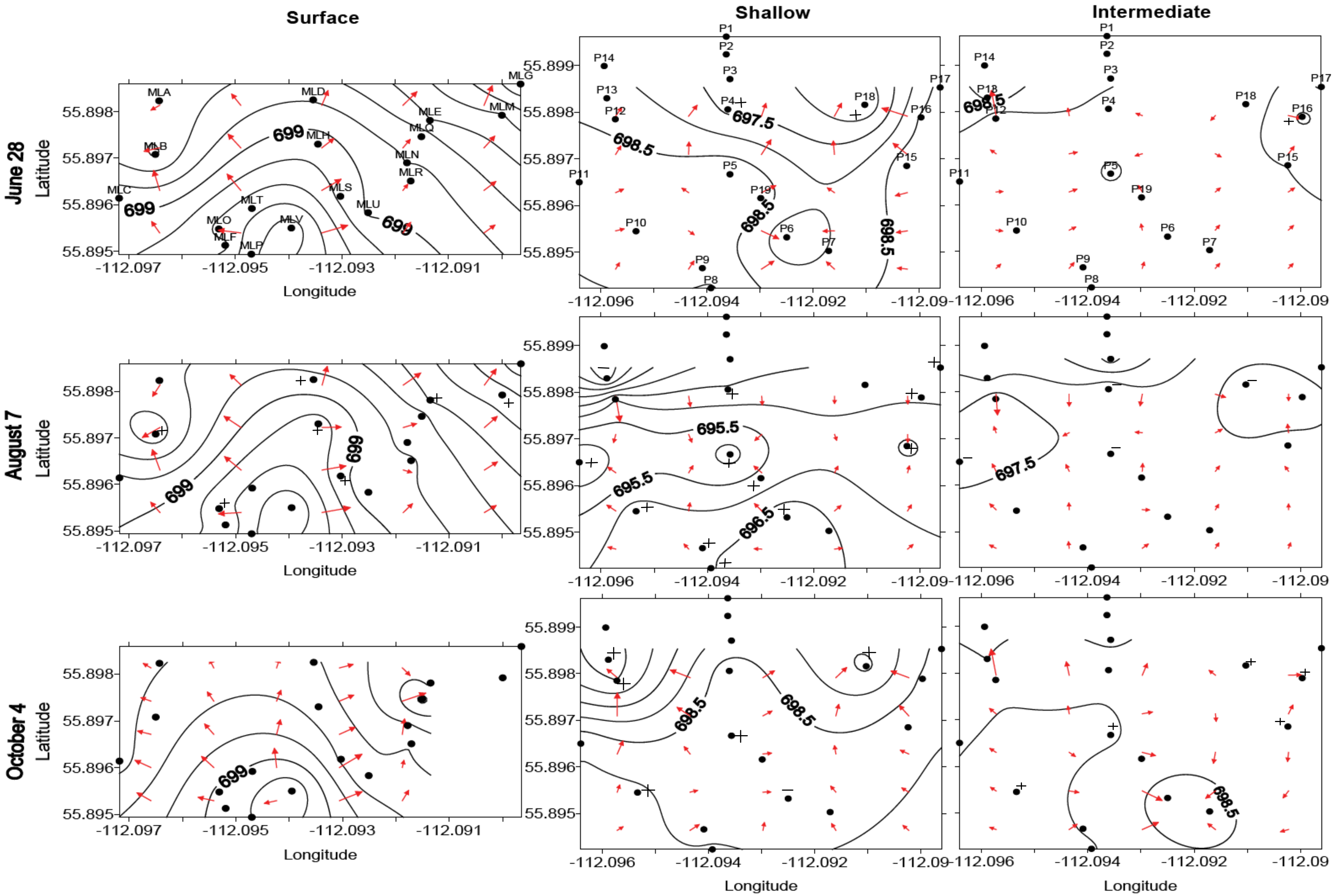


**Figure 2.10 Map views showing groundwater flow interpretation at ML for 2011 using potentiometric contours with flow arrows at 0.05m for surface wells, and at 0.5 m for shallow (~ < 2 meters below the surface) and intermediate ( ~ 2 to 4 m below the surface) wells. Seasons represented here are spring (June) summer (August) and fall (October). Vertical hydraulic gradients directions are indicated by (+) for recharging conditions (for ~ >1) and (-) for discharging conditions (for ~ <-1).**

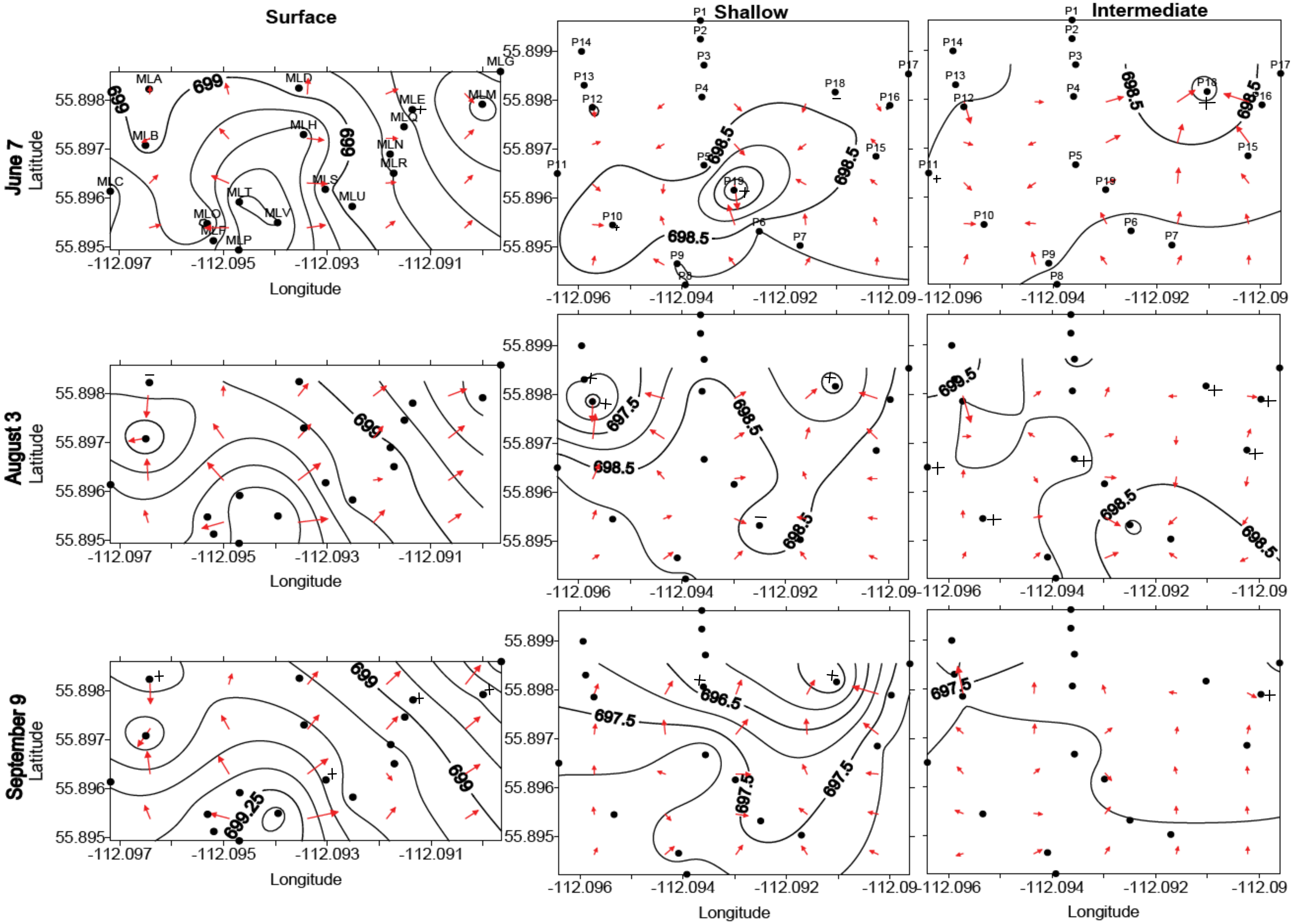


**Figure 2.11 Map views showing groundwater flow interpretation at ML for 2012 using potentiometric contours with flow arrows at 0.05m for surface wells, and at 0.5 m for shallow (~ < 2 meters below the surface) and intermediate ( ~ 2 to 4 m below the surface) wells. Seasons represented here are spring (June) summer (August) and fall (September). Vertical hydraulic gradients directions are indicated by (+) for recharging conditions (for ~ >1) and (-) for discharging conditions (for ~ <-1).**

At ML seepage fluxes were averaged for the different wells at differing depths. The well sites ranged from $1.4x10^1$ to $-7.5x10^3$ $mmyr^{-1}$ (Table 2.1), and the overall average including both years was $5.1x10^2$ $mmyr^{-1}$. All wells within the peatland, including both fen and bog wells, are recharging the deeper groundwater. The greatest movement of groundwater is noticeably close to the surface and diminishes with depth. The seepage flux in the bog well sites is slightly smaller than that of fen sites. A noteworthy contrast, the upland site has the only discharging flux of groundwater (P6), while the largest recharging flux is at P18 at shallow depths.

**Table 2. 1 The mean seepage flux for 2011 and 2012 from the average vertical hydraulic gradient (VHG) at nested piezometers at ML. Negative values indicate a recharging flux of water. – is no data collected.**

| | | | 2011 | | | | | 2012 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 28-Jun | 7-Aug | 4-Oct | Seepage Flux | | 7-Jun | 3-Aug | 9-Sep | Seepage Flux | |
| | ML | Depth (m) | VHG | VHG | VHG | Mean $ms^{-1}$ | Mean $mmyr^{-1}$ | VHG | VHG | VHG | Mean $ms^{-1}$ | Mean $mmyr^{-1}$ |
| Fen | P17 | 0.0-2 | -0.08 | 0.63 | -- | -5.1E-08 | -1.6E+02 | 0.09 | -- | 0.44 | -4.9E-08 | -1.5E+02 |
| | | >2.0-4.0 | 0.09 | 0.96 | 0.02 | -1.5E-09 | -4.7E+00 | -0.13 | 0.05 | 0.13 | -6.2E-11 | -2.0E-01 |
| | | >4.0-6.0 | 0.26 | 0.72 | 0.28 | -2.1E-08 | -6.6E+01 | 0.42 | 0.29 | 0.53 | -2.1E-08 | -6.5E+01 |
| Bog | P16 | 0.0-2 | 0.23 | 0.85 | -- | -2.5E-08 | -7.9E+01 | 0.10 | 0.09 | 0.71 | -1.4E-08 | -4.4E+01 |
| | | >2.0-4.0 | -0.09 | 0.95 | 0.05 | -1.4E-08 | -4.4E+01 | 0.09 | 0.08 | -0.03 | -2.1E-09 | -6.7E+00 |
| | | >4.0-6.0 | 1.69 | -0.16 | 1.74 | -1.6E-09 | -5.2E+00 | 0.29 | 1.47 | 2.79 | -2.3E-09 | -7.2E+00 |
| Fen | P18 | 0.0-2 | -0.03 | 0.91 | -0.05 | -5.1E-07 | -1.6E+03 | 0.58 | 0.01 | 0.60 | -7.4E-07 | -2.3E+03 |
| | | >2.0-4.0 | 1.90 | 0.78 | 1.18 | -2.4E-06 | -7.5E+03 | -0.65 | 1.25 | 2.26 | -1.8E-06 | -5.5E+03 |
| | | >4.0-6.0 | -- | -1.15 | 1.68 | -1.3E-08 | -4.2E+01 | 1.82 | 1.60 | -- | -8.6E-08 | -2.7E+02 |
| Fen | P5 | 0.0-2 | 0.19 | 0.91 | -- | -7.6E-08 | -2.4E+02 | 0.09 | -- | -- | -1.2E-08 | -3.9E+01 |
| | | >2.0-4.0 | -0.07 | 0.96 | 0.04 | -4.3E-08 | -1.4E+02 | 0.04 | 0.04 | -0.05 | -1.1E-09 | -3.5E+00 |
| | | >4.0-6.0 | -- | -1.42 | 2.84 | -2.6E-09 | -8.2E+00 | 0.56 | 2.70 | -- | -6.0E-09 | -1.9E+01 |
| Fen | P19 | 0.0-2 | 0.13 | 0.81 | -0.01 | -2.9E-08 | -9.1E+01 | 0.09 | 0.08 | 0.83 | -3.1E-08 | -9.8E+01 |
| | | >2.0-4.0 | 0.01 | 0.95 | 0.04 | 0.0E+00 | 0.0E+00 | 1.10 | 0.05 | 0.08 | 0.0E+00 | 0.0E+00 |
| Bog | P10 | 0.0-2 | 0.09 | 0.77 | -0.03 | -5.1E-08 | -1.6E+02 | 0.14 | 0.04 | 0.49 | -4.1E-08 | -1.3E+02 |
| | | >2.0-4.0 | 0.14 | 1.00 | -0.01 | -7.0E-08 | -2.2E+02 | 0.52 | 0.01 | 0.16 | -4.2E-08 | -1.3E+02 |
| | | >4.0-6.0 | -- | -0.33 | 1.70 | -1.7E-08 | -5.4E+01 | 0.33 | 1.51 | -- | -2.3E-08 | -7.2E+01 |
| Upland | P6 | 0.0-2 | -- | 1.01 | -0.65 | -4.5E-09 | -1.4E+01 | 0.10 | -0.47 | -- | 4.5E-09 | 1.4E+01 |
| Upland | P13 | 0.0-2 | -- | -0.38 | 1.34 | -1.2E-08 | -3.8E+01 | 0.15 | 1.73 | -- | -2.4E-08 | -7.4E+01 |

In wetlands, such as ML where peat is present, a common research approach is to represent the system using a two-layer model (acrotelm-catotelm) as hypothesised by Ingram (1978). This model limits activity of water in peat at depth (the catotelm) because of declining hydraulic conductivity gradients and the location of the water table in peat. Yet, the hydraulic gradients observed in at the ML site act as recharge points in the middle of the fen such as P18, P12, and P19. These areas may be moving water vertically through preferential flowpaths, which may occur as pipes comprised of material such as roots with higher rates of decomposition (Holden et al. 2002; Hill 2012) or may move through via piston flow (McEachern et al. 2006).

The dominant flow in shallow groundwater during the open water season at JPH, as seen in the constructed flow nets for all transects, is lateral rather than vertical as shown in Figure 2.12 and 2.13. In transect P11-2-1-7-10 (Figure 2.12) flow is a lateral movement of water from the uplands to the rich fen. When surface water is present in the rich fen (such as on Sept. 12, 2012) the shallow groundwater flow lines tend to emerge closest to the surface. For the upland transect on August 24, 2011 flow lines are parallel to the surface elevation, while flow lines are closer to the surface at P12 when the water table is higher (Figure 2.13b, Upland). Flow along the axis of the fen (Figure 2.13, Fen) shows a large contrast in water tables from 2011 and 2012, and as a result, flow lines differ. On August 24, 2011, flow is parallel to the surface of the fen. In contrast, flow lines on Sept 12, 2012 suggest an area of recharge close to P8 and a flow line that increases with depth along the rich fen. Groundwater flow at the JPH site shows no indication that flow from the fen to the upland occurs.

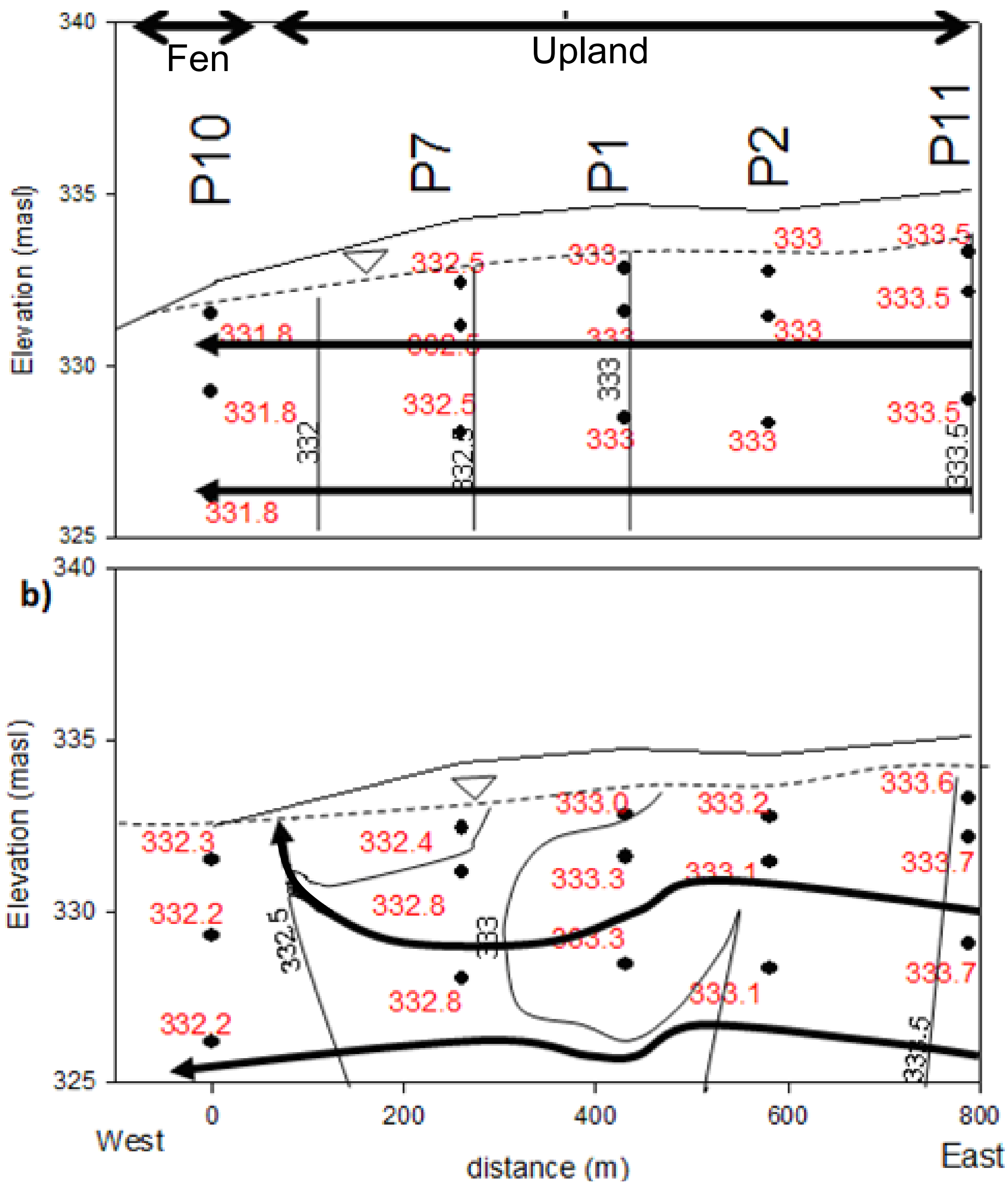


**Figure 2. 12 Hydraulic head contours in the uplands and rich fen at JPH (equipotential lines) at 0.5 m intervals with interpreted groundwater flow for a) Aug 24, 2011 with a low water table and b) on Sept 12, 2012 with a higher water table.**

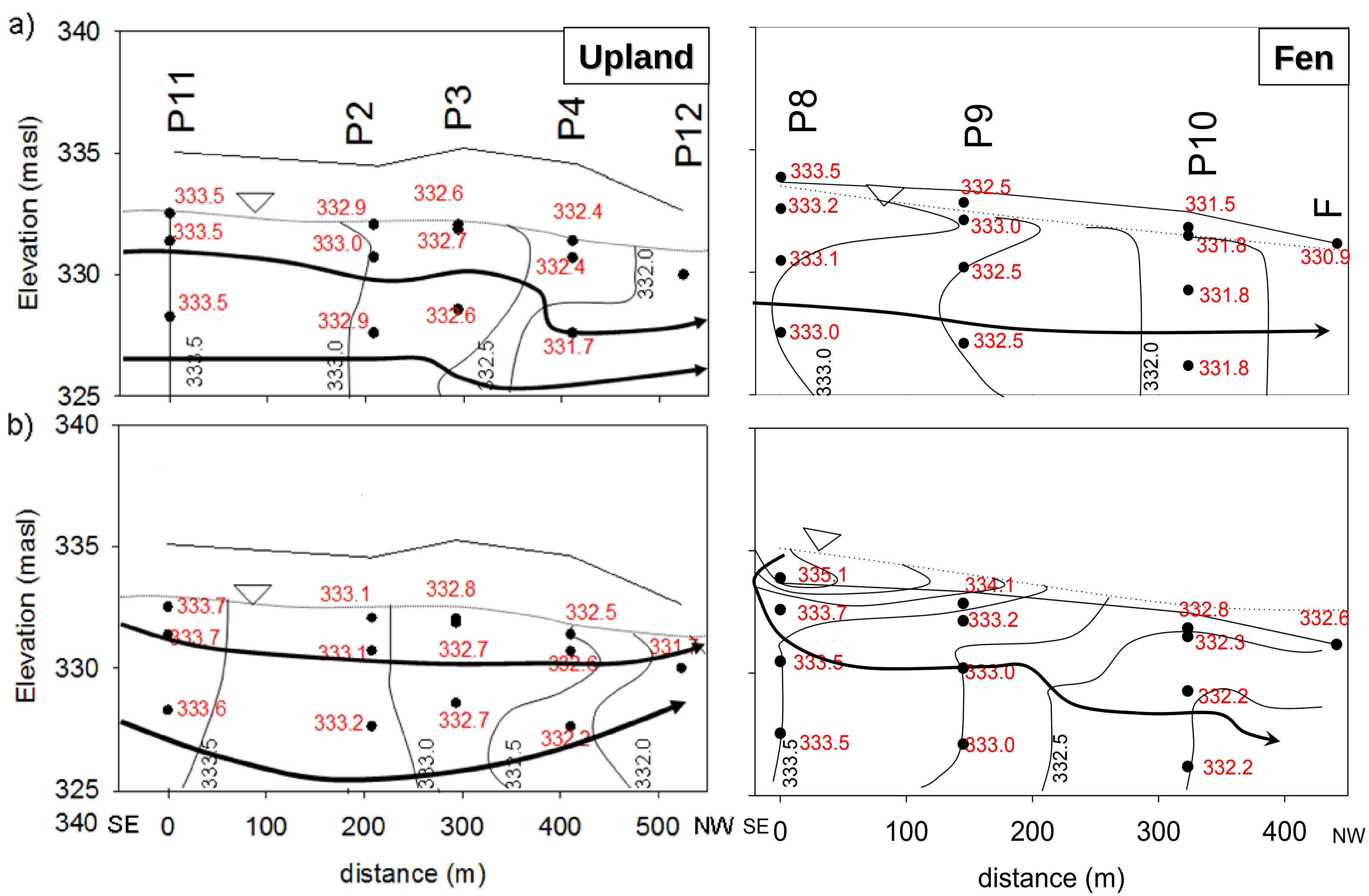


**Figure 2.13 Hydraulic head contours at JPH in the upland transect in left panels and fen transect in right panels (equipotential lines) at 0.5 m intervals with interpreted groundwater flow for a) Aug 24, 2011 with a low water table and b) on Sept 12, 2012.**

Based on the flownets, connections at JPH appear to be largely influenced by one thing; the overall uniformity of the hydraulic conductivity at this site allows the shallow groundwater to align well with the topography. Thus this site is more topographically driven, and this challenges that all areas within the AOSR follow the framework outlined by Devito et al. (2005). We would anticipate seeing dramatically differing connections due to the noteworthy changes in water levels in the fen. However, the connections did not change. The fen shallow groundwater did not connect to the uplands in neither shallow nor high water levels. Rather this connection appears to be unidirectional, and is in agreement with the findings of the DEM for sub-catchments A and C.

*2.4.4 Stable Water Isotopes Results*

There are systematic seasonal variations in the isotopic labelling of precipitation at JPH, with winter precipitation being characterized by more negative $\delta^{18}O$ and $\delta^{2}H$ values and summer precipitation by more positive $\delta^{18}O$ and $\delta^{2}H$ values (Figure 2.14). Precipitation sampled at JPH falls along a local meteoric water line (LMWL) close to that of Edmonton (Rozanski et al. 1993).

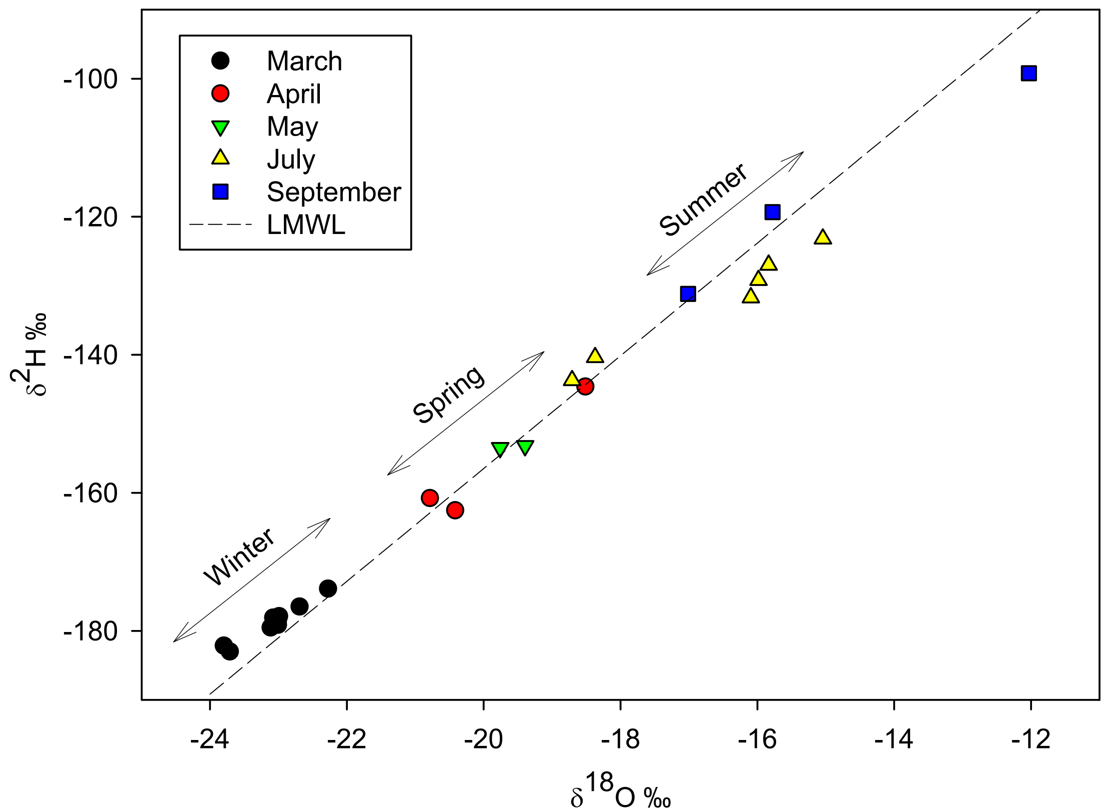


**Figure 2.14 The isotopic composition of precipitations collected at JPH site for the 2012 field season, with the LMWL defined for Edmonton defined by Rozanski et al. 1993.**

A summary table (Table 2.2), summary box plots (Figure 2.15) and a $\delta^2$H versus $\delta^{18}$O plots (referred to here as delta-delta plots) (Figures 2.16) are shown for both sites and years, and reveal basic variations in the composition of waters throughout the 2011 and 2012 field seasons. Seasonal shifts are noted in the isotopic compositions of water sampled in piezometers and at the surface. Most variation in surface water and groundwater were also found to occur along the LMWL (Figure 2.16). A tendency towards more depleted and less variable isotopic compositions is generally observed with depth in the piezometers reflecting differences in degree of influence of seasonally recharged waters. Isotopically distinct rain events are also found to be detectable including a large well-labelled rain event that occurred late in the summer of September

2012 (Figure 2.16). Surface waters at JPH and ML have heavier isotopic signatures than shallow groundwaters due to the influences of late summer rains. In addition, surface waters sampled from ML reflect the influence of seasonality as snowmelt signatures are seen in June contrasting shallow groundwater sampled.

**Table 2.2 Average and range of $\delta^{18}O$ and $\delta^{2}H$ stable isotopes of water at different depths and landscape units for 2011 and 2012.**

| | Depth (m) | | $\delta^{18}O$‰ | | | | | $\delta^{2H}H$ ‰ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | N | Mean | Std | Maximum | Minimum | Mean | Std | Maximum | Minimum |
| ML | | | | | | | | | | |
| All Fen | -- | 168.0 | -17.3 | 0.8 | -15.0 | -18.8 | -135.4 | 5.7 | -115.9 | -145.0 |
| | 0.0 | 57.0 | -17.0 | 1.0 | -14.8 | -18.5 | -132.9 | 8.0 | -114.3 | -144.8 |
| | 0.0 - 2.0 | 39.0 | -17.4 | 0.5 | -16.7 | -18.4 | -136.0 | 2.8 | -128.7 | -141.9 |
| | >2.0 - 4.0 | 34.0 | -17.3 | 0.5 | -16.3 | -18.5 | -136.1 | 2.9 | -132.0 | -144.4 |
| | >4 | 19.0 | -17.1 | 0.5 | -16.3 | -17.9 | -135.7 | 3.0 | -130.9 | -139.4 |
| All Bog | -- | 77.0 | -18.0 | 1.0 | -14.9 | -19.5 | -139.3 | 7.8 | -114.6 | -153.5 |
| | 0.0 | 33.0 | -17.3 | 1.1 | -14.9 | -18.7 | -133.5 | 9.1 | -114.6 | -143.8 |
| | 0.0 - 2.0 | 22.0 | -18.2 | 0.6 | -16.7 | -18.9 | -140.5 | 4.2 | -128.1 | -145.5 |
| | >2.0 - 4.0 | 19.0 | -18.6 | 0.6 | -17.3 | -19.4 | -143.0 | 3.2 | -137.4 | -148.4 |
| | >4 | 11.0 | -18.5 | 0.2 | -18.1 | -18.6 | -141.9 | 0.9 | -140.5 | -143.5 |
| All Upland | -- | 43.0 | -18.0 | 0.7 | -16.7 | -20.1 | -140.6 | 5.1 | -128.1 | -155.1 |
| | 0.0 - 2.0 | 28.0 | -18.0 | 0.7 | -16.7 | -19.2 | -140.5 | 5.3 | -128.1 | -150.0 |
| | >2.0 - 4.0 | 17.0 | -18.1 | 0.6 | -17.4 | -20.1 | -140.8 | 4.5 | -135.5 | -155.1 |
| JPH | | | | | | | | | | |
| All Upland | -- | 124.0 | -18.8 | 0.6 | -17.6 | -20.5 | -146.8 | 4.1 | -137.1 | -158.0 |
| | 0.0 - 2.0 | 41.0 | -19.2 | 0.5 | -17.6 | -20.5 | -150.0 | 3.5 | -137.1 | -158.0 |
| | >2.0 - 4.0 | 40.0 | -19.0 | 0.3 | -18.2 | -19.7 | -147.9 | 1.6 | -143.9 | -150.8 |
| | >4 | 40.0 | -18.2 | 0.4 | -17.6 | -19.1 | -142.5 | 2.3 | -139.1 | -147.3 |
| All Fen | -- | 89.0 | -17.8 | 1.2 | -14.7 | -20.9 | -139.9 | 9.5 | -112.1 | -163.8 |
| | 0.0 | 15.0 | -17.5 | 1.4 | -14.7 | -20.9 | -136.2 | 11.6 | -112.1 | -163.8 |
| | 0.0 - 2.0 | 15.0 | -18.3 | 0.9 | -17.0 | -19.9 | -143.3 | 6.8 | -133.5 | -156.3 |
| | >2.0 - 4.0 | 15.0 | -18.1 | 0.2 | -17.8 | -18.5 | -141.6 | 1.0 | -140.5 | -143.4 |
| | >4 | 15.0 | -18.6 | 0.3 | -18.3 | -19.1 | -146.3 | 1.9 | -143.3 | -149.2 |

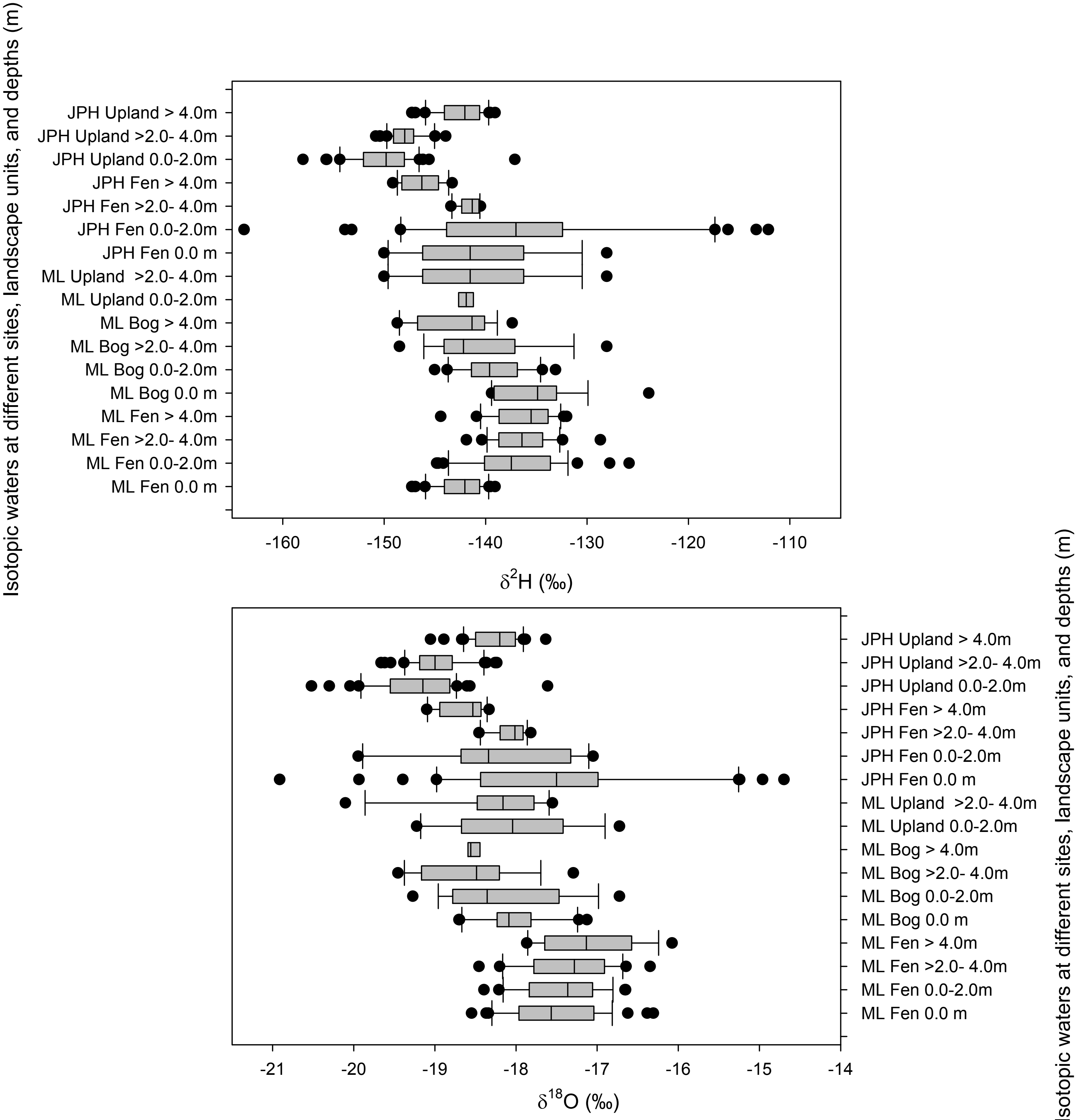


**Figure 2. 15 Summary box plots of all isotopes form 2011 and 2012 for $\delta^{18}O$ (bottom panel) and $\delta^{2}H$ (top panel), into distinct landscape units at specific depths for both ML and JPH.**

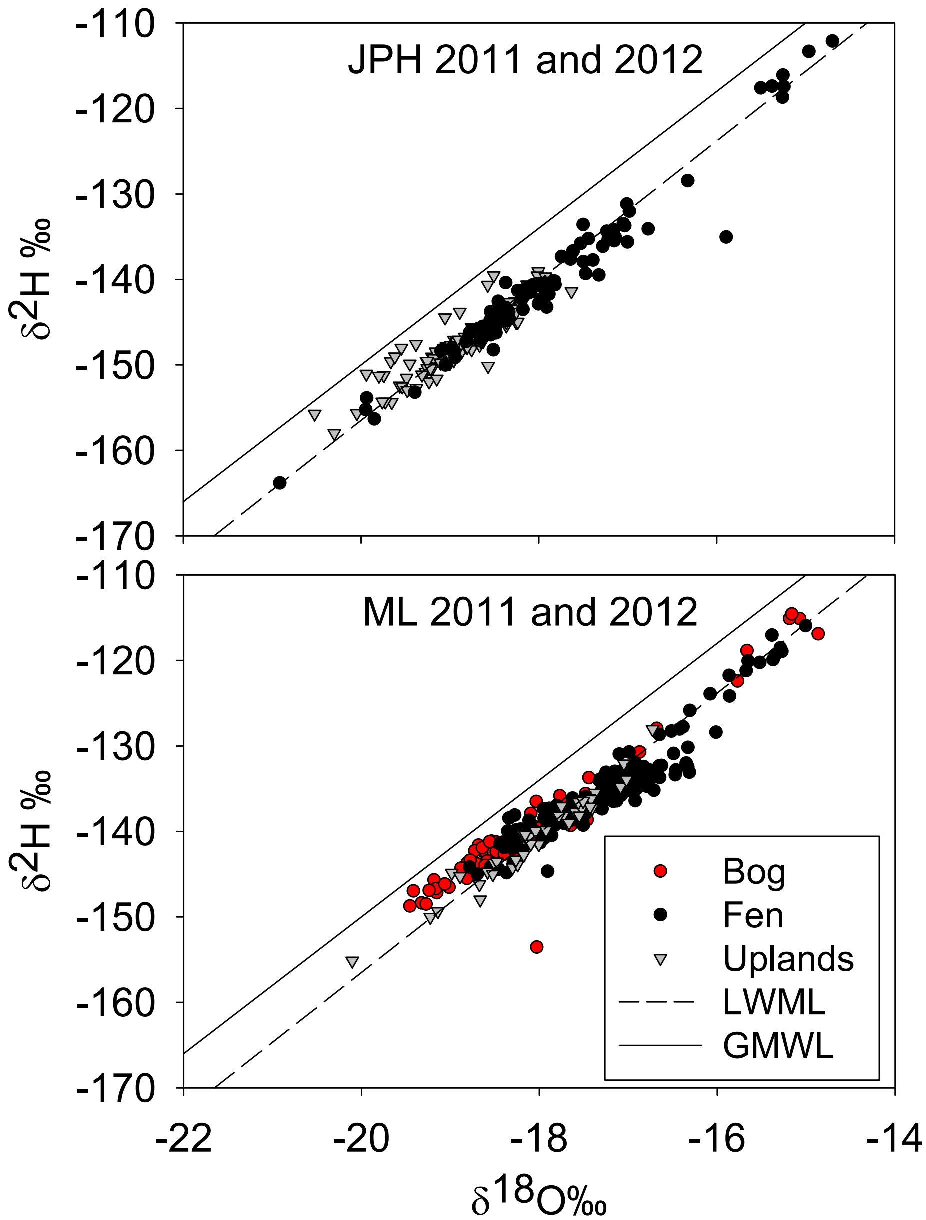


**Figure 2.16 Delta delta plots of isotopic composition of waters for both 2011 and 2012 for JPH (on top) and ML (on bottom). Water samples are plotted in vegetation type, bog in red, fen in black and uplands in grey. The GMWL is based on Craig (1961) and the LMWL is based on observations at Edmonton (Rozanski et al. 1993).**

In general, a more depleted (snow-rich) signature is seen in the shallow uplands wells at JPH, specifically in May 2012 (Figure 2.17). Ground waters with more negative delta values characteristic of snowmelt are also evident at the ML bog site (Figure 2.16), and in upland areas such as P1 intermediate (in June 2011, Figure 2.18), possibly due to deeper snowpacks noted in this area.

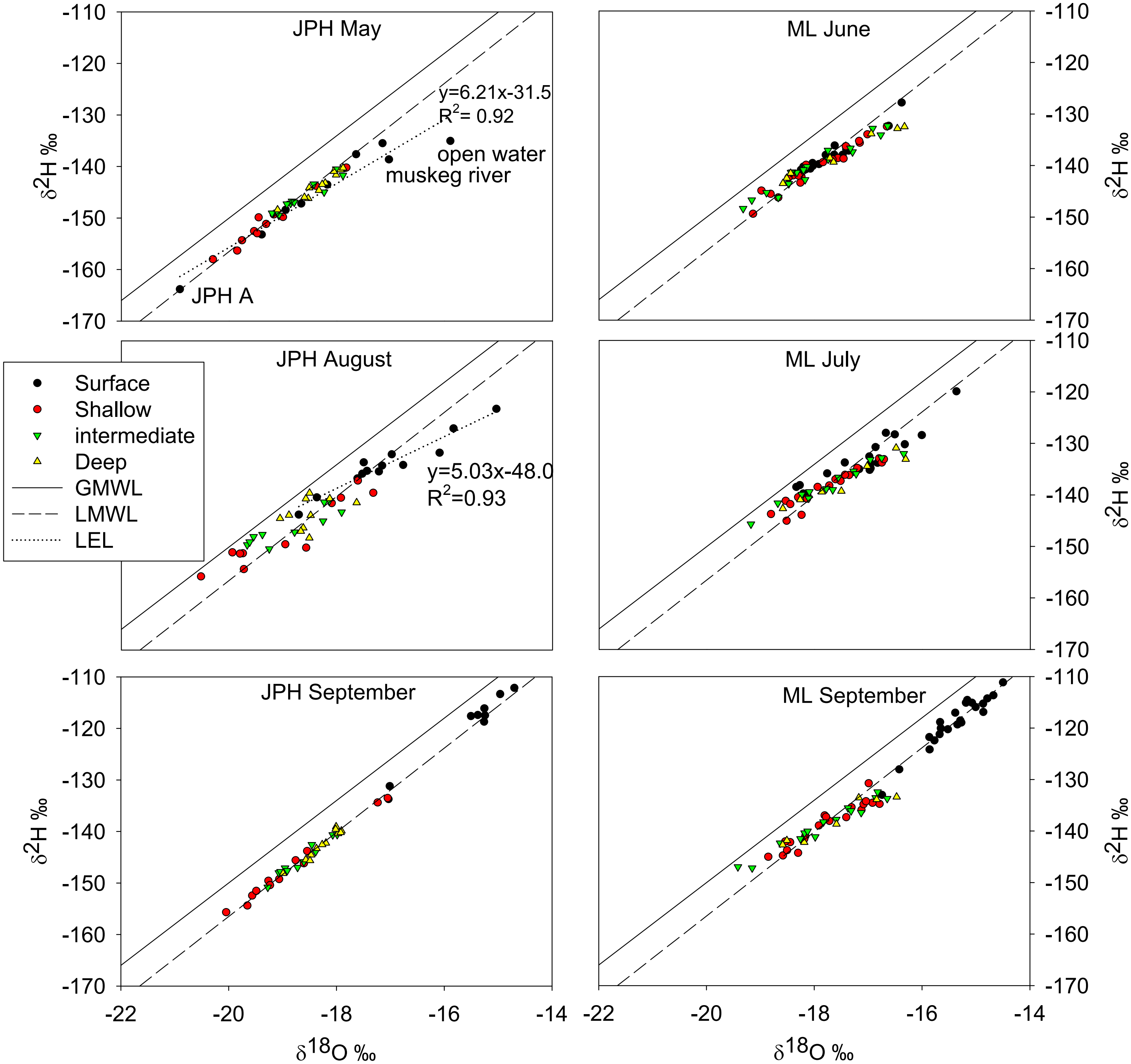


**Figure 2.17 Delta-delta plots showing isotopic composition of waters for late spring, and early and late summer at both study sites for 2012. Left panels correspond to JPH and the right to ML. Upper panels show June conditions whereas lower panels show August conditions. Water samples are distributed into surface waters i.e. from water table wells (black circles), shallow piezometers i.e. ~1**

**to 2 m deep (red circles), intermediate piezometers i.e. ~2 to 4 m deep (green triangles), and deep piezometers i.e. ~4 to 7 m deep (yellow triangles). The GMWL is based on Craig (1961) and the LMWL is based on observations at Edmonton (Rozanski et al. 1993). The LEL is local evaporation line based on regression of surface water data.**

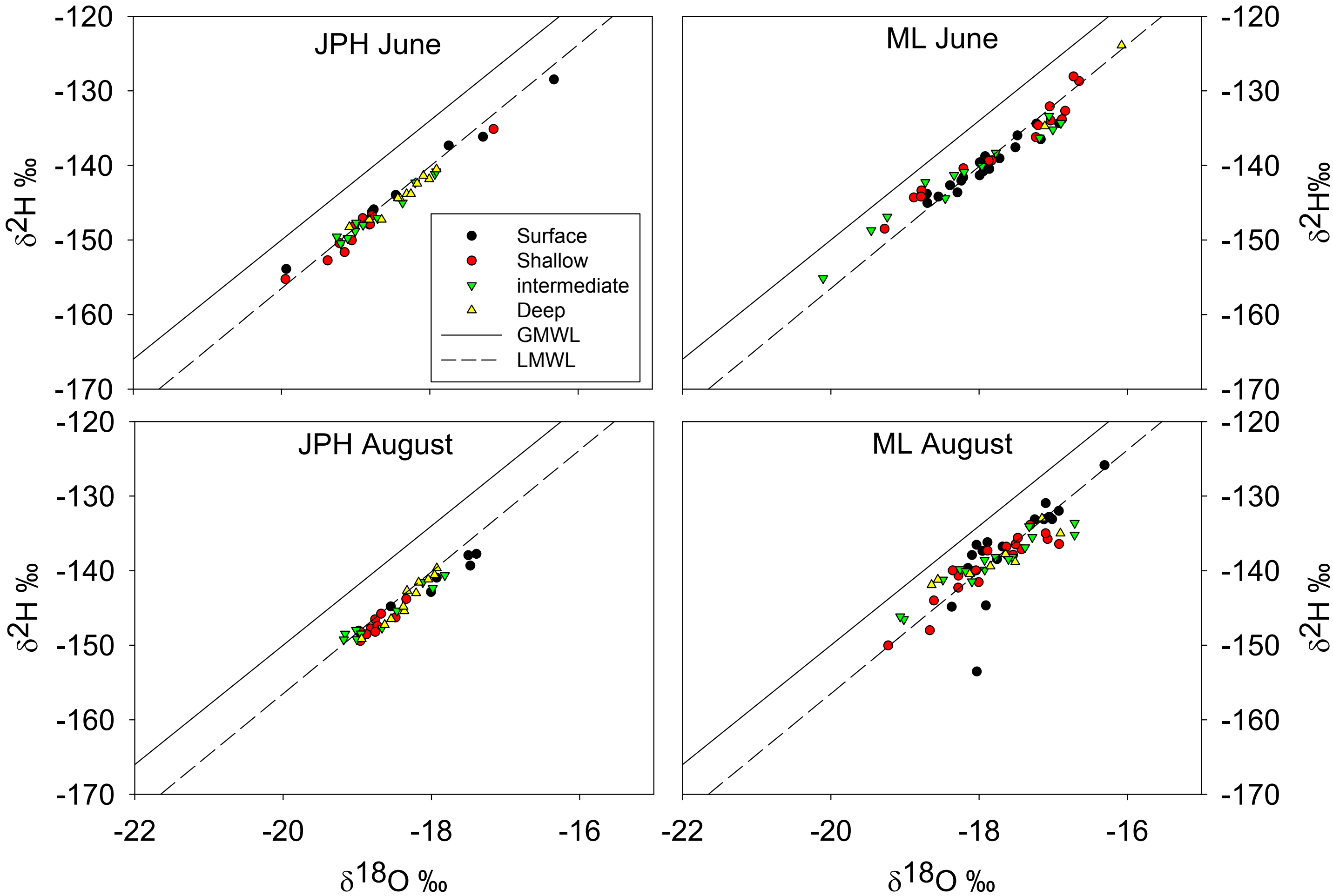


**Figure 2.18 Delta-delta plots showing isotopic composition of waters during early and late summer at both study sites for 2011. Left panels correspond to JPH and the right to ML. Upper panels show June conditions whereas lower panels show August conditions. Water samples are distributed into surface waters i.e. from water table wells (black circles), shallow piezometers i.e. ~1 to 2 m deep (red circles), intermediate piezometers i.e. ~2 to 4 m deep (green triangles), and deep piezometers i.e. ~4 to 7 m deep (yellow triangles). The GMWL is based on Craig (1961) and the LMWL is based on observations at Edmonton (Rozanski et al. 1993).**

As noted, surface waters in both ML and JPH show an evaporative enrichment signature, isotopically heavier (less negative), and are characterized by deviation below LMWL (e.g. Gat 1996). The most pronounced evaporatively enriched signatures are noted for JPH in August of 2012 (Figure 2.17), with surface waters plotting along a line with a slope of about 5 in delta-delta space. Surface waters sampled during May of 2012 at the JPH site had a slightly lower slope of about 6, but also likely reflecting evaporative modification. In ML, the evaporative signal appears in the shallow piezometers as well as in water table wells as is seen during June and July 2012 (Figure 2.17). Interestingly, the surface water samples from September 2012 from both sites have fairly positive $\delta^{18}O$ and $\delta^{2}H$ signatures, but still plot along the LMWL. 2012 was a particularly wet year, and this isotopic enrichment without a corresponding shift along a LEL indicate that there was sufficient precipitation that the surface waters acquired a more positive isotopic labelling from late summer precipitation without significant evaporative enrichment.

*2.4.5 Active recharge zone*

Variations in $\delta^{18}O$ compositions of groundwater sampled at ML and JPH were used to identify areas with more active groundwater mixing, where there is higher temporal variability in isotopic labelling and a deeper groundwater zone where seasonal variations in isotopic labelling are not evident. The results were separated by terrain unit and sampling date (Figures 2.19 and 2.20).

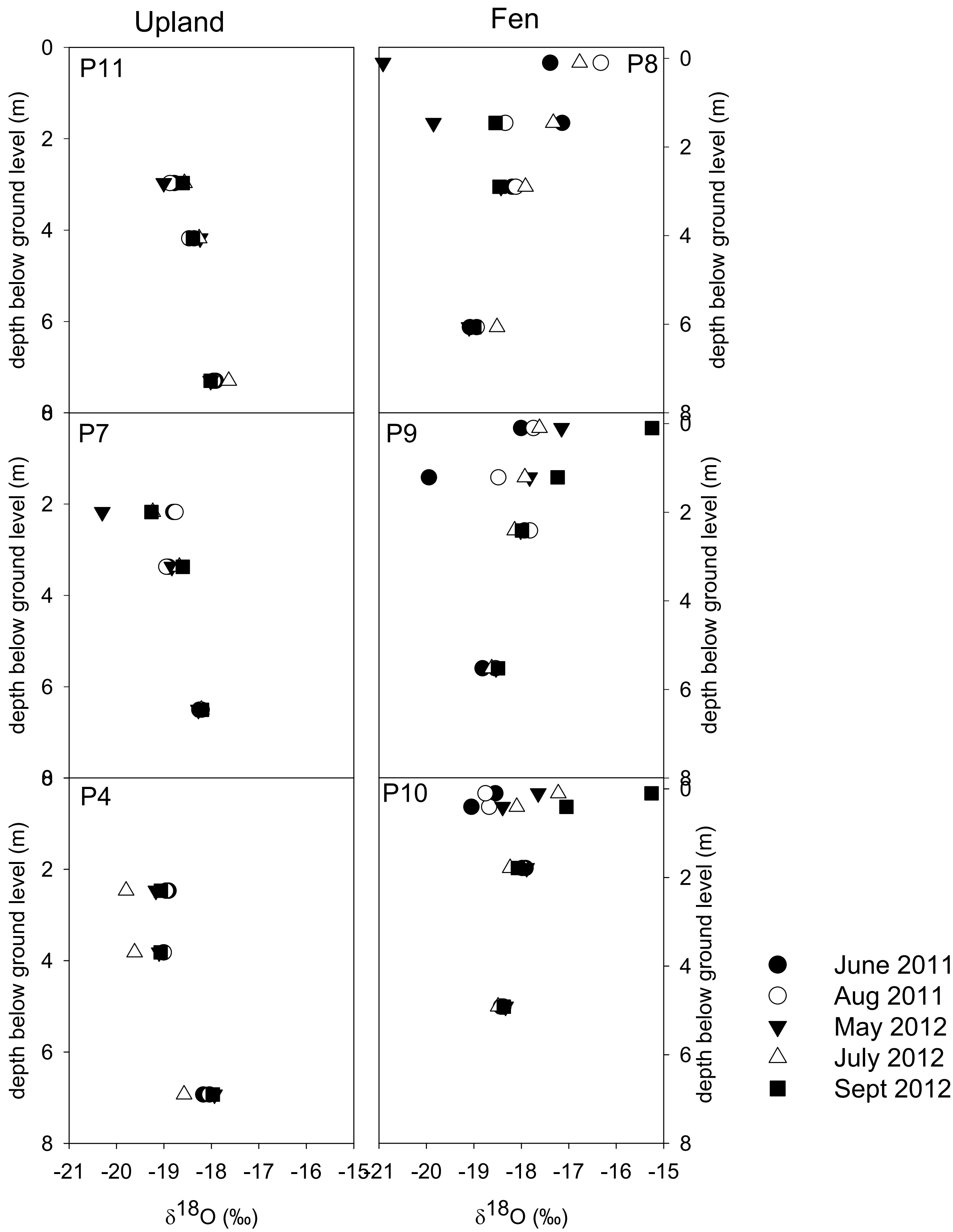


**Figure 2.19 Isotope depth profiles for select piezometer locations for 2011 and 2012 in JPH, upland wells on the left and fen wells on the right.**

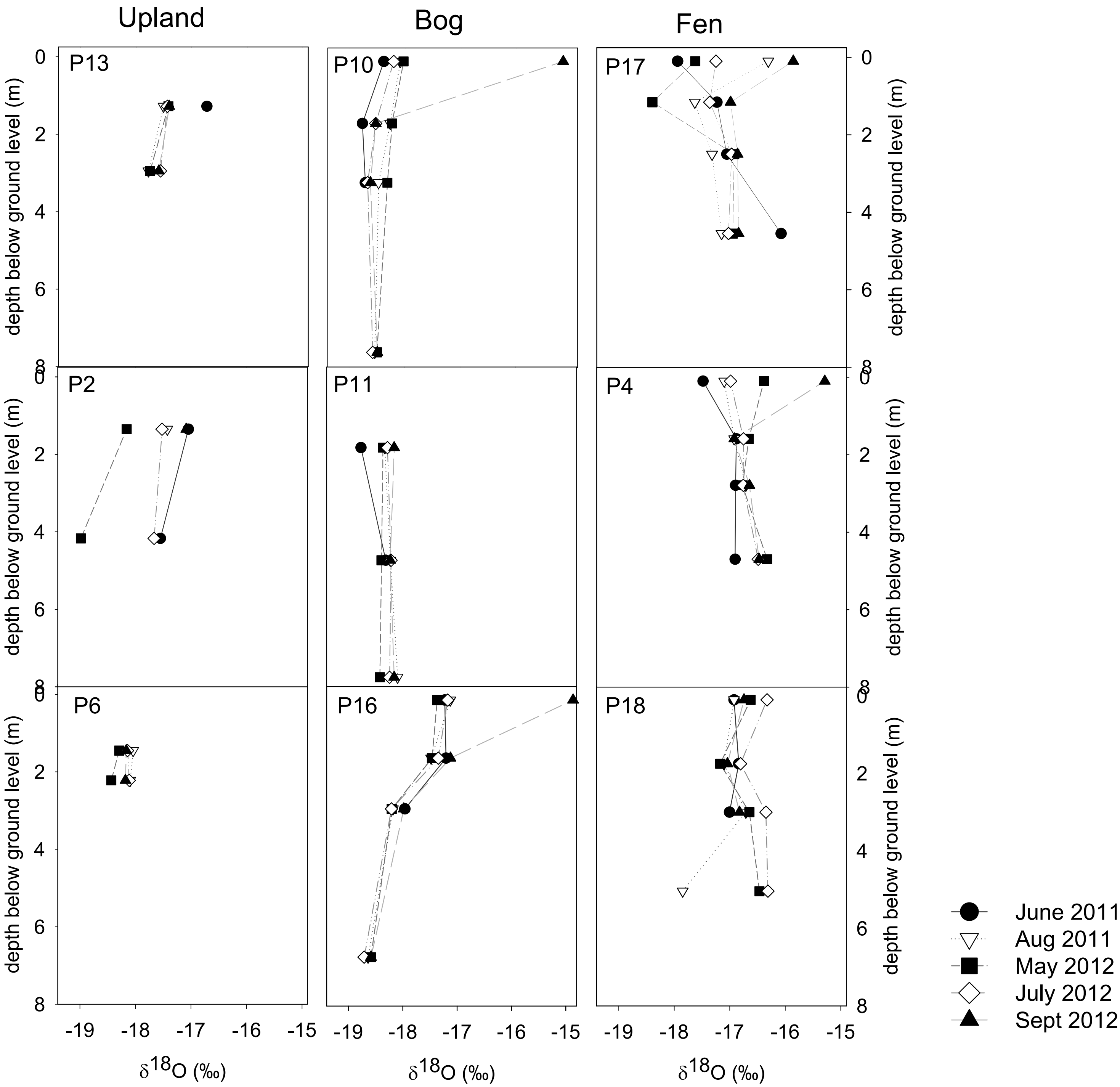


**Figure 2.20 Isotope depth profile with select piezometer locations for 2011 and 2012 in ML. The uplands are on the left, the bog in the centre and the fen on the right.**

At the JPH site there were differences in the isotopic labelling of groundwater in the uplands and the fens (Figure 2.19). The uplands had a relatively constant isotopic signature, both with depth and over the different seasons. Shallow groundwater in the uplands was isotopically lighter ($\delta$ values more negative) than groundwater sampled at depth. This may have been due to pulses of summer rain ($\delta^{18}O$ = -15 to -19 ‰) mixing with snow (averaging -23 ‰ in $\delta^{18}O$), which resulted in the lighter isotopic signatures seen than that of deeper groundwater, approximately -18 ‰ in $\delta^{18}O$. At most of the upland wells sites, the depth at which the seasonal variations in $\delta^{18}O$ disappeared was about 3 m below the surface. An exception to this was P4 where the July 2012 sample was isotopically lighter than any of the other sampling events, possibly indicating a higher recharge during this month. The limited seasonal variability of $\delta^{18}O$ is reflective of a uniformity observed for the hydraulic conductivity of this site, as well as the location of the water table ~2 m.

In contrast, the isotopic composition of water within the fen at JPH was more enriched in the shallow wells (Figure 2.19). We should note that in the uplands a significant unsaturated zone exists. The water table on average is about 2 m below the ground surface in the uplands, whereas in the fen the water table varies from just above the surface to about 0.5 m below surface. The seasonal fluctuations in $\delta^{18}O$ in the fen at JPH are consistent with the very shallow water table and downward vertical hydraulic gradients. The depth at which the seasonal variations are no longer obvious is about 2 m below the ground surface indicating active mixing of recharge and groundwater in this region. The more positive $\delta^{18}O$ values in the shallow water tables in the fen are consistent with evaporative enrichment of ponded surface water observed in the field, and is seen when a local evaporation line (LEL) is identified in Figure 2.17. A seasonal trend of evaporative enrichment in the fen is seen in at P10, as enrichment progressed from spring to late summer.

At the ML site the upland, bog and fen all had varying isotopic signatures with depth (Figure 2.20). The bog has the most consistent isotopic depth profile, and the least temporal variability. Most seasonal variations dissipated within 2 m. From sampled precipitation the mean weighted precipitation of $\delta^{18}O$ in the ML site is -18.9 ‰, and the bog exhibits similar values at depth within the deeper groundwater. In contrast, the fen and upland show greater variations with depth and between sampling locations. In the uplands, P13 and P6 have limited seasonal variation, and an integrated signature of groundwater is seen close to the surface (<2 m). Whereas at P2, in the uplands, a higher temporal variability is noted possibly indicating a higher recharge area, and a deeper groundwater zone that has not been reached by our instrumentation. In addition, the depleted isotopic signature is observed in May of 2012 at depth, indicating a recharging of snow signatures at depth.

For the ML fen, isotopic signatures approached a fairly uniform composition at depth, ranging from ~ -17 to -16 ‰ in $\delta^{18}O$, as is seen generally in P17 and P4 at depths greater than 2 m. These $\delta^{18}O$ signatures are relatively enriched in contrast to the bog and uplands. However, there are isolated incidences during 2011 with variations at depth of both relative depletion (P18) and relative enrichment (P17). Differences in the signatures at depth coincided with hydraulic gradients seen in the potentiometric surfaces (Figure 2.10 and 2.11). P17 was isotopically heavier at depth in June 2011, and following a recharging vertical gradient. This water could represent recharge of isotopically enriched summer precipitation. P18 showed a lighter isotopic signature at depth for August 2011; this may be an isolated discharging signal of deeper groundwater. These varying results can also be related to differences in snowmelt or frost table in the fen (Gibson et al. 2005). In addition, researchers have indicated piston flow and mixing of surface with shallow groundwater in fen and peatland locations (e.g. McEachern et al. 2006; Kværner and Kløve 2008).

***2.5 Implications on groundwater connectivity and nitrogen transport***

The fate and transport of dissolved nitrogen between and within upland-fen-bog complexes will depend on the potential surface and groundwater flowpaths and the geochemical conditions along those pathways. There are three main factors that can result in the production or consumption of nitrogen along a flowpath 1) carbon content, 2) available nitrate, and 3) anoxic conditions (Bowden 1987). In peatlands, the largest limiting factor for nitrification is aerobic conditions, therefore limiting the production of nitrate ($NO_3^-$), and a build up of available ammonium would be anticipated at depth. If this pool of reduced nitrogen is present at depth there is the potential for it to be converted to nitrate if oxic conditions were introduced. This suggests decreasing the water table in peatlands may result in nitrification occurring at depth. If the water tables are high and anoxic conditions are created then denitrification could occur, reducing nitrates into nitrites ($NO_2^-$) and conversely releasing $N_2O$ and $N_2$ from wetland sites, as has been recorded by researchers in peatland-complexes in the area (Wray and Bayley 2007). In the fen and bog locations, nitrification is expected under drying conditions as the water table draws down. This nitrification will probably occur within the variable recharge locations (~2 m in both fen and bog) identified through the stable water isotopes, while denitrification in all probability is consistently occurring within depths greater than ~2 m. In addition, we would anticipate the greatest nitrogen flux potential in the JPH minerotrophic fen, followed by the fen at ML specifically in proximity to the main water track and P18, as the greatest hydraulic conductivity was noted at JPH fen followed by the fen in ML. While the smallest flux within the wetland would be at the ombrotrophic bog, as has been shown by others based on general fluctuations of water tables (Regina et al. 1996). Overall, waterlogged soils will limit nitrification from occurring at large quantities.

Since nitrification does not occur readily in waterlogged soils, wetlands are often considered as sinks for nitrogen (e.g. Wray and Bayer 2007). Recharging hydraulic gradients observed in fens at both sites may act to move dissolved oxygen, found within the first 5 cm of a peat column (Thomas et al. 1995), to depths (resulting in nitrification); however, no data was collected for dissolved oxygen for this study.  Recharging hydraulic gradients may also move nitrates at the surface downward to anoxic locations were denitrification most likely follows. Or on the other spectrum, discharging hydraulic gradients may move ammonium to the surface, and nitrification would follow. Therefore, areas where vertical hydraulic gradient result in the discharge of water to the surface may be sources of nitrate to the surface. These infrequent upward gradients were only observed in the fen and at one upland well at ML (P6).

The hydrological data collected for this study was used to identify recharge and discharge areas in the various terrain units at the study sites. In the region, hydrological connections are strongly dependent on the variations in precipitation (Devito et al. 2005) and consequently, interannual variations in the behaviour of these different terrain units can vary considerably. This study only captured two contrasting hydrological field seasons, and a longer-term evaluation of the hydrological conditions at the site would be required for an equivalent analysis, we offer some basic conclusions on the recharge/discharge conditions in individual terrain units and the resulting hydrological connectivity of the sites.

The initial hypothesis was uplands would be a source of water to wetlands, and that wetlands would recharge uplands. This was found to be partially true at JPH. Adjacent uplands (< 200 m in distance) at the JPH site may be connected to the rich fen as seen in the flow nets. But there was no evidence to support the uplands being fed by the wetlands. Therefore, we would anticipate additional nitrogen that is not readily utilized in upland areas could eventually be transported towards the fen. In locations where the hydraulic conductivities are very low, such as at depth in the fens and bogs at ML, the implications are quite different. The bog is recharged by precipitation and shows a limited change in isotopic signatures temporally and at depth. This suggests that nitrogen species may not be laterally transported via subsurface water from this terrain, nor laterally transferred to this terrain by adjacent units, but rather may move vertically and become utilized or stored. In the fen at the ML site, variations of stable isotopes of water and hydraulic gradients suggest connections of surface water and shallow groundwater, possibly because of either piston flow or dispersion, despite lower hydraulic conductivities at depth and may therefore, be more important for nitrogen fluxes than the bog. Ultimately, adjacent uplands appear to add surface runoff that acts to recharge the wetland, and possibly will also connect to the wetlands during intense summer precipitation as has been observed at other wetlands (Hayashi et al. 1998).

Finally as was observed by stable isotopes of water, snow and snowmelt contribute a large pulse of water into the system and may consequently deliver nitrogen species deposited during the winter months. This pulse is seen in the bog and the uplands near the surface, while is slightly more mixed and muted in the fens. This pulse of snowmelt is also evident at depth with the peat and may indicate the potential for oxygenated waters to reach areas where pools of reduce nitrogen is present.

***2.6 Terrain unit roles of fen, bog and upland for connectivity***

In general, our results confirmed most hypothetical connections identified in the conceptual model (see Chapter 1). Results reveal that the bog is mostly an isolated or slowly leaking terrain, and has limited connection to the adjacent fen except near the surface. This was in agreement with our hypothesis. In the fen, connection with the upland appears to be mostly unidirectional, where the uplands mainly feed fens. There were small occurrences of uplands being fed by wetlands, in ML under dry condition; however, this was not a common observation as previous research in the area has noted for outwash plains (Smerdon et al. 2005). Most lateral flow at ML occurred near the surface where the hydraulic conductivity permits it, as is seen in the stable isotopes.

Finally, we found that fens are fed by bogs at the surface, are recharged by uplands in the spring, and infrequently discharging hydraulic gradients can occur under relatively dry conditions, though the lateral and vertical hydraulic gradients were predominately recharging the shallow groundwater.

### *2.7 Summary*

This research builds on the current understanding of surface and shallow groundwater movement in the Boreal Plains region, and confirms that connections between terrain units are temporally variable and dependent on antecedent moisture conditions. This research highlights the significance of hydrological connectivity being affected by hydraulic conductivity on a landscape. The two study sites are both situated within the AOSR, but have differing hydraulic conductivity resulting in contrasting sites. At the JPH site surface and groundwater is influenced by the topography. At the ML site complexities in groundwater flow become evident due to heterogeneity of peat and low hydraulic conductivity. Although lower hydraulic conductivity was recorded at depth in peat, recharging hydraulic gradients coinciding with variations of $\delta^{18}O$ at depth suggest episodic connectivity of deep peat waters with the surface or underlying/adjacent groundwater. This research is in agreement with previous conceptual models, confirming the largest flux of water is still lateral within peatlands at shallow depth.

**3.0 Examination of surface runoff in the bogs, fens and uplands of the Boreal Plains**

**Abstract**

Determining the impact of additional nitrogen in the Athabasca Oil Sands Region (AOSR) is complex because of the mosaic landscape of terrestrial and aquatic ecosystems in the Boreal Plains. This study aims to strengthen the conceptual model for the potential surface pathways for water and nitrogen within the AOSR by examining vertical water balance and runoff potential of terrain units representative of the Boreal Plains. Two sites were examined surrounding Fort McMurray, Alberta, and field data was collected during 2011 and 2012. We used an unconventional hydrological technique based on vertical water balance, to estimate the surface runoff on this landscape, together with stable water isotopes data, to trace surface flowpaths.

Our results show the vertical water balance for the different peatland terrain types have lower surface runoff potential in the bog when compared to the fen. The results also show the importance of antecedent moisture conditions. When large precipitation events occur under high antecedent moisture conditions, the runoff potential of the bog was found to increase significantly, although this will typically occur only after depression storage thresholds are exceeded. This type of hydrological response can be termed 'fill and spill'. Deuterium excess from stable water isotopes was found to decrease from bog to fen revealing the likely effect of evaporative losses along surface flow pathways (fen water tracks). These findings have significant implications for the movement of nitrogen deposition in the system, as they suggest that in dry

years/periods nitrogen will be retained within the system whereas in wet years/periods it may episodically serve as a source of water and nitrogen to adjacent wetlands, lakes and rivers.

### *3.1 Introduction*

Wetlands ecosystems are complex landscapes and need to be investigated in detail because of their important ecological functions. It is known that wetlands help regulate flow (Kimmel and Mander 2010), serve hydrochemical functions (Prepas et al. 2006), act as a carbon sink (Vitt et al. 2001), are important for wildlife habitat (Gorham 1991), and regulate biogeochemical processes for catchments (Bowden 1987). In the Boreal Plains region, wetlands can account for 50% or more of the landscape (Vitt et al. 2001). This region is characterized by minimal relief and runoff mechanisms are driven by precipitation, evaporation and storage changes (Devito et al. 2005). Predicting the routing of runoff in these landscapes is difficult because of the intrinsic physical properties of terrains such as bogs and fens, and the potential connections to adjacent uplands (van der Kamp and Hayashi 2009).

Raised bogs are characterized by limited connectivity to adjacent peatlands. They typically are fed exclusively by precipitation input with negligible groundwater connectivity. They are defined as being more acidic than fens, with greater hummocks and hollows (Zoltai and Vitt 1995). In addition, bogs have a greater depth to the water table than fens. In contrast, fens are characterized by having surface flow-through, may have connections to the groundwater and a water table very close to the surface (Zoltai and Vitt 1995).

Runoff in wetlands varies due to the previously mentioned characteristics. More importantly, runoff can vary based on antecedent moisture conditions (Devito et al.

2005; Redding and Devito 2008), and it is argued that connections of different terrain units are dynamic in both space and time (Spence et al. 2011). Studies capturing both spatial and temporal hydrological variation in wetlands have been limited. Runoff modelled under changing hydrological conditions has revealed connections variable in space (Shook et al. 2011), and runoff in time is largely non-uniform during high flow periods in wetlands (Richardson et al. 2012). The interplay of various terrain types within these systems has yet to be examined in detail.

Where water moves, nitrogen can be expected to do the same; therefore, it is imperative to understand the surface runoff of the typical Boreal plain landscape. Extensive research has gone into wetland runoff in the Canadian Shield (e.g. Oswald et al. 2011; Phillips et al. 2011; Spence et al. 2011) and areas where blanket peat exists (e.g. Kværner and Kløve 2006; Laudon et al. 2007; Kværner and Kløve 2008). Yet, limited research exists on the dynamics of surface runoff in mosaic landscapes. Recent work completed by Devito et al. (2012) has described the dynamics of runoff for the reclamation of wetlands in the Boreal Plains. Understanding surface runoff in the Athabasca Oil Sands Region (AOSR) is crucial for scoping the implications of increased emission by industry and vehicles, as there is concern for acidification of the terrain (Whitfield et al. 2010a) and surface waters (Gibson et al. 2010). Characterization of the mosaic landscape's runoff and geochemical functions, both spatially and temporally, will further our understanding of the behaviour of wetlands and uplands. Consequentially, this will help to distinguish terrain types as sources or sinks for additional nitrogen.

In this study two wetlands were examined over a two year study (2011 and 2012) near Fort McMurray, Alberta. Traditional gauging techniques are difficult to apply in the Boreal Plains because minimal relief results in limited channelized flow. Our attempts to gauge were unsuccessful for this study because variability in flow, ranging from a trickle to extreme, resulted in wash out of equipment and poor quantification of some fluxes, particularly streamflow. As an alternate approach, vertical water balance, a method demonstrated by Tattrie (2011) for wetlands in Fort McMurray area, was used to estimate runoff potential on a daily time step. This study aims to understand the occurrence and strength of hydrological connections that exist within wetlands and uplands in typical watersheds of the AOSR. The objectives of this study are: to estimate runoff potential in an ungauged setting, to assess the responsiveness to rain events, and to determine the degree of hydrological connections that develop between various terrain units during the runoff process.

### *3.2 Study site*

The AOSR is found in northeastern Alberta within the Boreal Plains region (EcoRegions Working Group, 1989). The two sites selected for study are situated near Mariana Lakes (100 km south of Fort McMurray) and Jack Pine Highland (25 km north of Fort MacKay) (Figure 3.1). The Mariana Lakes site (hereafter referred to as ML) is a peatland complex situated within a 23 $km^2$ catchment, comprised of nutrient poor jack pine (*Pinus banksiana*) islands and uplands, bordering a poor fen, and ombrotrophic bogs. On the uplands the majority of jack pines are standing burnt timber with a thick floor of saplings. Shrubs are dominated in the uplands by roses (*Rosa arkansana*), labrador tea

(*Rhododendron groenlandicum*), and blueberries (*Vaccinium corymbosum)*. Soils in this region are somewhat characteristic of Boreal Plains region, consisting of low hydraulic conductivity silts and clay. Vegetation in peatlands at this site, comprised of a fen and a treed bog, is dominated by *Sphagnum* mosses (*S. angustifolium, S. magellanicum, and S. fuscum),* sundews (*Drosera*), cloudberries (*Rubus chamaemorus*) and cranberries (*Vaccinium vitis-idaea*). Trees in the bogs are black spruce (*Picea mariana***),** and tamarack (*Larix laricina*).

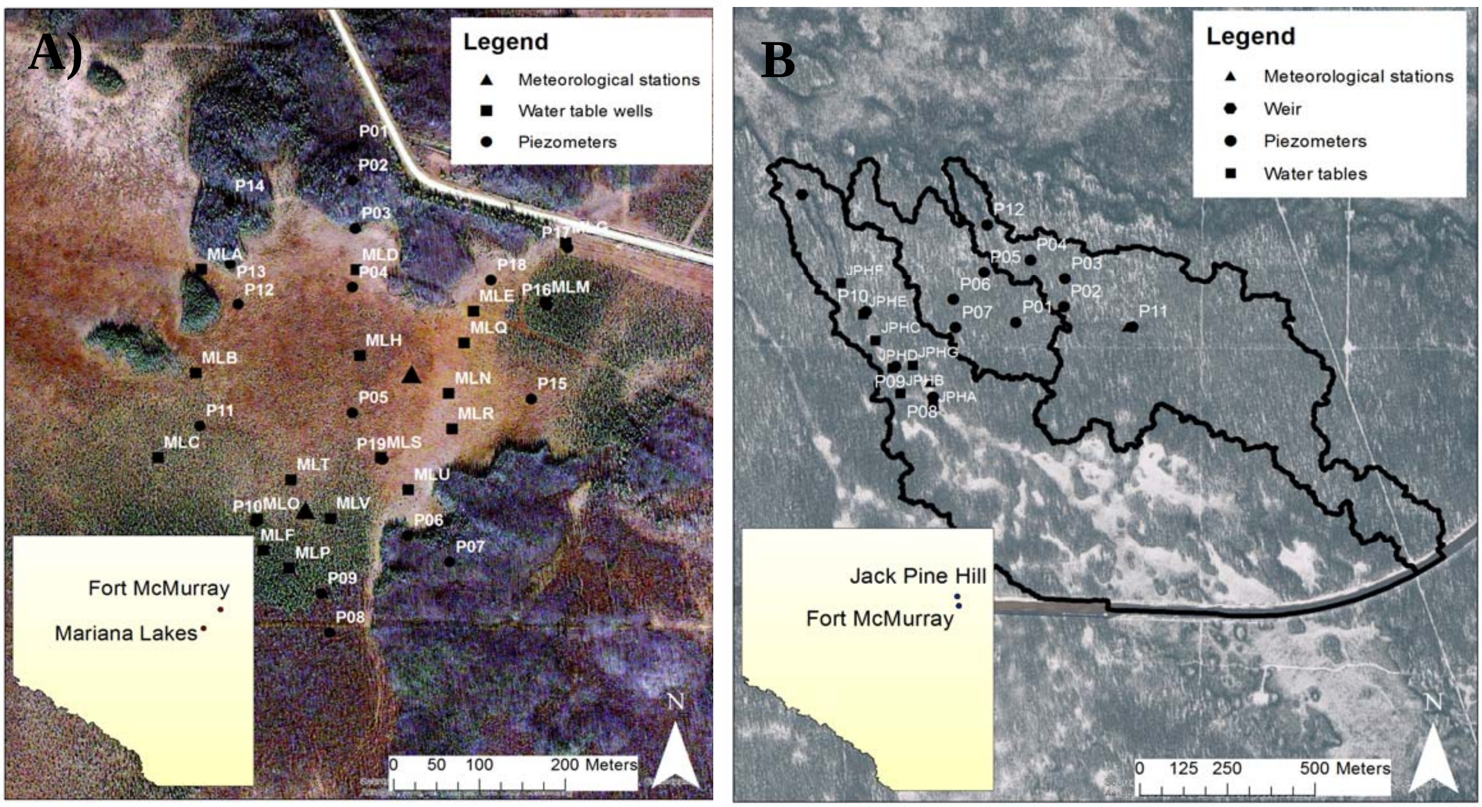


**Figure 3. 1 A and B represent ML and JPH sites with instrumentation locations.**

Jack Pine Highland (JPH), a 7 $km^2$ catchment, is dominated by jack pine (*Pinus banksiana*) trees averaging 40 years of age in the uplands, and the soil is sandy and nutrient poor. There is a low-lying, rich, minertrophic fen that runs north through the site. Vegetation in the upland portion of this site is dominated by many types of lichen (*Cladina*) found on both forest floor and as epiphytes on trees and branches, as well as labrador tea (*Rhododendron groenlandicum*), and blueberry (*Vaccinium corymbosum)*. The fen is comprised of alders (*Alnus),* paper birch (*Betula papyrifera*) and sedge species (*Carex*). As well, Sphagnum species were present yet sporadic within the fen.

### ***3.3 Field methods***

#### *3.3.1 Groundwater monitoring*

The sites analyzed were instrumented with piezometers, water table wells and micro-meteorological stations (Figure 3.1). Nested piezometers consisting of 2 to 4 wells were installed at depths ranging from 1.5 to 7 m. Each piezometer was constructed out of either PVC pipe or high carbon steel, threaded into a stainless steel Solinst™ model 615 drive-point screened piezometer tip. To maintain the integrity of the water sampled from wells, polyethylene tubing (PET) was installed inside the pipes. Piezometers were installed using a Pionjar™ percussion hammer. Water table wells were manually installed into the peat, or in the case of some fen sites, with an auger. Water table wells were constructed from slotted PVC pipe of 0.076 m width by ~1 m length and these were covered with Nitex mesh to avoid sediment flow into wells. The water table wells were instrumented with Water Level Capacitance Loggers (Odyssey™) to record the water table level in millimetres. Water levels were measured every 10 minutes during the summer and hourly during the spring, fall and winter. Water table wells were anchored into the substrate using rebar posts to maintain relative elevation and minimize vertical error because of fluctuations in the surface elevation of the peat. The elevations of the water table wells and piezometers were taken from the LiDAR survey with an accuracy of ~5 cm. Deep piezometers were driven into the substrate and levelled off at the top of the casing for visual confirmation of maintained elevation. In addition, the length from the top of the casing to the ground surface of each well was measured annually with an accuracy of ~1 cm.

*3.3.2 Outflow gauging methods*

A 45° V-notched weir was installed at both sites. At JPH the weir was constructed in the rich fen. Minimal flow for 2011 resulted in no water flowing over the weir. In 2012 the weir became active in the spring, but sedimentation shortly after resulted again in an inactive weir. There was no channelized flow at the ML site in 2011, so it was difficult to find a suitable location for a weir that could capture the entire outflow from the fen. The peatland in 2011 did not show channelled flow. The ML site eventually flows out to Highway 63. At the highway a weir was constructed and a staging well was actively working for the fall of 2011 until the falling limb of the freshet in the spring of 2012. During the freshet, the weir was washed out below. Discharge was larger in 2012 than in the previous year and the weir could not be repaired.

*3.3.3 Water sampling for isotopes and geochemistry*

The d-excess is used in this study to identify progressive evaporation along surface flowpaths, and to provide a measure of flushing or connectivity. Whitfield et al. (2011b) similarly used d-excess to identify areas of flow-through and groundwater input in nearby wetlands. Gibson et al. (2000) suggested the use of the d-excess for determining the residence time of a parcel of water in a catchment. The same method is used in this study to assess if d-excess can be attributed to the distance along the flowpath. In this study, we used the mapped drainage pathways identified from the LiDAR flowpaths derived in Chapter 2 to identify headwater locations in the wetlands. At ML, headwater locations were the start of surface flowpaths which carried water to the drainage outlet of the watershed. The headwaters were situated in proximity to well MLP and various wells were located along the flowpath towards the watershed outlet. At JPH headwater areas corresponded roughly to the location of JPHA and likewise were monitored in a series of wells toward the watershed outlet. See Figure 2.4 and 2.5 for MLP and JPHA for well locations, respectively.

Water samples were collected from all water table wells and piezometers, at the outflow point, and from precipitation collectors (event and bulk). Collection from wells and piezometers occurred after purging three well volumes of water from each well. Geochemical samples were collected for a complementary study by Kusel (2014). Water samples for stable water isotopes were placed in 30 mL air-tight high density polyethylene bottles to minimize potential for isotopic fractionation by evaporation. Samples were analyzed by Alberta Innovates Technology Futures in Victoria using a Delta V Advantage mass spectrometer. Results are reported in per mil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW) with an analytical uncertainty of 0.01‰ for $^{18}O$ and 1 ‰ for $^{2}H$. The oxygen-18 and deuterium composition are calculated according to:

$$\delta^{18}O \text{ or } \delta^{2}H = [R_{sample}/R_{standard} - 1] * 10^{3}\text{ ‰}, \quad (1)$$

where $R_{sample}$ = $^{18}O/^{16}O$ sample, or $^{2}H/^{1}H$ sample

$R_{standard}$ = $^{18}O/^{16}O$ V-SMOW, or $^{2}H/^{1}H$ V-SMOW

Deuterium excess (d-excess, d) is expressed according to:

$$d(‰) = \delta\,^{2}H - 8\,\delta\,^{18}O \quad (2)$$

Where $\delta\,^{2}H$ and $\delta\,^{18}O$ are deuterium and oxygen-18 compositions of water, respectively. Previous studies for investigating precipitation-climate processes as shown by Froehlich et al. (2002) have used d-excess for labelling of vapour source regions and evaporation effects. Graphically, d-excess represents offset from the global meteoric water line (GMWL) defined by Craig (1961) which has a d-excess equal to 10 as shown in $\delta^{18}O$ versus $\delta^{2}H$ space (seen in Figure 3.2). A negative deviation from the GMWL, i.e. d-excess less than 10 is common for evaporated water bodies undergoing heavy isotope enrichment, whereas a positive d-excess is often associated with evaporated moisture or closed basin precipitation, as in the Mediterranean regions.

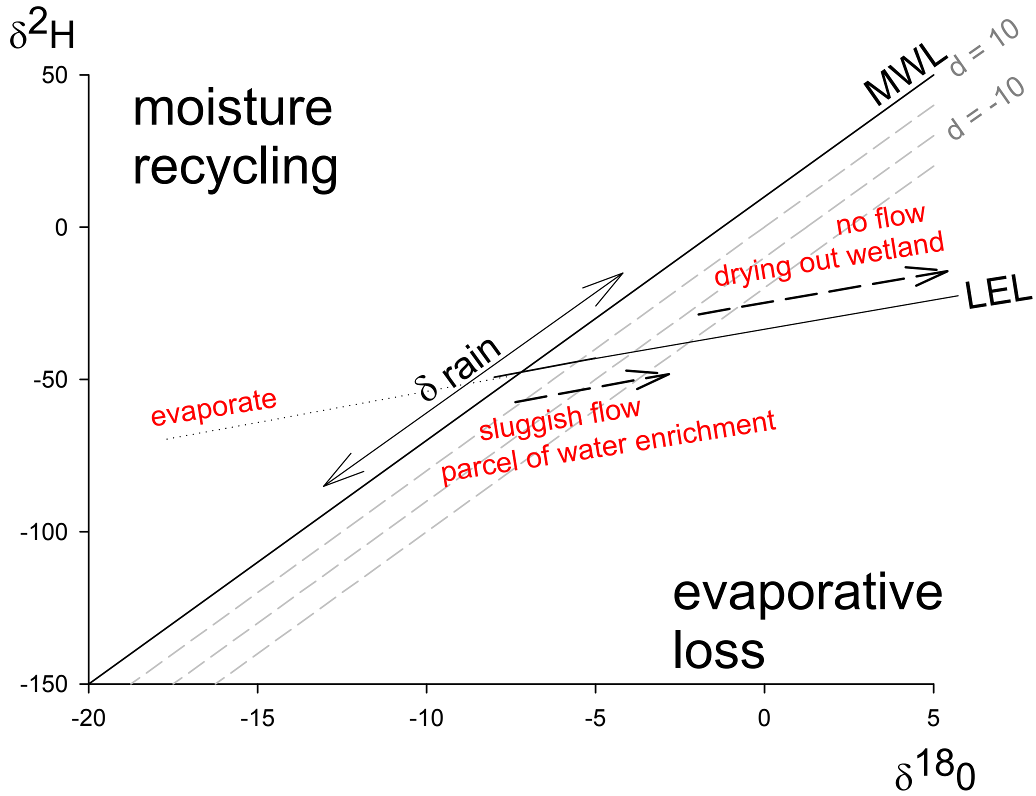


**Figure 3.2 Schematic of d-excess parameter adapted from Froehlich et al 2002 for application to wetlands. The global meteoric water line (GMWL) has a d excess = 10 and a slope of 8, as defined by Craig (1961). The local evaporation line has a slope of less than 8 and a variable d-excess based on moisture conditions. In this figure, a decrease in d-excess represents an evaporative loss of water, while an increased d-excess would correspond to rain because of an increase in moisture recycling.**

When a parcel of water undergoes evaporative enrichment due to kinetic fractionation, the deuterium intercept will decrease in magnitude. The d-excess, which contains information from both $\delta^2H$ and $\delta^{18}O$ can therefore be used as a simple metric of offset along the local evaporative line (LEL), as shown in Figure 3.2, and as commonly observed in the AOSR (Gibson et al. 2011). The hypothesis in this study is that water parcels with longer exposure to evaporation will acquire a lower d-excess.

*3.3.4 Micro-meteorological methods*

Four micro-meteorological stations were installed at the study sites. At ML the stations were situated in the treed bog and the open fen, and at the JPH site stations were situated in the upland forest and the open fen. All stations consisted of sensors mounted onto a 3 m tripod tower which was installed and levelled periodically. All stations collected data from 2011 and 2012 during the open water season (~ June to October). Each station consisted of an array of sensors to record: wind speed ($ms^{-1}$) and direction (°), precipitation (mm), net radiation ($Wm^{2-1}$), relative humidity (%), air temperature (°C), soil temperature (°C), and air pressure (kPa). All parameters were recorded on a Campbell Scientific CR 23X Data Logger (Table 3.1). Measurements were made every 30 seconds and averages were recorded at 30 minute intervals. Data for 2011 at JPH was also compiled from the Terrestrial Ecological Effects Monitoring (TEEM) meteorological station located 3 km away. The TEEM meteorological station recorded hourly averages of similar parameters. Owing to lack of an atmospheric pressure record from the TEEM meteorological station for 2011, the ML atmospheric pressure record was used.

**Table 3. 1 Overview of field measurements methods.**

| Variables measured | Height of Measurement (m) | Measurement method |
|---|---|---|
| Air temperature (°C) | 1.8 above the surface | thermistor in a radiation shield |
| Net radiation ($Wm^{2-1}$) | 1.8 above the surface | pyranometer |
| Relative humidity (%) | 1.8 above the surface | thermistor in a radiation shield |
| Rainfall (mm) | 1.8 above the surface | Tipping bucket rain gauge |
| Soil Temperature (°C) | At 0.1, 0.25 and 0.4 below the surface. | Thermistor |
| Wind speed (m/s) and direction (°) | 2 above the surface | Gill ultrasonic wind sensor (anemometer and vane) |

| | | |
|---|---|---|
| Air Pressure (kPa) | 1.8 above the surface | Young barometric air pressure sensor |

*3.3.5 Energy balance*

Evaporation was estimated through a simplified energy balance approach using parameters from each sensor on the micro-meteorological station. The most practical methods for determining evapotranspiration from land surfaces in the region using similar equipment are Priestly Taylor (1972) method, the Penman method and the Penman Combination method (Winters et al. 1995). These methods were found to yield comparable results in a study in the region (Tattrie 2011). The Penman Combination method was selected for this analysis as previous workers have noted it to be slightly better due to the aerodynamic resistance function being nonlinear, resulting in fewer incidences of over-estimation of evaporation (Chow et al. 1988). The micro-meteorological data, averaged over a daily time step, is used to compute evaporation using the following formula:

$$E_p = \frac{\Delta}{\Delta + \gamma} E_r + \frac{\gamma}{\Delta + \gamma} E_a \quad (\text{mmday}^{-1}) \qquad (3)$$

where:

$\Delta$ = the slope of the saturated vapour pressure (Pa°C$^{-1}$)

$\gamma$ = psychrometric constant (Pa°C$^{-1}$)

and,

$$E_r = \frac{Rn\text{-}H\text{-}G}{l_v \rho_w} \qquad (4)$$

where:

Rn = net radiation

H = sensible heat flux

G = ground heat flux

$l_v$= latent heat of vaporization

$\rho_w$=water density

For the aerodynamic component, Ea, is the difference in saturated ($ea_s$) and actual vapour pressure (ea) and is multiplied by the wind speed ($w_s$), where

$$Ea = (ea_s - ea)w_s \quad (5)$$

(Chow et al. 1988: 88)

## 3.4 Data analysis

### *3.4.1 Vertical water balance*

To estimate runoff in an ungauged catchment a method known as the vertical water balance was used. As developed by Tattrie (2011), this method involved estimations of runoff potential for wetland surface based on the precipitation-evapotranspiration deficit, the change in storage observed in the water table wells, and an assumed threshold of surface depression storage. Boudreau and Rouse (1995) utilized similar site specific balances for wetland terrains to estimate runoff values. The vertical water balance (VWB) uses a bucket model approach in this case with an assumed 15 mm depression storage capacity across all of the wetland areas found to be suitable for nearby wetlands by Tattrie (2011). This threshold is also in general agreement with other depressional storage estimates reported in similar wetland studies outside the AOSR but within the Boreal Plains (e.g. Goodbrand 2013). Meteorological data, used for characterizing precipitation and evapotranspiration by the Penman Combination method were combined with water level records from specific sites to estimate runoff potential by the vertical water balance method on a daily time step. The water balance takes into account precipitation (P), evapotranspiration (ET) and storage change ($\Delta S$) according to:

$$R = P - ET - \Delta S \qquad (6)$$

where R is runoff potential (mm), P is precipitation (mm), ET is evapotranspiration (mm) and the change in storage ($\Delta S$) is defined as the water table (WT) change on a daily time step multiplied by the specific yield ($S_y$) of peat (Boudreau and Rouse 1995). Specific yield values for peat have been shown to vary considerably, ranging from between 0.3 and 0.6 depending the bulk density (Thompson 2012). In this study, to be consistent with Tattrie (2011), we have used Johnston's (1967) estimate of 0.44 for specific yield. Compressibility function in peat ($bS_z$) exists based on Price and Schlozhauer (1999) study findings, but they state storage can be a function of gravity rather than compressibility. In addition, in this region Petrone et al. (2008) found peat resistant to compressibility. For simplicity purposes of this estimate, this study ignored the compressibility value and assumes storage is affected only by gravity.

In wetlands where slope gradient is minimal, runoff is not typically visible or measureable. Therefore, estimates of runoff potential help to predict the amount of water excess above a fixed depression storage threshold. To estimate the runoff potential, it was assumed that groundwater plays a minimal role in the wetland surface water balance, as underlying tills have low hydraulic conductivities ranging in this region from $10^{-8}$ $ms^{-1}$ to $10^{-9}$ $ms^{-1}$ (Hayashi et al. 1998). As well, based on Chapter 2, we found minimal groundwater connections.

From Chapter 2 the changing hydraulic head of upland piezometers adjacent to the fens (P6 and P13) on a biweekly to monthly time scale are included in this analysis but the VWB was not applied to them as groundwater is known to be important in the upland water balance.

*3.4.2 Antecedent precipitation index*

Antecedent moisture has been shown to be an important factor in understanding the hydrological response of wetlands. Previous research has shown that memory effects in these systems can change potential flow routing and connections (Creed et al. 2008; Shook et al. 2011). This study applied the antecedent precipitation index (API), to the summer seasons to quantify event antecedent moisture according to:

$$API_t = API_{t-1} * C + P_{\Delta t} \quad (7)$$

(Linsley et al. 1982)

where $P_{\Delta t}$ are precipitation events, $API_{t-1}$ are previous precipitation events on a decaying scale, and C is the decaying constant ranging from 0.9 to 0.7 varying depending on water residence time in the watershed (Linsley et al. 1982; Bousfield 2008). For a peatland with minimal flow potential, a recession coefficient of 0.9 was used on a 0.1 decaying factor for each time step. These choices were adopted because of the small scale of sites and the recorded hydraulic conductivities. The API is evaluated on a daily time step in this study and is applied to better understand the watershed response during and between precipitation events.

The API was used qualitatively to categorize precipitation events based on the antecedent moisture conditions (AMC) to test the hypothesis that there may be different types of hydrological responses within the different terrain types depending on the AMC. This study classified the AMC into low, medium, and high based on the magnitude and duration of each event. A precipitation threshold for lateral flow of 15 mm in magnitude was used (Redding and Devito 2008). While a conservative threshold of 25 mm was used to differentiate the medium and high antecedent moisture conditions regimes. The API index was most relevant to isolate rain events and infiltration capacity, while duration was used again as an identifier between medium and high events. Below is a table (Table 3.2) of the quantitative values used for each AMC class.

**Table 3. 2 Quantitative framework for classifying antecedent moisture conditions.**

| AMC Conditions | Duration (hrs) | Magnitude of precipitation event (mm) | Magnitude of API for event (mm) |
|---|---|---|---|
| Low | <10 | <25 | <19 |
| Medium | <10 | <25 | >19-49 |
| High | >10 | >25 | >49 |

Using the AMC, instantaneous unit hydrographs were created for select rain events on a ten minute resolution. Water level data from all wells sampled at the ML site were placed onto one hydrograph. To identify the hydrologic response to a single rain event, the water level was set at the beginning of each event to zero and differences in water level were determined until the peak of each event. The examination of the falling limbs did not occur as it is difficult to determine the terminus of a rain event in peat. By placing all sites on one hydrograph, the overall slopes were compared for the rising limbs. Tradif et al. (2009) used a similar method to determine terrains on a larger scale, based on different responses which were visible between fens and areas flooding in wetlands. This analysis was used to assess if different responses were visible between the bog and fen terrain at the ML site under different precipitation events.

## *3.5 Results and discussion*

### *3.5.1 Precipitation, Evapotranspiration and Water levels*

The time series of precipitation, evapotranspiration and water levels changes are presented in Figure 3.3. Precipitation totals during the study period of 2011 (111 days) and 2012 (96 days) were 229 mm and 335 mm, respectively highlighting the wetter conditions in 2012. In addition, the evapotranspiration was also greater in 2011 in comparison to 2012, by approximately 100 mm.

As shown in Figure 3.3, comparing 2011 and 2012, three larger rainfall events occurred in 2011 of approximately 20 to 30 mm in magnitude, while in 2012 there were three events that exceeded 50 mm and many smaller rainfall events. In 2011 the water table at JPH was never observed at surface in the fen, while in 2012 (around DOY 180) the water table appeared above the fen surface and remained high for the duration of the season. At ML, the wetter conditions in 2012 resulted in saturated ground in many areas of the fen that were not present in 2011.

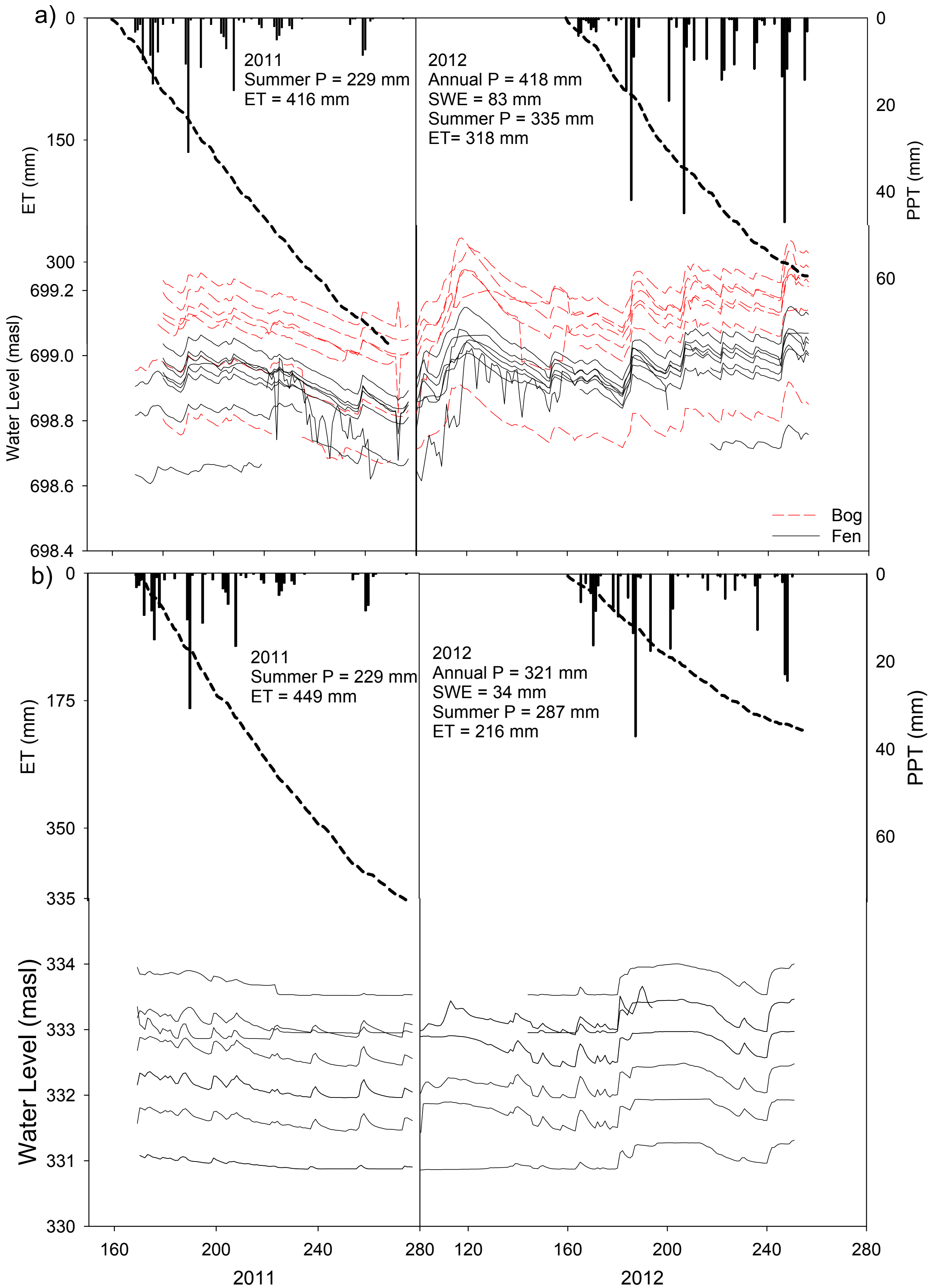


**Figure 3.3 Summary of water table levels, cumulative evapotranspiration, and precipitation for both hydrological years a) is ML and b) is JPH.**

*3.5.2 Vertical water balance*

The results of the vertical water balance calculations are summarized in Table 3.3 and graphed in Figure 3.4. The range in runoff potential from the VWB analysis is large within each of the terrain units. The average runoff potential for the ML fen for 2011 was negative (-212mmyr $^{-1}$) and for 2012 was 76 mmyr$^{-1}$. Negative runoff potential suggests that surface outflow from the site is likely to be negligible, and that storage is likely on the decline. The runoff potential in the ML fen was found to be more uniform and more positive in 2012 under wetter conditions than in 2011. Compared to ML fen, the ML bog was found to have similar but lower runoff potential, with a deficit of 269 mmyr$^{-1}$ in 2011 and a surplus of 55 mmyr$^{-1}$ in 2012. In the ML fen, it was hypothesized that the largest runoff would be at sites farthest along the flowpath (MLE or MLG), as these sites would be receiving the largest surface flow through from a proportionately larger drainage area. But, MLU and MLS had the largest runoff in the fen. Both of these wells are situated on the edge of the bog. MLC had largest runoff potential for the bog terrain and is also very close to the edge of the bog. The bog fen transition zone is therefore identified as a potentially important generator of runoff at the ML site.

**Table 3.3 Runoff potential rate for 2011 and 2012. Mariana Lakes site is represented by the fen and the bog; JPH is represented by the rich fen.**

| Terrain Type | Well Site | 2011 Runoff Potential (mm/yr) | 2012 Runoff Potential (mm/yr) |
|---|---|---|---|
| ML Fen | ML A | -245 | 77 |
| | ML B | n/a | 78 |
| | ML D | -164 | n/a |
| | ML E | -169 | 69 |
| | ML G | -191 | n/a |
| | ML N | -218 | 74 |
| | ML Q | -267 | 68 |
| | ML R | -217 | 75 |
| | ML S | -221 | 83 |
| | ML U | -222 | 81 |
| ML Bog | ML F | -286 | 65 |
| | ML M | -248 | 43 |
| | ML O | -284 | 59 |
| | ML P | -290 | 64 |
| | ML T | -287 | 26 |
| | ML C | -196 | 78 |
| | ML V | -289 | 48 |
| JPH Rich Fen | JPH A | -386 | 286 |
| | JPH B | -392 | 301 |
| | JPH C | -408 | 303 |
| | JPH D | -428 | 303 |
| | JPH E | -391 | 262 |
| | JPH F | -332 | 267 |
| | JPH G | -327 | 174 |

Similar to the ML sites, at JPH the rich fen was found to have negative runoff potential in 2011 because of the relatively dry conditions. Runoff potential rarely exceeded the 15 mm threshold of depression storage. During 2012, runoff potential was similarly positive although higher at JPH than ML, estimated at 271 $mmyr^{-1}$. Lateral surface flow was visible at the rich fen in JPH from July to September 2012 throughout the study period. A secondary channel became active only when overland flow is present. This is thought to be why the record of JPHG, shows dramatically less runoff potential than the mean by ~100 $mmyr^{-1}$.

In the rich fen at JPH for both years, the VWB (Figure 3.4) reflects several large spring runoff events, followed by periods of drying, and finally late summer rains causing significant runoff. Large variances in runoff estimates at sites within the rich fen can most likely be related to the physical width of the fen channel. Some wells are located in reaches of the fen over 45 m wide, resulting in a small water level rise as compared to reaches where the fen narrows to less than 20 m causing a funnelling of water and larger water level rises.

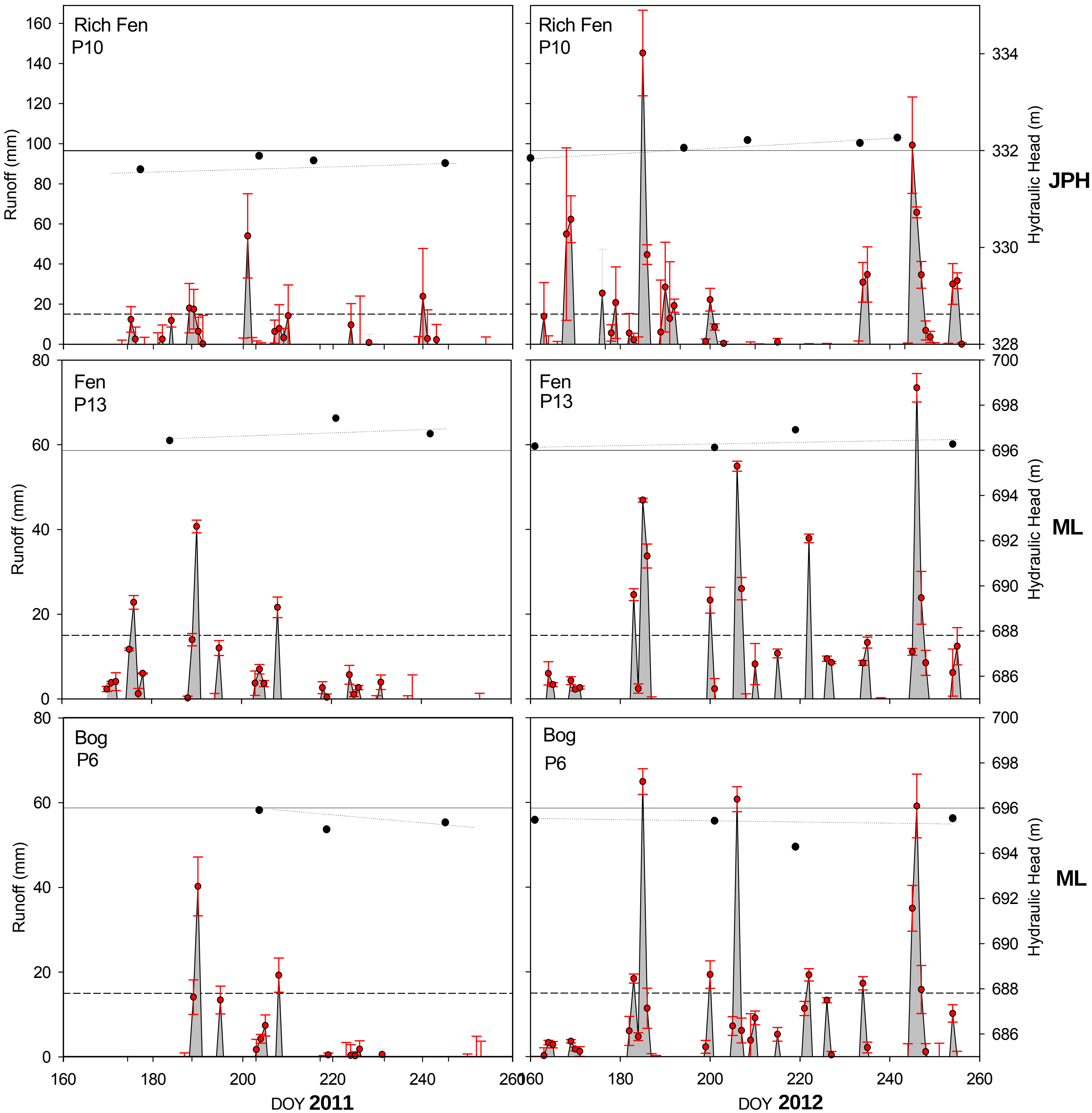


**Figure 3.4 Vertical water balance for each terrain unit in 2011 on left and 2012 on right. JPH is represented by the rich fen and ML by the fen and bog. Error bars represent range of runoff from all wells within the represented terrain. The dash line at 15 mm indicates the approximate (and assumed) runoff threshold. Hydraulic head of adjacent shallow upland wells (ML (P6, P13), and JPH (P10) are plotted with respective scales, reference line and dotted trend line.**

It is important to note that the bog terrain units had minor runoff potential from small scale precipitation events with minimal exceedance of the 15 mm threshold, as opposed to the fen which had two incidents of exceedance in 2011 and three in 2012 seen in Figure 3.4. In 2011, no visible surface flow was observed in the wetlands during precipitation events, whereas in 2012 surface runoff was observed at MLG on Sept. 10 2012 (DOY: 253), following a very large precipitation event. Based on this observation of surface runoff at MLG, we anticipate lateral runoff is likely to occur under similar magnitude precipitation events (> 50 mm); although different hydrologic regimes can result in dramatically contrasting runoff potentials.

A past study that focused on the interaction of wetlands and uplands has shown a cyclical lateral flux of water moving from uplands to wetlands in the winter/spring and opposite in the summer/fall (wetlands recharge uplands) (Hayashi et al. 1998). Based on this previous research, ML would be expected to be maintaining or increasing the hydraulic head of adjacent uplands throughout the open water season. The results from the adjacent uplands and the VWB (Figure 3.4) indicate this trend occurred in some fen locations (P13 and P10 of JPH), whereas it did not occur in others (P6) situated relatively close to the bog. This cyclical lateral flux of water may exist in ML weakly, as hydraulic heads of adjacent uplands increases throughout the open water season. However, it is clear that the largest flux of water is generated laterally near the surface of the fen.

### *3.5.3 Statistical analysis of VWB*

Basic statistical analysis was conducted to compare VWB for ML fen, ML bog and JPH rich fen wells for 2011 and 2012. A box plot illustrates the differences in average runoff potential for the terrain units (Figure 3.5). A t-test was performed and revealed that the median values between the fen and the bog at ML for 2011 and 2012 were statistically different at a significance of $p < 0.006$ and $p < 0.009$, respectively. It is reasonable to assume that these differences in runoff responses arise because the bog is a recipient of only precipitation, whereas the fen receives precipitation as well as some groundwater inflow.

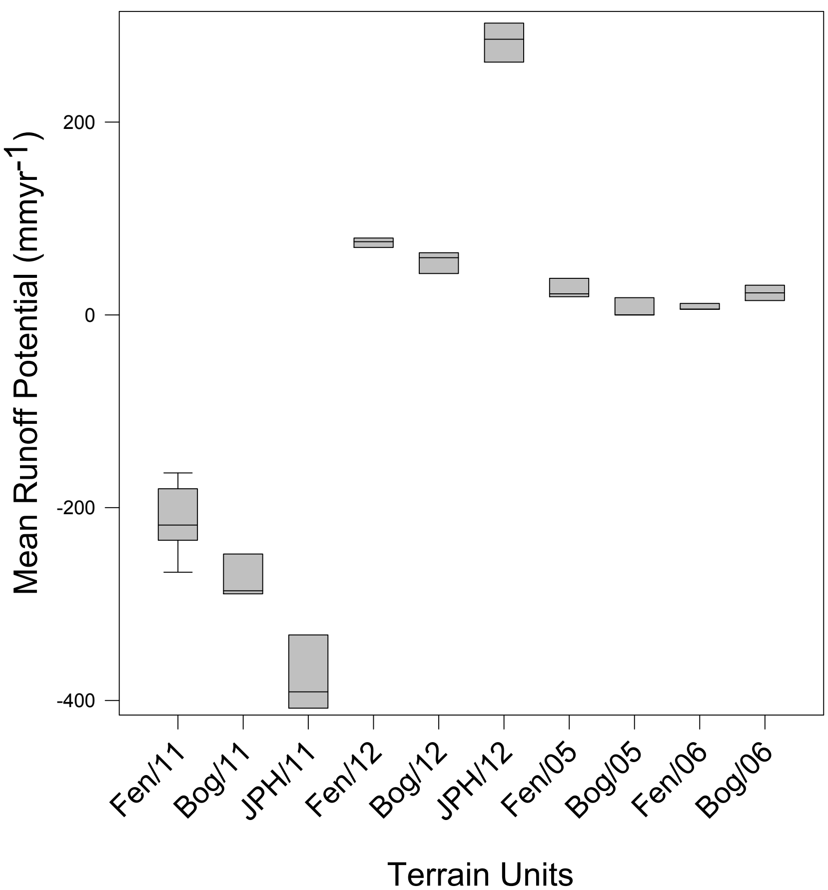


**Figure 3.5 Mean runoff potential differences for terrain units. Fen and bog are at ML, and JPH represents a rich fen for 2011 and 2012. Results from Tattrie's (2011) findings are plotted for fen and bog terrain in 2005 and 2006.**

Similar trends are seen in comparing these findings with previous VWB estimates completed by Tattrie (2011). ML fen has the largest runoff estimates and the lake fen in Tattrie's study does as well. Total precipitation from Tattrie's study in both years (2005 and 2006) was less than observed in 2011 and 2012; thus, accounting for the differences found in runoff potentials. Tattrie observed a decreasing runoff potential as the summer progressed. A similar occurrence was found in this study during 2011, but the trend was not present for 2012. No negative runoff potential was recorded in Tattrie's findings rather the runoff was defined as zero; this accounts for the differences observed in 2011. Overall, differences seen in runoff potentials between this study and Tattrie's may be a function of the characteristics of these distinct study areas.

*3.5.4 Antecedent moisture variations in ML*

The shapes of the hydrographs (Figure 3.6 and 3.7) revealed differences between the fen and the bog responses in ML depending on the AMC. In circumstances when antecedent moisture was high the bog response was most obvious and typically peaked at higher water levels than that of the fen; whereas when antecedent moisture was low, the response of the bog was muted relative to the fen. In 2011, under relatively low AMC, all bog responses were largely muted in comparison to the fen (see Figure 3.6). The 2011 AMC appear to have minimal difference from low to medium antecedent moisture. In contrast to 2011, in 2012 (see Figure 3.7) there was an evident difference in the hydrologic response to increasing AMC. In low AMC, the water level response in the bog was strongly muted and differed to the water level response in the fen. In medium AMC, the bog responses were similarly to the fen. Finally, for cases when AMC was high, the bog showed a threshold of responsiveness exceeding the fen. In episodically large precipitation events the bog may showcase *fill and spill* hydrology (Woo 2012).

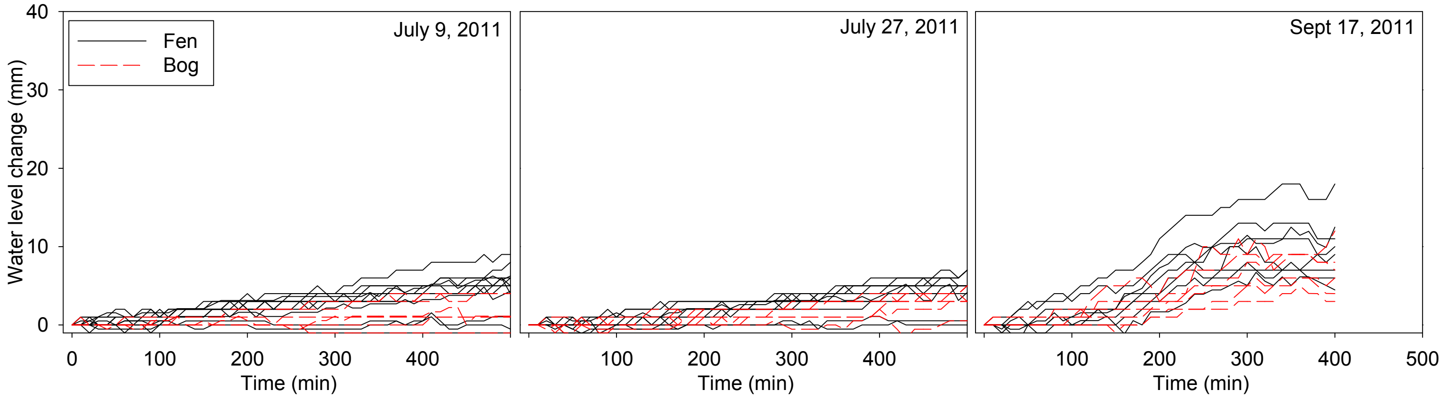


**Figure 3.6 Examples of water level response for water table wells during 2011 situated in the fens and bogs under low (left), medium (centre) and medium (right) AMC. Stacked graphs are on the same time scale and the water level corresponds with being below an arbitrary defined datum.**

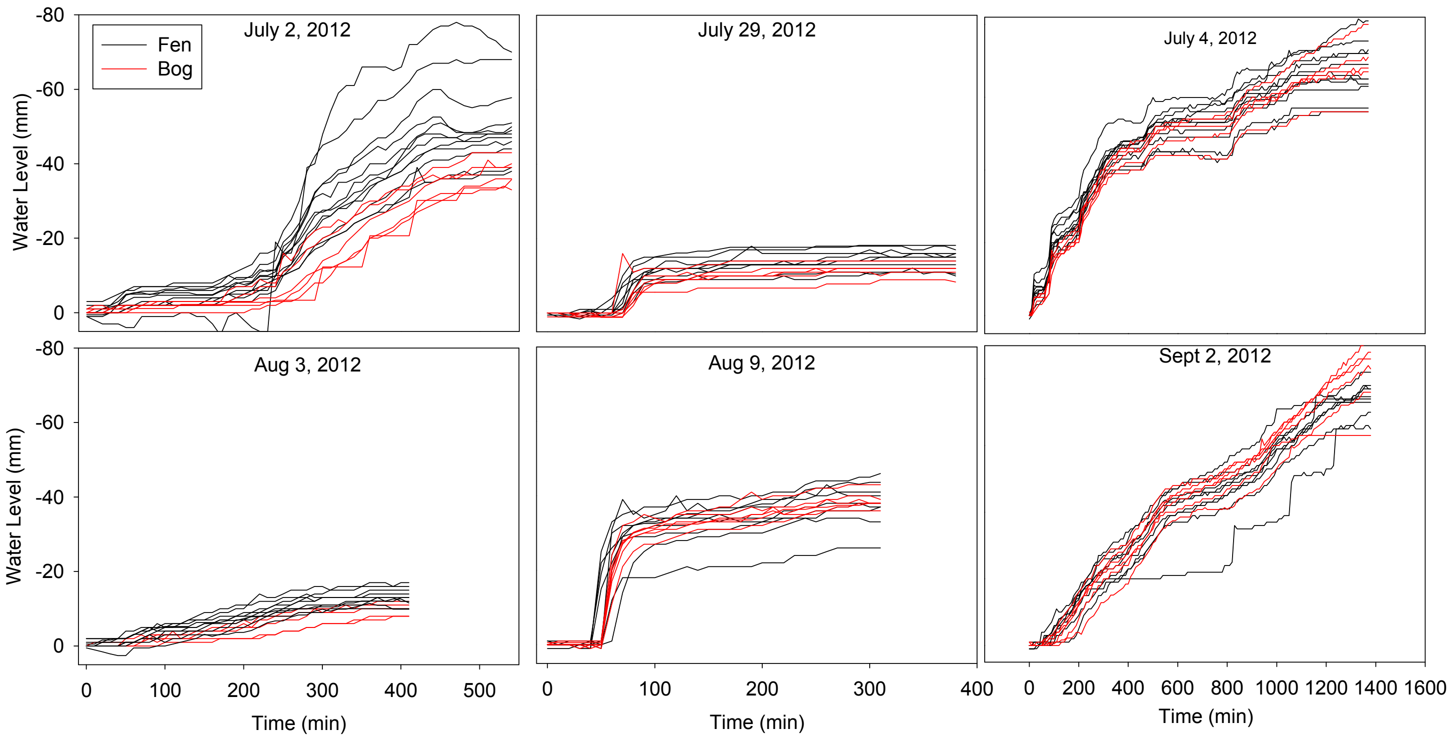


**Figure 3.7 Examples of water level responses for water table wells during 2012 situated in the fen and bog under low (left), medium (centre), and high (right) AMC. Stacked graphs are on the same time scale and the negative water level corresponds with being above an arbitrary defined datum.**

It is probable that differences are because of the changes in surface micro-topography and roughness. Quinton and Roulet (1998) observed this type of response based on micro-topography creating different storage thresholds. They recorded that three quarters of annual runoff was based on the exceedance of this threshold connecting the wetlands. Bogs tend to have more hummock and hollows prevalent, whereas fens exist as lawns, and surface roughness substantially decreases. So, in events with low to medium AMC, the bog, having deeper hollows and higher porosity than the fen, fills those hollows and a rise in the hydrograph is therefore limited. At a certain threshold, when AMC is high, the empty hollows are full and spillage may occur to surrounding areas. Storage thresholds can influence hydrological connectivity (Spence 2010), and is a key factor that determines if runoff exists or not.

If the storage thresholds are exceeded when the AMC is high and a large precipitation event occurs, spillage can occur over the surface as water tables rise. It is interesting to note that runoff potential based on the VWB was found to be highest in the transition zone between the bog and the fen i.e. at sites MLU, MLS, and MLC. These are the sites where water levels were found to be most responsive during high AMC events, and likely are a significant source of water during high runoff episodes.

The storage capacity of the different terrain units within prairie regions has been shown to be a significant parameter controlling runoff response. In prairie wetlands, runoff from wetland potholes typically occurred when the storage thresholds were exceeded (Su et al. 2000). Conceptually, a bucket model approach was used to describe runoff with slow and fast moving areas depending on antecedent moisture. In the case of ML, a fast moving area would dominate once surface storage capacity is exceeded during large precipitation events and at high AMC. Retention of water appears to be limited in large precipitation events, and these large events may also act to connect the upland areas. After large precipitation events, evidence of surface flow was visible such as matted vegetation and twig transport that suggested overland flow had occurred along open rill channels off the hillslope; therefore, uplands surface runoff to wetlands most likely occurred.

Another factor that may influence the storage threshold in the wetlands is the frost table. Frost tables are often close to the surface at the beginning of the open water season and decline steadily due to melting as the season progresses. Petrone et al. (2007) found that a higher frost table corresponded with a larger lateral movement of water within a peat complex and storage was limited, although that parameter was not measured in this study.

*3.5.5 Lateral movement of water*

The d-excess was found to decrease systematically from bog to fen along the dominant surface flowpath at ML site. Using data from both 2011 and 2012, the trend in d-excess versus distance from surface water at the ML site produced a linear regression with $R^2 = 0.34$, and a slope of -0.007 ($p < 0.0001$). Largest d-excess values were seen in the bog and values generally decreased along the flowpath towards the fen (Figure 3.8). This negative relationship is in agreement with the hypothesis that water would become progressively enriched along the water track. Transpiration, which does not typically produce isotopic enrichment, is clearly not the primary mechanism for enrichment of the water, although transpiration may also be occurring in conjunction with evaporation.

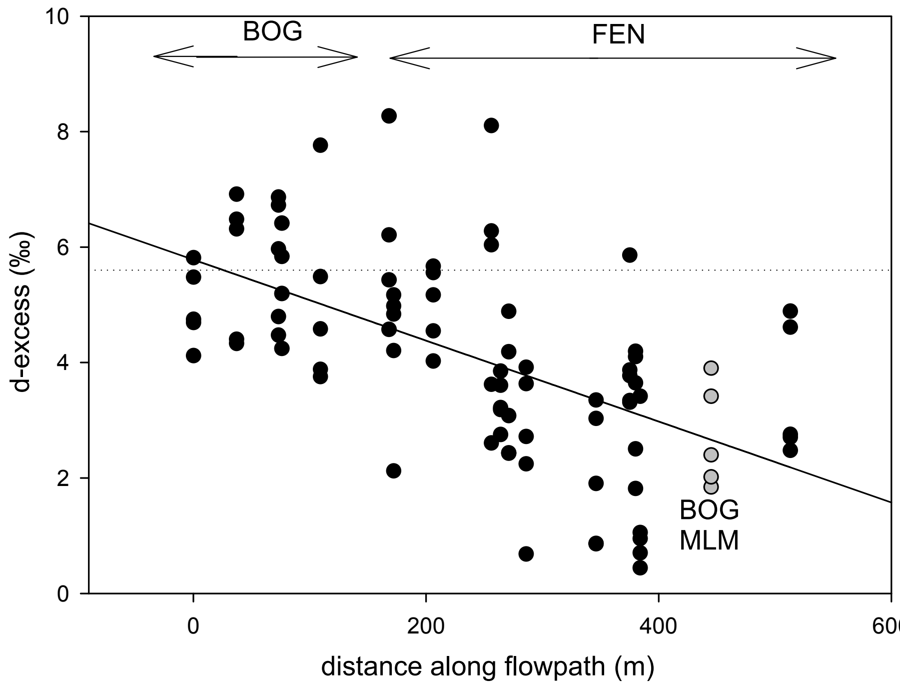


**Figure 3.8. D-excess of ML for 2011 and 2012 across different terrain units (bog and fen) along a flowpath with trend line representing surface water table wells. The dotted line represents weighted mean d-excess of Edmonton's local meteoric water line (Rozanski et al. 1993).**

It is important to note that the secondary bog (MLM) falls along the trend line. This was not hypothesised. Based on the conceptual terrain unit, bogs are primarily atmospherically feed (precipitation), and therefore would fall close to the d-excess of the local meteoric water line.  This is suggestive of two things; first that vegetation used to identify a bog does not necessary predict how the hydrology of a terrain unit will act. Secondly, that not all bogs are alike, rather position within a larger peat complex may be more important determinant of bog hydrologic response.

In ML there were two bogs identified, one situated south and somewhat central to the larger complex, and the other in close proximity to the main water track. At this site the secondary bog, (MLM and P16) situated close to the main water track, definitely undergo evaporative enrichment suggesting there is a connection from the adjacent fen. This challenges the conceptual notion that bogs are ombrotrophic, but also shows that isotopes may be used to detect non-ombrotrophic responses.

Closer examination of temporal trends in d-excess at different times during 2011 and 2012 (Figure 3.9) shows a similar relationship is recorded at most times during the study; however, no significant relationship was noted for August 2011, and the strongest significant relationship is found in September 2012. This is mostly likely corresponding to the difference in seasonal wetness. During August 2011, the water table and AMC were the lowest, while the opposite was observed during September 2012 (wettest with highest AMC). These results suggest that during wet years when the runoff potential is higher, d-excess can be explained by distance, while when the runoff potential is low and therefore limiting the movement of water d-excess is not explained by distance along the flowpath. In general, the gradient of d-excess versus distance tends to decrease during lower flow periods and increase during higher flow periods.

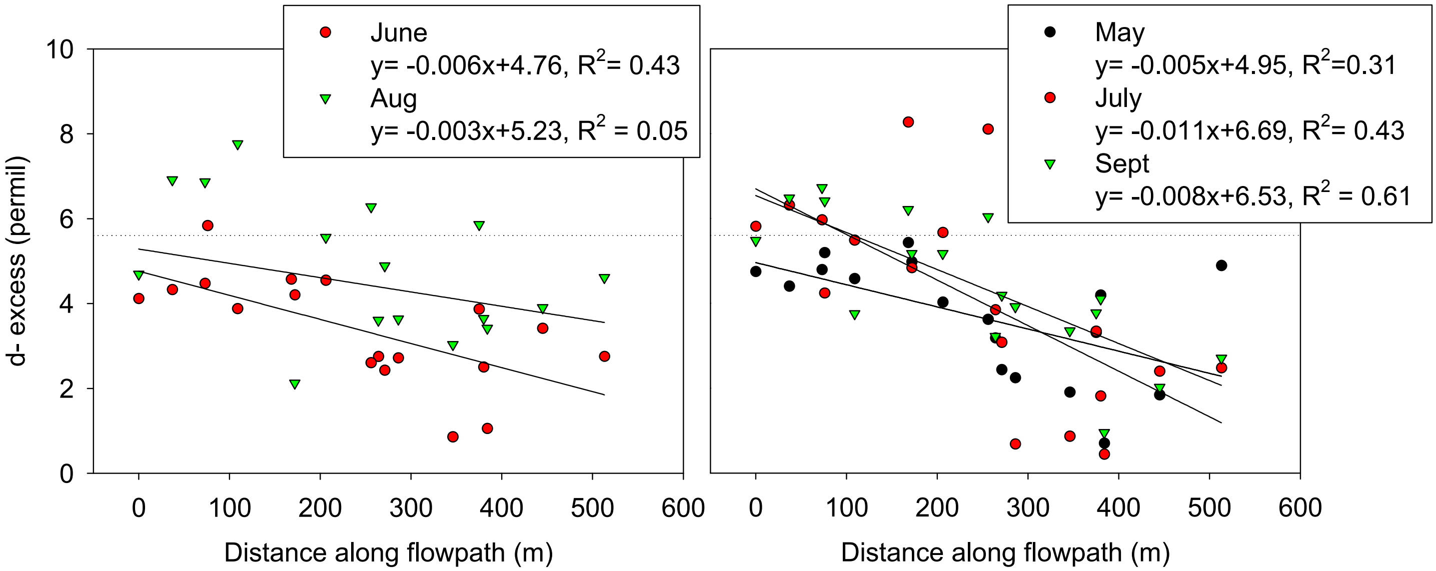


**Figure 3.9 D-excess for ML in 2011 on the left and 2012 on the right representing surface water table wells. The dotted line represents weighted mean d-excess of Edmonton's local meteoric water line (Rozanski et al. 1993).**

Further investigation of d-excess along the flowpath, including piezometers from shallow and intermediate depths, are in agreement with a decreasing d-excess trend with distance as was seen at the surface water table wells (Figure 3.10). In general, a stronger relationship of decreasing d-excess with distance is seen in June 2011 and September 2012, again following the highest AMC. The last piezometer along the flowpath, P17, does not follow the observed trend suggesting that locally processes may be more complex.

Current understanding of peatlands suggest minimal mixing of water may occur because of lower hydraulic conductivity of decomposed compact peat (ex. Reeve 2000); therefore, water within peatlands moves along the flowpath at the surface. However, as was discussed in Chapter 2, there may be mixing of surface and subsurface waters particularly under recharging conditions. From the d-excess results, we observe that there is a decreasing d-excess signature at the surface with distance, suggesting a slow movement of surface waters. But we also examined the mixing of surface and subsurface waters along that flowpath. From piezometers on the flowpath (Figure 3.10) we found wells that were further along the flowpath (P18 and 17) had a smaller d-excess signal at depth. A variation of d-excess with depth of 3 m at P18 ranging from -1.2 to 2.1 ‰ is seen. This is in agreement with research presented by Levy et al. (2013), suggesting a recharging of waters underneath the water track. Research completed by Levy et al. found recharging signature at depth in large (>100 $km^2$) peatlands, and our findings confirm that surface water recharge can be seen in small catchments as well (<4m $km^2$). However, not everywhere has a recharging signal at depth; P19 outside of the bog, appears relatively unchanged with depth, and contrasts Levy et al.'s findings. This may be accounted for due to variations in specific landscape type, and scale.

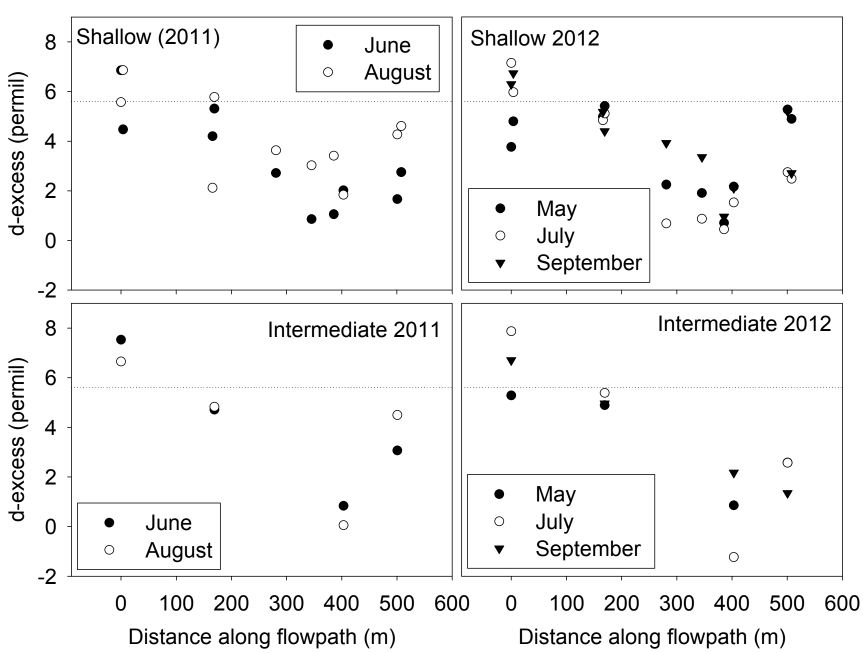


**Figure 3.10 D-excess examined with distance along the flowpath with P10 representing zero distance following this flowpath sequence P10, O, S, P19, N, Q, E, P18, P17, and G as the final distance along**

**the flowpath. The top graphs represent shallow wells (~0-2 m depth) and the bottom represents intermediate wells (~2-4 m depth). The dotted line represents weighted mean d-excess of Edmonton's local meteoric water line (Rozanski et al. 1993).**

For JPH, (Figure 3.11) d-excess had a positive relationship with distance along the flowpath and contrasted results from ML. In general, there was larger variability of d-excess when compared to ML. D-excess was smallest near JPHA in July 2011, coinciding with visible water ponding at surface. This inverse relationship may indicate that further downstream along the flowpath groundwater is recharging the fen during drier years, as was predicted in Chapter 2 (Figure 2.8). However, when runoff within the rich fen was quite pronounced, during wet periods such as in 2012, the d-excess signatures remained relatively consistent with the local meteoric water line and the relationship is limited. This contrast with results from both sites highlights the variability of terrain response within the Boreal Plains.

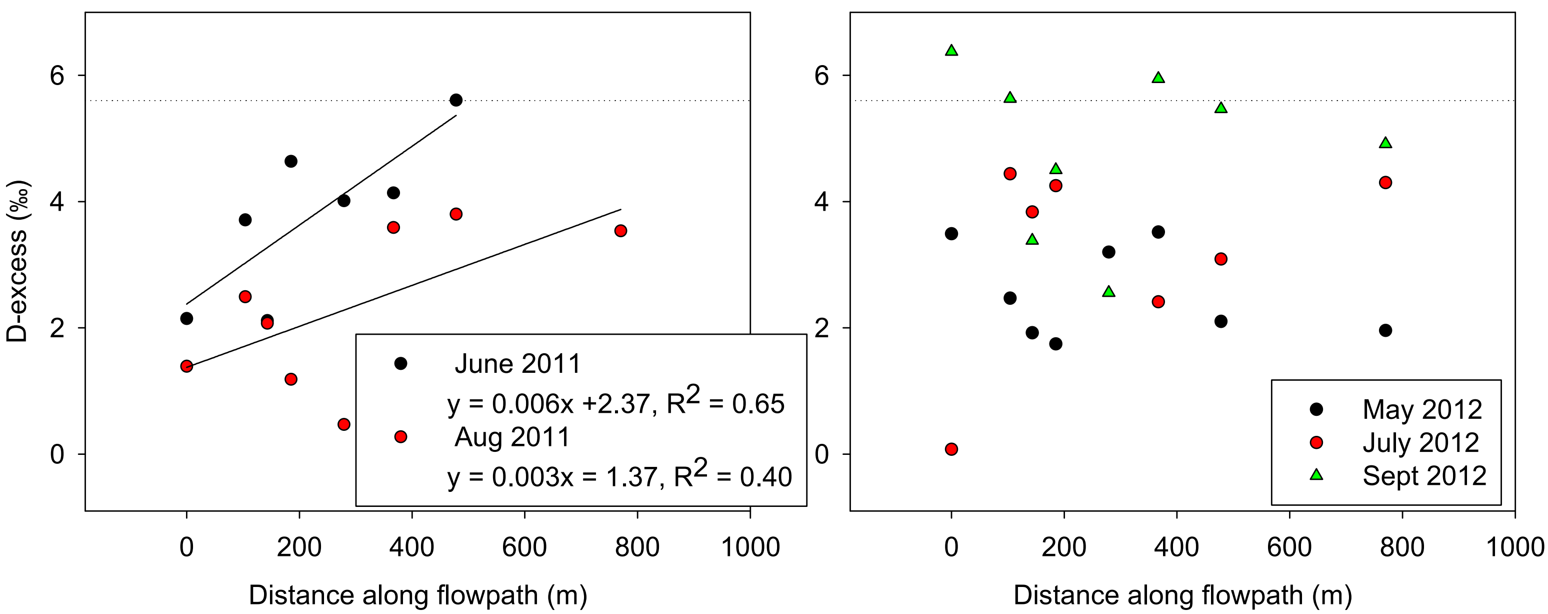


**Figure 3.11 D-excess for JPH fen, on the left is 2011 and on the right is 2012 representing surface water table wells. The dotted line represents weighted mean d-excess of Edmonton's local meteoric water line (Rozanski et al. 1993).**

*3.5.6 Fill and spill in the Boreal Plains and runoff*

In the Boreal Plains, underlying substrate and soil moisture is a large determining factor in whether potential overland flow occurs in the form of lateral flow or vertical recharge. Previous research has found that vertical flow will occur if soil moisture conditions are in a deficit and if underlying substrate permits it (Redding and Devito 2008).

However, vertical water movement is substantially limited in Boreal Plains wetlands with low hydraulic conductivity. In the wetlands observed at ML, differing responses during 2011 and 2012 are evidently related to antecedent moisture conditions. During low AMC, precipitation falling on the wetland is largely taken up into shallow subsurface storage in the acrotelm and little runoff may be observed. During moderate AMC conditions, precipitation is stored either in the shallow subsurface of the acrotelm or in partly filled depressions or hollows on the wetland and surface flow remains limited. During high AMC, precipitation input may exceed the storage capacity of both the acrotelm and surface depressions, and connections begin to form between surface pools which may eventually coalesce to form more extensive water tracks.

Displacement of older water by event precipitation is common in wetlands systems and has been observed through isotopic hydrograph separation techniques (Kværner and Kløve 2008). Lateral flow in peatland complexes can be explained through *fill* and *spill* hydrology as storage thresholds are met and water moves to the edges of the bog. *Fill* and *spill* usually is applied to a meso-scale such as a catchment with a chain of lakes

(Woo and Mielko 2007). However, these same basic concepts can be applied to a site specific/small scale hydrology especially when micro-topography is present.

Micro-topography can function as micro-catchments; each smaller area has specific peat characteristics such as specific yield and compressibility, and can alter the storativity threshold of that unit of peat (Price and Schlotzhaucer 1999; Waddington et al. 2010). On a small scale, Oswalt et al. (2011) found that micro-depressions defined as hydrological response units acted as areas of runoff when saturated following precipitation events. At ML, the differences in runoff responses for various terrain units are seen in the runoff estimates. With larger storativity and increased roughness the bogs appear to take longer to saturate. Once saturated, according to observations at ML and in previous studies (e.g. Oswalt et al. 2011), the micro-depressions or hollows will act as runoff areas. Runoff on the small scale becomes a key eco-hydrological link that helps move nutrients around at these nutrient limited sites.

*3.5.7 Implications to nitrogen movement in these ecosystems*

Based on our analysis of the runoff potential it appears water may be a significant conduit for nitrogen movement in large rain events and in times when the AMC is high. Comparison between the bog and fen shows that the bog will act as a sink for water but has the potential to transform into a source during large precipitation events. As well, during large precipitation events runoff from uplands is expected to occur and may bring new sources of nitrogen into the wetland. During a wet year, nitrogen species may be diluted as more surface flowpaths may connect adjacent hollows within the bog and fen. Yet, during a dry year, such as 2011, a runoff deficit may act to accumulate excess nitrogen species within hollows. Furthermore, in dry years when the storage thresholds are not exceeded, nitrogen is restricted to moving vertically within its unit of peat, and the accumulation of nitrogen is anticipated to follow the vertical hydraulic gradient.

From the d-excess evaluation, we would anticipate if a surplus of nitrogen was present, it would be moved slowly at the surface of the fen and most likely would be utilized along this flowpath, during drier conditions. We would also anticipate excess nitrogen to move into deeper flowpaths, as recharged signals were seen a depths, and may be an important mechanism to move nitrates (at the surface) and transform them to nitrites at depths, resulting in denitrification in anoxic conditions.

### *3.6 Summary*

Based on the working conceptual model of uplands-peatland systems in the region (see Chapter 1) we expect water near the surface of the mosaic Boreal Plains landscape to follow flowpaths from uplands to fens. We also expect that water near the surface of the bogs will flow out to the fens in high water table conditions. We found based on the VWB runoff potential, that the fen generally produced a larger runoff potential and therefore acted as a main conduit for runoff; however, the bog was active and more responsive during large precipitation events when the AMC and the water table were highest. The d-excess provided some supporting evidence of evaporation and evolution of connectivity along the general flowpath of water. However, it is important to note that a weak recharge signal was seen at deeper depths in piezometers along the flowpath. Therefore, the majority of water must exit these systems at the surface, and only a small amount of surface water infiltrate into depth along the flowpath.

The most significant insight resulting from this study relates to the roles within the mosaic, as these roles may transition from recharging to discharging depending on the inputs of the water balance. In wet hydrological years, the bog which for the most part is recharging may discharge water predominately via fill and spill of water in depressions and between hummocks. Transport of nitrogen along these pathways remains to be quantified but is thought to be small. In these nutrient-limited systems, any additional nitrogen is expected to be utilized by the ecosystem, but may be flushed out downstream under wetter conditions as influenced by high antecedent moisture, larger precipitation events, and seasonal frost tables which may limit storage thresholds.

Characterizing runoff potential for a catchment provides insight regarding where water is moving throughout the wetland at a fine scale. However, it does not provide much understanding of runoff of the catchment as a whole. Future work should also look at comparing a VWB with a gauged site and assess the differences in runoff from the VWB and discharge. The implications of this surficial vertical water balance, leaves much unknown below the surface. When runoff does not appear laterally, it must move below into the peat substrate and possibly recharge into shallow groundwater. In addition, the use of d-excess with more intensive transects would give more robust results on the connectivity and dynamics of the wetlands.

**4.0 Conclusion**

This research examined groundwater and surface water movement. The results recorded a mixing of shallow waters, seen through isotopes, which occurred mostly at the surface of the fen and were limited in the bog. This was in agreement with runoff within the acrotelm layer of the wetland. Mixing of shallow groundwater was also seen at JPH. However, lateral movement was difficult to quantify and runoff along the flowpath with isotopic signatures did not reveal strong quantitative results. Runoff in the bog was muted, until storage thresholds were met, then more dynamic fill and spill runoff channels developed joining depressions between peat hummocks and allowing substantial overland flow.

Groundwater recharge was minimal based on hydraulic conductivity, but hydrological regimes proved to be important, as dissimilar results were shown from wet years and dry years (ML: P6 discharging). As well, seasonal trends in water movement were difficult to see in ML. Shallow groundwater tended to flow towards the outflow (P17) or P13. At JPH a seasonal trend was vaguely visible with increased flow towards the rich fen from the uplands in early summer. Groundwater flow at JPH predominately followed the topography of this site, flowing northwest.

Based on the conceptual model from Chapter 1 the results confirmed some of the connections that were found in the literature. A revised conceptual model is shown below (Figure 4.1) with only the connections that were confirmed. In Chapter 2, the focus was on shallow groundwater. The results illustrate that in the fen deeper groundwater connections exist (ML: P17, P18), but were sporadic based on seasonality and hydrological regime (wet and dry) (Figure 4.1a). Our results suggest that surface water in the fen recharges subsurface water and potential groundwater in very small amounts due to low hydraulic conductivities at both sites (Figure 4.1a and b). Isotope depth profiles showed a mixing of shallow waters (Figure 4.1b) with an integrated signature around 2 to 3 m at both sites. Chapter 3 examined the surface of the fens and their connection to the bogs. Results indicated lateral movement of water from the bog to the fen in high antecedent moisture conditions (Figure 4.1c).

The d-excess shows active recharge of surface water in the fen at ML (Figure 4.1 b), and is in agreement with recharging vertical hydraulic gradients. And finally, adjacent uplands feed the wetlands in the spring and during wet years (seen at ML: P6) (Figure 4.1d). The results were unable to identify a recharging effect underneath the bog and any connection of fens feeding uplands. These results are constrained by the instrumentation of this study. Although a connection may not have been confirmed during the course of two years, it does not mean the connection does not exist.

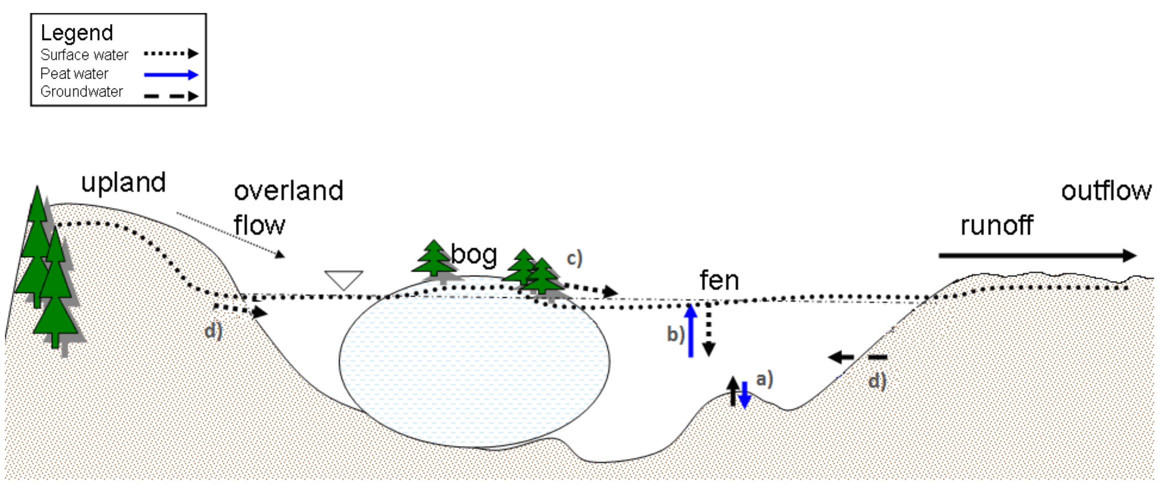

**Figure 4.1 Revised conceptual model of study sites. Arrows indicated the connections and directions of water flow. The wetland is comprised of the fen (in white) the bog (circle in blue) and the uplands and similar substrate are in brown.**

New studies are providing more comprehensive understanding of hydrological and biogeochemical processes occurring in the Boreal Plains region. Most studies have examined the movement of water within the landscape units of peat-pond complexes and uplands. Most studies have also focused on landscapes with the presence of aspen and outwashed plains. This study examined two landscapes where both aspen and a peat-pond complex were absent, rather focusing on landscapes units of uplands, fens, and bogs. Our research is in agreement with most of the previous findings in the area. This research builds more evidence that the largest lateral transfer of water within wetlands is near the surface. However, stable isotopes of water identified relatively enriched waters at depth within areas of the wetland indicating a downward movement of surface waters. New findings from our research suggest that wetlands do not necessarily feed uplands. We found minimal evidence that this could be a common occurrence in our study sites. Finally, this study highlights the importance of hydraulic conductivity of substrate within the Boreal Plains region, as an indicator for topographical driven shallow groundwater flow.

### *4.1 Significance to the project*

The common theme of sources and sinks for atmospheric nitrogen with respect to water was present in both previous chapters. Although we are unable to definitively state which terrain units will act as sources and sinks under different antecedent moisture conditions, it appears based on only flowpaths the bog may generally act as a sink for nitrogen. Unchanging isotopic signatures and consistent downward vertical hydraulic gradients show that the bog will retain its role as a sink for additional nitrogen even through changing wet and dry hydrological regimes. The fill and spill mechanism, a surface-focused process, may aid in the cycling of nutrients and nitrogen between different hummocks and hollows across the wetland.

*4.2 Limitations*

The findings from the work pertain mainly to the study sites examined. Limited work has been done to test whether relationships noted at specific sites are applicable to wider areas or on a regional basis. Although a key factor in the selection of the study sites was representativeness of the terrain in the overall Athabasca Oil Sands Region, the results of the study are associated with the specific properties of the site, such as land position, geology, and soil characteristics.

Due to budgetary, time limitations, and technical challenges, this research did not extensively examine the role of upland soils and geology at the ML site. This remains to be carried out. Notably, hydraulic conductivity of the ML's upland soil and the peat substrate need further analysis. This will identify where the zone of oxidation is, where the water table fluctuations occur, and if there is uniformity of upland substrate.

A large limitation of this study was the inability to properly gauge the two sites. Gauging sites was unsuccessful due to large variability's in runoff; 2011 was a dry year and 2012 was a wet year. Gauging small scale catchments in the Boreal plains area still is a large challenge. Future work should look at attempts to establish a more permanent weir.

*4.3 Future research*

One of the main findings of this research was the relative disconnection of terrain units at ML, specifically the uplands and the fen. Future work should examine why such a disconnection exists. The analysis should focus on the interface between the terrain units. Some of the recommendations for study of this interface would be the installation of lysimeters as well as seepage meters. The examination of lithology would greatly aid in filling this knowledge gap.

Runoff potentials from Chapter 3 are approximations that may be subject to measurement and human sampling error. In order to make these estimates more robust, it is recommended to set up a permanent heavy duty outflow gauge where discharge could be quantified, if such a location can be found. In addition, the implementation of a surface elevation meter would remove an error term from the runoff estimates from changes in the depth of the top of casing to the surface. Price (2003) highlighted that peat is highly compressive and effective stress may cause an increase in the depth of the top of the casing to the surface. The subsidence recorded by Price ranged between 2.5 to 7.2 cm. Changes in the surface elevation will be important in the understanding of lateral movement of water in the acrotelm.

In conclusion, this research attempts to give clarity to the movement of water within a typical Boreal Plains region. Water was found to move laterally in fens near the surface, experienced a storage threshold in bogs, and had limited connections to the uplands. Hydrological regimes of wet and dry in this region will be critical as to when wetlands terrains act as sources or sinks for additional nitrogen. In the scope of the AOSR, wetlands which comprised up to 75 % of the landscape are hydrologically important determinant as to how increased nitrogen loads will be utilized.

Continued development in the AOSR increases pressure on these terrains to absorb additional nitrogen. In an area dominated by nitrogen limited plant species, this seems feasible. Yet, when the landscape is saturated, the downstream lakes will likely be affected. It should be noted that in this area, some lakes may already be sensitive to acidification. Therefore, it is critical to continue examining the effects of development to understand the role of wetlands in absorbing and/or periodically transferring acidic inputs. Development, however, is just one factor affecting this region; the larger issue of climate change also poses many uncertainties to wetland hydrology and sustainability.

***References***

*Chapter 1*

Aldous, A.R. 2002. Nitrogen translocation in *Sphagnum* mosses: effects of atmospheric nitrogen deposition. *New Phytologist*, 156: 241-253.

Allen, E. 2004. *Effects of nitrogen deposition on forest and peatlands: A literature review and discussion of the potential impacts of nitrogen deposition in the Alberta Oil Sands Region*. Wood Buffalo Environmental Association, Fort McMurray, AB. <http://www.wbea.org/library/terrestrial-monitoring>. [accessed: Nov. 23, 2011].

Andriashek, L.D. and Meeks, J. 2001. Bedrock Topography, Drift Thickness and Buried Channels, Northeast Alberta. Geo 2000-01. Alberta Geological Survey. < http://www.ags.gov.ab.ca/publications/abstracts/GEO_2000_01.html> [accessed Apr. 17, 2013].

Andriashek, L.D. and Atkinson, N. 2007. Buried Channels and Glacial-Drift Aquifers in the Fort McMurray Region, Northeast Alberta. Earth Sciences Report 2007-01 Alberta Geological Survey. <http://www.ags.gov.ab.ca/publications/abstracts/ESR_2007_01.html> [accessed Apr. 17, 2013].

Barson, D., Bachu, S. and Esslinger, P. 2001. Flow systems in the Mannville group in the east-Central Athabasca area and implications for steam-assisted gravity drainage (SAGD) operations for in situ bitumen production. *Bulletin of Canadian Petroleum Geology*, 49: 376–392.

Bayrock, L.A. 2006. Surficial geology of the Bitumount area, Alberta. NTS 74E (GIS data, polygon features). Digital Data 2006-0046; Alberta Geological Survey. < http://www.ags.gov.ab.ca/publications/abstracts/DIG_2006_0046.html> [accessed: May 4, 2014].

Bougon, N., Auterives, C., Aquilina, L., Marmonier, P., Derrider, J. and Vanderkoornhuyse. P. 2011. Nitrate and sulphate dynamics in peat subjected to different hydrological conditions: batch experiments and field comparison. *Journal of Hydrology*, 411: 12-24.

Bowden, W.B. 1987. The biogeochemistry of nitrogen in freshwater wetlands. *Biogeochemistry*, 4: 313-348.

Bytnerowicz, A., Fraczek, W., Schilling, S., and Alexander, D. 2010. Spatial and temporal distribution of ambient nitric acid and ammonia in the Athabasca Oil Sands Region, Alberta. *Journal of Limnology*, 69: 11-21.

Carou, S., Dennis, I., Aherne, J., Ouimet, R., Arp, P.A., Watmough, S.A., DeMerchant, I., Shaw, M., Vet, B., Bouchet, V., and Moran, M. 2008. *A national picture of acid deposition critical loads for forest soils in Canada.* Canadian Council of Ministers of the Environment 2008. ISBN 978-1-896997-82- <http://www.ccme.ca/assets/pdf/national_picture_acid_deposition_pn1412.pdf > [accessed: Nov. 19, 2011].

Carroll, S.B. and Bliss, L.C. 1982. Jack pine – lichen woodland on sandy soils in northern Saskatchewan and northeastern Alberta. *Canadian Journal of Botany*, 60: 2270-2282.

CEMA. 2013. Air Quality Working Group. < http://cemaonline.ca/index.php/working-groups/awg > [accessed: Apr. 15, 2013].

CEMA. 2004. Acid Deposition Management Framework Recommendations. *Recommendations for the Acid Deposition Management Framework for the Oil Sands Region of North-Eastern Alberta.* <http://cemaonline.ca/index.php/administration/cat_view/2-communications/39-admf> [accessed:Sept. 27, 2013].

Chanasyk, D.S., Whitson, I.R., Mapfumo, E., Burke, J.M. and Prepas, E.E. 2003. The impact of forest harvest and wildfire on soils and hydrology in temperate forests: A baseline to develop hypotheses for the Boreal Plains. *Journal of Environmental Engineering and Sciences*, 2: S51- S62.

Cirmo, C.P. and McDonnell, J.J. 1997. Linking the hydrologic and biogeochemical controls of nitrogen transport in near-stream zones of temperate- forested catchments: a review. *Journal of Hydrology*, 199: 88-120.

Curtis, C.J., Flower, R., Rose, N. Shilland, J., Simpson, G.I., Turner, S., Yang, H., and Pla, S. 2010. Paleolimnological assessment of lake acidification and environmental change in the Athabasca Oil Sands Region, Alberta. *Journal of Limnology*, 69: 92-104.

Devito, K.J., Creed, I.F., Rothwell, R.L., Prepas, E.E. 2000. Landscape controls on phosphorus loading to boreal lakes: implications for the potential impacts of forest harvesting. *Canadian Journal of Fisheries and Aquatic Sciences*, 57: 1977-1984.

Devito, K., Creed,I., Gan, T., Mendoza, C., Petrone, R., Silins, U., and Smerdon, B. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrological Processes,* 19: 1705-1714.

Devito, K. Mendoza, C., Qualizza, C. 2012. Conceptualizing Water Movement in the Boreal Plains. *Implications for watershed reconstruction.* Synthesis report prepared for the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Research Group. 164 pp.

Ecological Stratification Working Group. 1996. A national ecological framework for Canada. Centre for Land and Biological Resources Research, Research Branch, Agriculture and Agri-food Canada, Ottawa, Ont.

Environment Canada. 2012. Canadian Normals and Averages 1971-2000; Fort McMurray Airport, Alberta. *National Climate Data and Information Archive*. <http://www.climate.weatheroffice.gc.ca/climate_normals> [accessed: Feb 21, 2012].

Eppinga, M.B., Rietkerk, M., Borren, W., Lapshina, E.D., Bleuten, W. and Wassen, M. J. 2008. Regular surface patterning of peatlands: confronting theory with field data. *Ecosystems*, 11: 520-536.

Fenton, M.M., Waters, E.J., Pawley, S.M., Atkinson, N., Utting, D.J. and McKay, K. 2013. Surficial Geology of Alberta. Map: 601. *Alberta Geological Survey.* <http://www.ags.gov.ab.ca/publications/abstracts/Map_601.html> [assessed: Arp. 17, 2013].

Ferone, J.M. and Devito, K.J. 2004. Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plain topographic gradient. *Journal of Hydrology*, 292: 75-95.

Fraser, C.J.D., Roulet, N.T. and Lafleur, M. 2001. Groundwater flow patterns in a large peatland. *Journal of Hydrology*, 246: 142-154.

Gibson, J.J., Price, J.S., Aravena, R. Fitzgerald, D.F. and Maloney, D. 2000. Runoff generation in a hypermaritime bog- forest upland. *Hydrological Processes*, 14: 2711- 2730.

Gibson, J.J., Birks, S.J., Jeffries, D.S., Kumar, S., Scott, K.A., Aherne, J. and Shaw, D.P. 2010. Site-specific estimates of water yield applied in regional acid sensitivity surveys across western Canada. *Journal of Limnology*, 69: 67-76. (a)

Gibson, J.J. Birks, J.S., Kumar, S., McEachern P.M., and Hazewinkel, R. 2010. Inter-annual variations in water yield to lakes in northeastern Alberta: implications for estimating critical loads of acidity. *Journal of Limnology*, 69: 126-134. (b)

Gorham, E., 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming .*Ecological Applications*, 1: 182-512.

Halsey, L.A., Vitt, D.H., Beilman, D., Crow, S., Mehelcic, S. and Wells, R. 2003. *Alberta Wetland Inventory Classification System Version 2.0*. Alberta Sustain able Resource Development.

Hayashi, M., van der Kamp, G., Rudolph, D.L. 1998. Water solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. *Journal of Hydrology*, 207: 42-55.

Hazewinkel, R.R.O., Wolfe, A.P., Pla, S., Curtis, C. and Hadley, K. 2008. Have atmospheric emissions from the Athabasca Oil Sands impacted lakes in northeastern Alberta, Canada? *Canadian Journal of Fisheries and Aquatic Sciences*, 65: 1554-1567.

Inamdar, S. 2007. Exports of dissolved ammonium (NH4+) during storm events across multiple catchments in a glaciated forested watershed. *Environmental Monitoring and Assessment*, 133: 347-363.

Jasechko, S., Gibson, J.J., Birks, S.J., and Yi.Y. 2012. Quantifying saline groundwater seepage to surface waters in the Athabasca oil sands region. *Applied Geochemistry*, 27: 2068-2076.

Macrae, M.L., Devito, K.J., Strack, M. and Waddington, J.M. 2012. Effect of water table drawdown on peatland nutrient dynamics: implications for climate change. *Biogeochemistry*, DOI 10.1007/s10533-012-9730-3

Morris P.L., Belyea L.R., and Baird A.J. 2011. Ecohydrological feedbacks in peatland development: a theoretical modelling study. *Journal of Ecology*, 99:1190-1201.

National Wetlands Working Group 1997. The Canadian Wetland Classification System: A Revision of the Wetlands of Canada. Edited by Barry G. Warner and Clayton D.A. Rubec. Wetlands Research Centre, University of Waterloo, ON.

Pawley, S.M. 2013. Surficial Geology of the Wabasca Area. NTS 84A/SW. (GIS data, polygon features) Digital Data 2013-0007; Alberta Geological Survey. <http://www.ags.gov.ab.ca/publications/abstracts/DIG_2013_0007.html > [accessed: May 3, 2014].

Pelster, D., Burke, J.M., Couling, K., Luke, S.H., Smith, D.W. and Prepas, E.E. 2008. Water and nutrient inputs, outputs, and storage in Canadian boreal forest wetlands: a review. *Journal of Environmental Engineering Sciences*, 7: S35-S50.

Petrone, K., Buffam, I. and Laudon, H. 2007. Hydrologic and biotic control of nitrogen export during snowmelt: A combined conservation and reactive tracer approach. *Water Resources Research*, 43: W06420, doi:10.1029/2006/WR005286.

Prepas, E.E., Burke, J.M., Whitson, I.R., Putz, G. and Smith, D.W. 2006. Associations between watershed characteristics, runoff, and stream water quality: hypothesis development for watershed disturbance experiments and modelling in the Forest Watershed and Riparian Disturbance (FORWARD) project. *Journal of Environmental Engineering Science*, 5: S27-S37.

Price, J.S., Branfireun, B.A., Waddington, J.M. and Devito, K.J. 2005. Advances in Canadian wetland hydrology, 1999-2003. *Hydrological Processes*, 19: 201- 214.

Proemse, B.C., Mayer, B., Fenn, M.E. and Ross, C.S. 2013. A multi-isotope approach for estimating industrial contributions to atmospheric nitrogen deposition in the Athabasca oil sands region in Alberta, Canada. *Environmental Pollution*, 182: 80-91.

Redding, T.E. and Devito, K.J. 2008. Lateral flow thresholds for aspen forested hillslopes on the Western Boreal Plans, Alberta, Canada. *Hydrological Processes,* 24:4287-4300.

Reeve, A.S., Siegel, D.I. and Glaser, P.H. 2000. Simulating vertical flow in large peatlands. *Journal of Hydrology*, 227: 207-217.

Reeve, A.S., Siegel, D.I. and Glaser, P.H. 2001. Simulating dispersive mixing in large peatlands. *Journal of Hydrology*, 242: 103-114.

Schindler, D.W., Dillon, P.J., and Schreier, H. 2006. A review of anthropogenic source of nitrogen and their effects on Canadian aquatic ecosystems. *Biogeochemistry,* 79: 25-44.

Schindler, D.W., and Lee, P.G.  2010. Comprehensive conservation planning to protect biodiversity and ecosystem services in Canadian boreal regions under a warming climate and increasing exploitation. *Biological Conservation*, 143: 1571-1586.

Siegel, D.I., Glaser, P.H. and Janecky, D.R. 2006. The dynamic balance between organic acids and circumneutral groundwater in a large boreal peat basin. *Journal of Hydrology*, 320: 421-431.

Turner, R.K., van der Bergh, J.C.J.M., Soderqvust, T., Barendregtm A., van der Straaten, J., Maltby, E. and van Ierland, E.C. 2000. Ecological-economic analysis of wetlands: scientific integration for management and policy. *Ecological Economic*, 35:7-23.

van der Kamp, G. and Hayashi, M. 2009. Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America. *Hydrogeology Journal,* 17: 203-214.

Vitt, D.H., Halsey, L.A., Campbell, C., Bayley, S.E. and Thormann, M.N. 2001. Spatial patterning of net primary production in wetlands of continental western Canada. *Ecoscience*, 8: 499-505.

Whitfield, C.J. Aherne, J., Cosby, B.J. and Watmough, S.A. 2010. boreal lake catchment response to anthropogenic acid deposition. *Journal of Limnology,* 69: 135-146.

Whitfield, C.J., Watmough, S.A. and Aherne, J. 2011. Evaluation of elemental depletion weathering rate estimation methods on acid-sensitive soils of north-eastern Alberta, Canada. *Geoderma*, 166: 189- 197.

Yan, E., Hu, Y., Salifu, F., Yan, X., Chen. Z.C., Chang, S. 2012. Effectiveness of soil N availability indices in predicting site productivity in the oil sands region of Alberta. Plant Soil. 359:215-231.

Zoltai, S.C. and Vitt, D.H. 1990. Holocene climatic change and the distribution of peatlands in western interior Canada. *Quaternary Research*, 33: 231-240.

*Chapter 2*

Andriashek, L.D. and Atkinson, N. 2007. Buried Channels and Glacial-Drift Aquifers in the Fort McMurray Region, Northeast Alberta. Earth Sciences Report 2007-01 Alberta Geological Survey. <http://www.ags.gov.ab.ca/publications/abstracts/ESR_2007_01.html> [accessed Apr. 17, 2013].

Baird, A.J., Surridge, B.W.J., Money, R.P. 2004. An assessment of the piezometer method for measuring the hydraulic conductivity of a *Cladium mariscus – Phragmites australis* root mat. *Hydrological Processes*, 18: 275-291.

Barr, A.G., van der Kamp, G., Black, T.A., McCaughey, J.H. and Nesic,Z. 2012. Energy balance closure at the BERM flux towers in relation to the water balance of the White Gull Creek watershed 1999-2009. *Agricultural and Forest Meteorology,* 153: 3-13.

Bennett, K.E., Gibson. J.J. and McEachern, P.M. 2008. Water-yield estimates for critical loadings assessment: comparison of gauging methods versus an isotopic approach. *Canadian Journal of Fisheries Aquatic Sciences*, 65: 83- 99.

Bowden, W.B. 1987. The biogeochemistry of nitrogen in freshwater wetlands. *Biogeochemistry,* 4: 313-348.

Clark, I., and Fritz, P. 1997. *Environmental isotopes in hydrology.*

Craig, H. 1961. Isotopic variations in meteoric waters. *Science*, 133: 1702-1703.

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus*, 16: 436- 468.

Devito, K., Creed,I., Gan, T., Mendoza, C., Petrone, R., Silins, U., and Smerdon, B. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plains: is topography the last thing to consider? *Hydrological Processes,* 19: 1705-1714.

Environment Canada. 2012. Canadian Normals and Averages 1971-2000; Fort McMurray Airport, Alberta. *National Climate Data and Information Archive*. <htp://www.climate.weatheroffice.gc.ca/climate_normals> [accessed: Feb 21, 2012].

Fetter, C.W. 2001. Applied Hydrogeology 4th ed. Prentice Hall, New Jersey. 124pp.

Fraser, C.J.D., Roulet, N.T. and Lafleur, M. 2001. Groundwater flow patterns in a large peatland. *Journal of Hydrology*, 246: 142-154.

Freeze, R.A. and Cherry J.S. 1979. Groundwater. Prentice Hall, Toronto.

Gat. J.R. 1996. Oxygen and hydrogen isotopes in the hydrological cycle. *Annual Review of Earth and Planetary Sciences*. 24:225-262.

Gibson, J.J., Edwards, T.W.D., Bursey, G.G. and Prowse, T.D. 1993 Estimating evaporation using stable isotopes: quantitative results and sensitivity analysis for two catchments in northern Canada. *Nordic Hydrology*, 24:79-94.

Gibson, J.J., Edwards, T.W.D., Birks, S.J., St. Amour, N.A., Buhay, W.M., McEachern, P., Wolfe, B.B. and Peters, D.L. 2005. Progress in isotopic tracer hydrology in Canada. *Hydrological Processes*, 19: 303-327.

Gibson, J.J., Birks, S.J., Jeffries, D.S., Kumar, S., Scott, K.A., Aherne, J., and Shaw, P.D. 2011. Site-specific estimates of water yield applied in regional acid sensitivity surveys across western Canada. *Journal of limnology,* 69: 67- 76.

Hackbarth, D.A. and N. Nastasa, 1979. *The Hydrogeology of the Athabasca Oil Sands Area, Alberta*. Alberta Research Council, Bulletin 38, Edmonton, Alberta.

Hayashi, M., van der Kamp, G., Rudolph, D.L. 1998. Water solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. *Journal of Hydrology*, 207: 42-55.

Hill, A.R. 2012. The impact of pipe flow in riparian peat deposits on nitrate transport and removal. *Hydrological Processes,* 26: 3135- 3146.

Holden, J., Burt, T. P., and Vilas, M. 2002. Application of ground-penetrating radar to the identification of subsurface piping in blanket peat. *Earth Surface Processes and Landforms,* 27: 235-249.

Holden, J., Chapman, P.J. and Labadz, J.C. 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography*, 28: 95-123.

Hvorslev, M.J. 1951. Time lag and soil permeability in groundwater observations. *Waterways Experimental Station Bulletin* 36, United States Army Corps of Engineers, Mississippi.

Ingram, H.A.P., 1978. Soil layers in mires: function and terminology. *Journal of Soil Sciences*, 29: 224–227.

Kettridge, N., Kellner, E., Price, J.S. and Waddington, J.M. 2013. Peat deformation and biogenic gas bubbles control seasonal variations in peat hydraulic conductivity. *Hydrological Processes*, 27: 3208-3216.

Kværner, J. and Kløve, B. 2008. Generation and regulation of summer runoff in a boreal flat fen. *Journal of Hydrology*, 360: 15-30.

Lee, P. and Boutin, S. 2006. Persistence and developmental transition of wide seismic lines in the western Boreal Plains of Canada. *Journal of Environmental Management*, 78: 240- 250.

Levy, Z.F., Siegel, D.L., Dasgupta, S.S., Glaser, P.H., Welker, J.M. 2013. Stable isotopes of water show deep seasonal recharge in northern bogs and fens. *Hydrological Processes*, DOI:10.1002/hyp.9983.

McEachern, P., Prepas, E.E. and Chanasyk, D.S. 2006. Landscape control of water chemistry in northern boreal streams of Alberta. *Journal of Hydrology*, 323: 303-324.

Morris, P.J., Waddington, J.M., Benscoter, B.W. and Turetsky, M.R. 2011. Conceptual frameworks in peatland ecohydrology: looking beyond the two-layered (acrotelm-catotelm) model. *Ecohydrology.* 4: 1-11.

Petrone, K., Buffam, I. and Laudon, H. 2007. Hydrologic and biotic control of nitrogen export during snowmelt: A combined conservation and reactive tracer approach. *Water Resources Research*, 43: W06420, doi:10.1029/2006/WR005286.

Price, J. 2003. The role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. *Water Resources Research*, 39: 1241, doi:10.1029/2002WR001302.

Quinton, W.L., Hayashi, M. and Carey, S.K. 2008. Peat hydraulic conductivity in cold regions and its relation to pore size and geometry. *Hydrological Processes*, 22: 2829- 2837.

Regina, K., Nykänen, H., Silvola, J. and Martikainen, P. J. 1996. Fluxes of nitrous oxides from boreal peatlands as affected by peatland type, water table level and nitrification capacity. *Biogeochemistry*, 35: 401-418.

Rozanski, R., Araguas-Araguas, L. and Gonfiantini, R. 1993. Isotopic Patterns in Modern Global Precipitation. In *Climate Change in Continental Isotopic Records*, Swart, P.K., Lohwan, K.L., McKenzie, J.A., Savin, S. (Ed.) *Geophysical Monograph*, 78:1-37. Washington DC, American Geophysical Union.

Schwärzel, K., Renger, M., Sauerbrey, R. Wessolek, G. 2002. Soil physical characteristics of peat soils. *Journal of Plant and Nutritional Soil Science*, 165: 479-486.

Smerdon, B.D., Devito, K.J., and Mendoza, C.A. 2005 Interactions of groundwater and shallow lakes on outwash sediments in the sub-humid Boreal Plains of Canada. *Journal of Hydrology,* 314: 246-262.

Surfer 8. Golden Software, Inc, 1993-2002.

Surridge, B.W.J., baird, A.J. and Heathwaite, A.L. 2005. Evaluating the quality of hydraulic conductivity estimates from piezometer slug tests in peat. *Hydrological Processes*, 19: 1227-1244.

Thomas, K.L., Price, D. and Lloyd, D. 1995. A comparison of different methods for the measurement of dissolved gas gradients in waterlogged peat cores. *Journal of Microbiological Methods*, 24:191-198.

van der Kamp, G. and Hayashi, M. 1998. The groundwater recharge function of small wetlands in the semi-arid northern prairies. *Great Plains Research*, 8: 39-56.

van der Kamp, G. and Hayashi, M. 2009. Groundwater- wetland ecosystem interaction in the semiarid glaciated plains of North America. *Hydrogeology Journal*, 17: 203-214.

Winter, T.C. 2001. The concept of hydrological landscapes. *Journal of the American Water Resources Association,* 37: 335-349.

Wray, H.E. and Bayley, S.E. 2007. Denitrification rates in marsh fringes and fens in two boreal peatlands in Alberta, Canada. *Wetlands*, 27: 1036-1045.

*Chapter 3*

Boudreau, L.D. and Rouse, W.R. 1995. The role of individual terrain units in the water balance of wetland tundra. *Climate Research*, 5: 31-47.

Bousfield, G. 2008. *Peakflow prediction using an antecedent precipitation index in small forested watersheds of the northern California coast range*. Humboldt State University. Masters of Sciences Thesis. 67pp.

Bowden, W.B. 1987. The biogeochemistry of nitrogen in freshwater wetlands. *Biogeochemistry*, 4: 313-348.

Brown, S.M., Petrone, R.M., Mendoza, C. and Devito, K.J. 2010. Surface vegetation controls on evapotranspiration from a sub-humid Western Boreal wetland. *Hydrological Processes,* 24: 1072-1085.

Chow, V.T., Maidment, D.R., and Mays, L.W. 1988. Applied Hydrology. McGraw-Hill Book Company, Toronto. 572 pp.

Craig, H. 1961. Isotopic variations in meteoric waters. *Science*, 133: 1702-1703.

Creed, I.F., Sass, G.Z., Wolniewicz, M.B. and Devito, K.J. 2008. Incorporating hydrologic dynamics into buffer strip design on the sub-humid Boreal Plains of Alberta. *Forest Ecology and Management*, 256: 1984-1994.

Devito, K., Creed,I., Gan, T., Mendoza, C., Petrone, R., Silins, U., and Smerdon, B. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrological Processes,* 19: 1705-1714.

Devito, K., Mendoza, C., Qualizza, C. 2012. *Conceptualizing water movement in the Boreal Plains. Implications for watershed reconstruction.* Synthesis report prepared for the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Research Group. 164 pp.

EcoRegion Working Group. 1989. Ecoclimatic Regions of Canada, First Approximation Ecological Land Classification Series, No. 23, Environment Canada, Ottawa 119p. Wiken, E.B. 1986. Terrestrial EcoZones of Canada, Ecological Land Classification Series No. 19. Lands Directorate, Environment Canada. 26p and map.

Environment Canada. 2012. Canadian Normals and Averages 1971-2000; Fort McMurray Airport, Alberta. *National Climate Data and Information Archive*. <http://www.climate.weatheroffice.gc.ca/climate_normals> [accessed: Feb 21, 2012].

Froehlich, K., Gibson, J.J., and Aggarwal, P., 2002. Deuterium excess in precipitation and its climatological significance. *Study of environmental change using isotope techniques*, C&S Papers Series 13/P, pp. 54-65, International Atomic Energy Agency, Vienna, Austria, ISBN 92-0-116402-5.

Gibson, J.J., Price, J.S., Aravena, R., Fitzgerald, D.F. and Maloney, D. 2000. Runoff generation in a hypermaritime bog-forest upland. *Hydrological Processes*, 14: 2711-2730.

Gibson, J.J., Birks, S.J., Kumar, S., McEachern, P.M., Hazewinkel, R. 2010. Inter-annual variations in water yield to lakes in northeastern Alberta: implications for estimating critical loads of acidity. *Journal of Limnology*, 69: 126-134.

Gorham, E. 1991. Northern peatlands: Role in the carbon cycle and probable response to climatic warming. *Ecological Applications*, 1: 182- 512.

Hayashi, M., Quinton, W. and Gibson, J. 1998. Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. *Journal of Hydrology*, 296: 81-97

Johnson A I, 1967. Specific yield – Compilation of specific yields for various materials. US Geological Survey Water Supply Paper 1662-D. 74pp.

Kimmel, K. and Mander, U. 2010. Ecosystem services of peatlands: implications for restoration. *Progress in Physical Geography,* 34: 491- 514.

Kusel, C. 2014. Baseline hydrogeochemistry and connectivity among landscape units of two wetland-rich Boreal sites in the Alberta oil sands region, Canada. Masters Thesis.

Kværner, J. and Kløve, B. 2006. Tracing sources of summer streamflow in boreal headwaters using isotopic signatures and water geochemical components. *Journal of Hydrology*, 331: 186-204.

Kværner, J. and Kløve, B. 2008. Generation and regulation of summer runoff in a boreal flat fen. *Journal of Hydrology*, 360: 15-30.

Laudon, H., Sjöblon, V., Buffam, I., Seibert, J. and Mörth, M. 2007. The role of catchment scale and landscape characteristics for runoff generation of boreal streams. *Journal of Hydrology*, 344:198-209.

Linsley, R.K., Kohler, M.A. and Paulhus, J.L.H. 1982. Hydrology for Engineers. McGraw Hill Book Company Inc. New York.

McEachern, P., Prepas, E.E. and Chanasyk, D.S. 2006. Landscape control of water chemistry in northern boreal streams of Alberta. *Journal of Hydrology*, 323: 303-324.

Oswald, C.J., Richardson, M. C. and Bransfireun, B.A. 2011. Water storage dynamics and runoff response of boreal shield headwater catchment. *Hydrological Processes,* 25: 3042- 3060.

Petrone, R.M., Devito, K.J., Silins, U., Mendoza, C., Brown, S.C., Kaufman, S.C. and Price, J.S. 2008. Transient peat properties in two pond-peatland complexes in the sub-humid Western Boreal Plains, Canada. *Mires and Peat,* 3: article 5: 1-13.

Petrone, K., Buffam, I. and Laudon, H. 2007. Hydrologic and biotic control of nitrogen export during snowmelt: A combined conservation and reactive tracer approach. *Water Resources Research*, 43: W06420, doi:10.1029/2006/WR005286.

Phillip, R.W., Spence, C. and Pomeroy, J.W.  2011. Connectivity and runoff dynamics in heterogeneous basins. *Hydrological Processes*, 25: 3061-3075.

Price, J.S. and Schlotzhauer, S.M. 1999. Importance of shrinking and compression in determining water storage changes in peat: the case of a mined peatland. *Hydrological Processes*, 13: 2591- 2601.

Price, J.S. 2003. Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. Water Resources Research, 39: 1241-1251.

Prepas, E.E., Burke, J.M., Whitson, I.R., Putz, G. and Smith, D.W. Associations between watershed characteristics, runoff, and stream water quality: hypothesis development for watershed disturbance experiments and modelling on the Forest Watershed and Riperain Disturbance (FORWARD) project. *Journal of Environmental Engineering and Sciences*, 5: S27- S37.

Priestley-Taylor CHB, Taylor RJ, 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, 100: 81-92.

Quinton, W.L. and Roulet, N.T. 1998. Spring and summer runoff hydrology of a subarctic patterned wetland. *Arctic and Alpine Research*, 30: 285-294.

Quinton, W.L., Hayashi, M. and Carey, S.K. 2008. Peat hydraulic conductivity in cold regions and its relation to pore size and geometry. *Hydrological Processes*, 22: 2829- 2837.

Redding, T.E. and Devito, K.J. 2008. Lateral flow thresholds for aspen forested hillslopes on the Western Boreal Plans, Alberta, Canada. *Hydrological Processes,* 24:4287-4300.

Richardson, M., Ketchesopn. S., Whittington. P. and Price, J. 2012. Influence of catchment geomorphology and scale on runoff generation in northern peatland complex. *Hydrological Processes*, 26: 1805- 1817.

Shook, K.R. and Pomeroy, J.W. 2011. Memory effects of depression storage in Northern Prairie hydrology. *Hydrological Processes,* 25: 3890-3898.

Spence, C. A. 2010. Paradigm shift in hydrology: storage thresholds across scales influence catchment runoff generation. *Geography Compass*, 4: 819-833.

Spence, C., Guan, X.J. and Phillips, R. 2011. The hydrological functions of a boreal wetlands-dominated basin. *Journal of Hydrology,* 319:15-35.

Su, W., Stolte, W.J., van der Kamp, G. 2000. Modelling Canadian prairie wetland hydrology using a semi-distributed streamflow model*. Hydrological Processes*, 14: 2405-2422.

Tardif, S. St-Hilaire, A., Roy,R., Bernier, M., Payette, S. 2009. Statistical properties of hydrographs in minertrophic fens and small lakes in mid-latitude Quebec, Canada. *Canadian Water Resources Journal*, 34: 365-380.

Tattrie, K. 2011. *Groundwater surface water interactions in a wetlands rich, low relief Boreal environment*. University of Victoria. Masters Thesis. .80pp.

van der Kamp, G. and Hayashi, M. 2009. Groundwater- wetland ecosystem interaction in the semiarid glaciated plains of North America. *Hydrogeology Journal*, 17: 203-214.

Vitt, D.H., Halsey, L.A., Campbell, C., Bayley, S.E. and Thormann, M.N. 2001. Spatial patterning of net primary production in wetlands of continental western Canada. *Ecoscience,* 8: 499-505.

Waddington, M., Kellner, E., Strack, M. and Price, J.S. 2010. Differential peat deformation, compressibility, and water storage between peatland microforms: implications for ecosystem function and development. *Water Resources Research*, 46: W07538, doi:10.1029/2009WR008802.

Whitfield, C.J., Aherne, J., Watmough, S.A. and McDonald, M. 2010a. Estimating the sensitivity of forest soils to acid depositions in the Athabasca Oil Sands Region, Alberta. *Journal of Limnology,* 69: 201-208.

Whitfield, C.J., Aherne, J., Gibson, J.J., Seabert, T.A. and Watmough, S.A. 2010b. The controls on boreal peatland surface water chemistry in Northern Alberta, Canada. *Hydrological Processes*, 24: 2143-2155.

Winter T.C., Rosenberry, D.O., and Sturrock A.M. 1995. Evaluation of 11 equations for determining evaporation for a small lake in north central United States. *Water Resource Research*, 31: 983-993.

Woo, M.K. 2012. Chapter 8 Northern Wetlands *in Permafrost Hydrology*. Springer-Verlag Berlin Heidelberg, DOI 10.1007/978-3-642-23462-0_8.

Woo, M.K., Mielko, C. 2007. An integrated framework of lakes-stream connectivity for a semi-arid subarctic environment. *Hydrological Processes*, 21: 2668-2674.

Zoltai, S.C. and Vitt, D.H. 1995. Canadian wetlands: Environmental gradients and classification. *Vegetatio*, 118: 131-137.

**Appendix 1 Hydraulic Conductivity**

# JPH 2012

| | | | OD | ID | Screen Interval | | | |
|---|---|---|---|---|---|---|---|---|
| well site | well type | t37 | R | r | Le | K | K | |
| | | s | m | m | m | m/s | m/d | cm/s |
| JPH 1A | steel | 38.7861 | 0.02863 | 0.012 | 0.085 | 2.37654E-05 | 0.205332818 | 2.38E-03 |
| JPH 1B | steel | 11.58802 | 0.02863 | 0.012 | 0.085 | 7.95447E-05 | 0.687266521 | 7.95E-03 |
| JPH 2A | steel | 20.29086 | 0.02863 | 0.012 | 0.085 | 4.54276E-05 | 0.392494866 | 4.54E-03 |
| JPH 2B | steel | 44.5853 | 0.02863 | 0.012 | 0.085 | 2.06742E-05 | 0.178625215 | 2.07E-03 |
| JPH 4B | steel | 22.05388 | 0.02863 | 0.012 | 0.085 | 4.17961E-05 | 0.361118289 | 4.18E-03 |
| JPH7A | steel | 12.79604 | 0.02863 | 0.012 | 0.085 | 7.20353E-05 | 0.622384716 | 7.20E-03 |
| JPH7B | steel | 43.39329 | 0.02863 | 0.012 | 0.085 | 2.12421E-05 | 0.183532041 | 2.12E-03 |
| JPH8A | steel | 102.5002 | 0.02863 | 0.012 | 0.085 | 8.99282E-06 | 0.077697963 | 8.99E-04 |
| JPH8B | steel | | 0.02863 | 0.012 | 0.15 | #DIV/0! | #DIV/0! | #DIV/0! |
| JPH8C | steel | 43.60756 | 0.04216 | 0.03505 | 0.11 | 0.000122804 | 1.061030333 | 1.23E-02 |
| JPH9A | steel | 110.4725 | 0.02863 | 0.012 | 0.085 | 8.34385E-06 | 0.072090894 | 8.34E-04 |
| JPH9B | steel | 397.7009 | 0.02667 | 0.012 | 0.15 | 2.0845E-06 | 0.018010048 | 2.08E-04 |
| JPH9C | steel | 44.5853 | 0.04216 | 0.03505 | 0.11 | 0.000120111 | 1.037762124 | 1.20E-02 |
| JPH10A | steel | | 0.02863 | 0.012 | 0.085 | #DIV/0! | #DIV/0! | #DIV/0! |
| JPH10B | steel | 93.79738 | 0.02667 | 0.012 | 0.15 | 8.83826E-06 | 0.076362602 | 8.84E-04 |
| JPH10C | steel | 50.46966 | 0.02667 | 0.012 | 0.15 | 1.64258E-05 | 0.141919172 | 1.64E-03 |

| Piezometer Tip | OD | ID | Screen Interval | OD | ID | Screen Interval |
|---|---|---|---|---|---|---|
| | mm | mm | mm | m | m | m |
| 1-1/4-inch PVC Jumbo Tip | 42.16 | 32.46 | 110 | 0.04216 | 0.03246 | 0.11 |
| 3/4-inch PVC Tip | 26.67 | 18.85 | 150 | 0.02667 | 0.01885 | 0.15 |
| 3/4-inch SS Tip | 28.63 | 21 | 85 | 0.02863 | 0.021 | 0.085 |
| 5/8x1/2-inch PE Liner | 16 | 12 | - | 0.016 | 0.012 | |
| 1-1/4-inch PVC Schd 40 Stand Pipe | 42.16 | 35.05 | - | 0.04216 | 0.03505 | |

# ML 2011

| wells | well type | t37 | OD R | ID r | screen interval Le | K | K |
|---|---|---|---|---|---|---|---|
| | | s | m | m | m | m/s | m/d |
| ML4B | pvc | 1242815.34 | 0.04216 | 0.03246 | 0.11 | 3.69564E-09 | 3.19304E-05 |
| ML4C | pvc | 99425.23 | 0.04216 | 0.03246 | 0.11 | 4.61956E-08 | 0.00039913 |
| ML10B | steel | 3314.17 | 0.02667 | 0.012 | 0.15 | 2.5014E-07 | 0.002161208 |
| ML10C | pvc | 4971.26 | 0.04216 | 0.03246 | 0.11 | 9.23911E-07 | 0.007982592 |
| ML16B | steel | 659367.47 | 0.02667 | 0.012 | 0.15 | 1.25727E-09 | 1.08629E-05 |
| ML16C | pvc | 165708.71 | 0.04216 | 0.03246 | 0.11 | 2.77173E-08 | 0.000239478 |
| ML17B | steel | 4971.261 | 0.02667 | 0.012 | 0.15 | 1.6676E-07 | 0.001440804 |
| ML17C | pvc | 165708.71 | 0.04216 | 0.03246 | 0.11 | 2.77173E-08 | 0.000239478 |
| ML18B | steel | 16570.87 | 0.02667 | 0.012 | 0.15 | 5.00279E-08 | 0.000432241 |
| ML18C | pvc | 142036 | 0.04216 | 0.03246 | 0.11 | 3.23369E-08 | 0.000279391 |
| ML19A | steel | 142036.04 | 0.02667 | 0.012 | 0.15 | 5.83659E-09 | 5.04281E-05 |
| ML19B | pvc | 12428.15 | 0.04216 | 0.03246 | 0.11 | 3.69565E-07 | 0.003193038 |

| Piezometer Tip | OD | ID | Screen Interval | OD | ID | Screen Interval |
|---|---|---|---|---|---|---|
| | mm | mm | mm | m | m | m |
| 1-1/4-inch PVC Jumbo Tip | 42.16 | 32.46 | 110 | 0.04216 | 0.03246 | 0.11 |
| 3/4-inch PVC Tip | 26.67 | 18.85 | 150 | 0.02667 | 0.01885 | 0.15 |
| 3/4-inch SS Tip | 28.63 | 21 | 85 | 0.02863 | 0.021 | 0.085 |
| 5/8x1/2-inch PE Liner | 16 | 12 | - | 0.016 | 0.012 | |
| 1-1/4-inch PVC Schd 40 Stand Pipe | 42.16 | 35.05 | - | 0.04216 | 0.03505 | |

# ML 2012

| | | | OD | ID | screen interval | | | |
|---|---|---|---|---|---|---|---|---|
| wells | well type | t37 | R | r | Le | K | K | K |
| | | s | m | m | m | m/s | m/d | cm/s |
| ML4B | pvc | 1242815.34 | 0.04216 | 0.03246 | 0.11 | 3.69564E-09 | 3.19304E-05 | 3.69564E-07 |
| ML4C | pvc | 33141.74 | 0.04216 | 0.03246 | 0.11 | 1.38587E-07 | 0.001197389 | 1.38587E-05 |
| ML6A | steel | 1.10E+06 | 0.02667 | 0.012 | 0.15 | 7.54365E-10 | 6.51771E-06 | 7.54365E-08 |
| ML6B | steel | 5.49E+05 | 0.02667 | 0.012 | 0.15 | 1.50873E-09 | 1.30354E-05 | 1.50873E-07 |
| ML10B | steel | 33141.74 | 0.02667 | 0.012 | 0.15 | 2.5014E-08 | 0.000216121 | 2.5014E-06 |
| ML10C | pvc | 24856.31 | 0.04216 | 0.03246 | 0.11 | 1.84782E-07 | 0.001596518 | 1.84782E-05 |
| ML16B | steel | 549472.89 | 0.02667 | 0.012 | 0.15 | 1.50873E-09 | 1.30354E-05 | 1.50873E-07 |
| ML16C | pvc | 99425.23 | 0.04216 | 0.03246 | 0.11 | 4.61956E-08 | 0.00039913 | 4.61956E-06 |
| ML17B | steel | 198850.45 | 0.02667 | 0.012 | 0.15 | 4.16899E-09 | 3.60201E-05 | 4.16899E-07 |
| ML17C | pvc | 24856.31 | 0.04216 | 0.03246 | 0.11 | 1.84782E-07 | 0.001596518 | 1.84782E-05 |
| ML18B | steel | 16570.87 | 0.02667 | 0.012 | 0.15 | 5.00279E-08 | 0.000432241 | 5.00279E-06 |
| ML18C | pvc | 2485.6307 | 0.04216 | 0.03246 | 0.11 | 1.84782E-06 | 0.015965184 | 0.000184782 |
| ML19A | steel | 110472.47 | 0.02667 | 0.012 | 0.15 | 7.50419E-09 | 6.48362E-05 | 7.50419E-07 |
| ML19B | pvc | 49712.614 | 0.04216 | 0.03246 | 0.11 | 9.23911E-08 | 0.000798259 | 9.23911E-06 |

| Piezometer Tip | OD | ID | Screen Interval | OD | ID | Screen Interval |
|---|---|---|---|---|---|---|
| | mm | mm | mm | m | m | m |
| 1-1/4-inch PVC Jumbo Tip | 42.16 | 32.46 | 110 | 0.0422 | 0.03246 | 0.11 |
| 3/4-inch PVC Tip | 26.67 | 18.85 | 150 | 0.0267 | 0.01885 | 0.15 |
| 3/4-inch SS Tip | 28.63 | 21 | 85 | 0.0286 | 0.021 | 0.085 |
| 5/8x1/2-inch PE Liner | 16 | 12 | - | 0.016 | 0.012 | |
| 1-1/4-inch PVC Schd 40 Stand Pipe | 42.16 | 35.05 | - | 0.0422 | 0.03505 | |

**Appendix 2 Hydraulic Head**

# JPH Hydraulic Head (m)

| | Water Table Wells | | | | | | |
|---|---|---|---|---|---|---|---|
| Date | JPH A | JPH B | JPH C | JPH D | JPH E | JPH F | JPH G |
| July-01-11 | 333.63 | 332.60 | 331.38 | 332.78 | 331.20 | 329.87 | 327.47 |
| August-07-11 | 331.89 | 330.59 | 329.09 | 330.43 | 329.33 | 328.77 | 326.13 |
| August-24-11 | 330.31 | 329.74 | 328.18 | 329.36 | 328.55 | 328.21 | 327.08 |
| October-04-11 | 330.29 | 329.72 | 328.04 | 328.95 | 328.23 | 328.21 | 326.39 |
| May-25-12 | 330.44 | 330.01 | 329.49 | 330.49 | 330.03 | 328.67 | 328.53 |
| June-06-12 | 330.41 | 329.74 | 328.71 | 329.61 | 329.32 | 328.41 | 327.85 |
| July-17-12 | 334.58 | 334.36 | 332.68 | 333.88 | 332.76 | 331.67 | 330.84 |
| August-03-12 | 334.60 | 334.29 | 332.82 | 333.98 | 332.90 | 332.18 | |
| September-02-12 | 332.70 | 332.73 | 331.44 | 332.58 | 331.54 | 330.43 | |
| September-12-12 | 335.10 | 334.85 | 333.19 | 334.06 | 332.76 | 332.58 | |

| | Shallow wells ~ 2 m | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | P1C | P2C | P3C | P4C | P5C | P6C | P7C | P8C | P9C | P10C | P11C | P12C |
| July-01-11 | 333.03 | 333.04 | 335.71 | 332.23 | 334.35 | 332.28 | 334.37 | 332.70 | 332.63 | 331.61 | 333.42 | |
| August-07-11 | 333.10 | 333.01 | - | 332.39 | - | 332.31 | - | 332.70 | 332.62 | 331.89 | - | |
| August-24-11 | 333.04 | 332.91 | 332.61 | 332.36 | 332.02 | 332.28 | 332.55 | 333.19 | 332.48 | 331.80 | 333.47 | |
| October-04-11 | - | - | - | 332.21 | - | - | - | 333.12 | 332.43 | 331.74 | - | |
| May-25-12 | 332.97 | 332.91 | 332.81 | 332.48 | 331.81 | 332.39 | 332.57 | 333.36 | 332.62 | 331.92 | 333.46 | |
| June-06-12 | 333.12 | 333.00 | 332.76 | 332.46 | 332.29 | 332.42 | 332.57 | 333.25 | 332.53 | 331.85 | 333.56 | |
| July-17-12 | 333.15 | 333.04 | 332.67 | 332.55 | 331.99 | 332.40 | 332.66 | 333.63 | 332.90 | 332.06 | 333.56 | |
| August-03-12 | - | 333.06 | - | 332.55 | - | 332.40 | 332.41 | 333.65 | 332.98 | 332.22 | 333.29 | 331.63 |
| September-02-12 | 332.98 | 332.91 | 332.71 | 332.35 | 332.01 | 332.30 | 332.48 | 333.62 | 333.01 | 332.16 | 333.36 | 331.57 |
| September-12-12 | 332.98 | 333.18 | 332.71 | 332.56 | 332.01 | 332.49 | 332.41 | 333.70 | 333.11 | 332.27 | 333.56 | 331.69 |

| Date | Intermediate wells ~ 4 m | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | P1B | P2B | P3B | P4B | P5B | P6B | P7B | P8B | P9B | P10B | P11B |
| July-01-11 | 334.66 | 334.54 | 335.71 | 335.18 | 334.32 | 332.28 | 332.64 | 333.23 | 331.84 | 331.58 | 333.35 |
| August-07-11 | - | - | - | 335.40 | - | 332.33 | 332.59 | 333.17 | 331.84 | 331.86 | 333.57 |
| August-24-11 | 333.05 | 332.99 | 332.67 | 332.42 | 332.04 | 332.28 | 332.54 | 333.06 | 332.52 | 331.82 | 333.53 |
| October-04-11 | 332.88 | 332.86 | 332.57 | 332.27 | 331.88 | 332.12 | 332.37 | 332.91 | 332.37 | 331.66 | 333.43 |
| May-25-12 | 333.00 | 333.94 | 332.65 | 332.27 | 333.01 | | 332.48 | 333.11 | 332.63 | 331.83 | 333.50 |
| June-06-12 | 333.03 | 333.00 | 332.67 | 332.27 | 332.03 | 332.39 | 332.46 | 334.02 | 332.51 | 331.84 | 333.51 |
| July-17-12 | 333.14 | 333.08 | 332.82 | 332.44 | 332.19 | 332.42 | 332.68 | 333.27 | 332.76 | 332.05 | 333.63 |
| August-03-12 | - | - | - | 332.46 | - | 332.40 | 332.66 | 333.27 | 332.78 | 332.07 | 333.63 |
| September-02-12 | 332.98 | 332.87 | 332.60 | 332.32 | 332.04 | 332.22 | 332.51 | 333.34 | 332.80 | 331.96 | 333.51 |
| September-12-12 | 333.28 | 333.11 | 332.73 | 332.46 | 332.15 | 332.51 | 332.82 | 333.53 | 332.97 | 332.17 | 333.75 |

| Date | Deep wells ~ 6 m | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | P1A | P2A | P3A | P4A | P5A | P6A | P7A | P8A | P9A | P10A | P11A |
| July-01-11 | 333.06 | 332.94 | 335.71 | 332.16 | 332.11 | 332.23 | 332.63 | 333.23 | 330.46 | 331.60 | 333.33 |
| August-07-11 | 333.12 | 332.95 | - | 332.35 | 332.03 | 332.26 | 332.57 | 333.12 | 332.62 | 331.87 | 333.55 |
| August-24-11 | 333.05 | 332.90 | 332.64 | 332.32 | 331.73 | 332.24 | 332.53 | 333.01 | 332.52 | 331.80 | 333.53 |
| October-04-11 | 332.94 | 332.81 | 332.51 | 332.24 | 331.92 | 332.09 | 332.36 | 332.91 | 332.43 | 331.71 | 333.43 |
| May-25-12 | 332.99 | 332.84 | 332.63 | 332.15 | 331.96 | 332.32 | 332.48 | 333.05 | 332.66 | 331.84 | 333.48 |
| June-06-12 | 332.97 | 332.84 | 332.60 | 332.10 | 331.94 | 332.19 | 332.44 | 332.87 | 332.50 | 331.79 | 333.47 |
| July-17-12 | 333.16 | 333.02 | 332.76 | 332.01 | 332.17 | 332.38 | 332.67 | 333.22 | 332.71 | 332.04 | 333.63 |
| August-03-12 | 333.15 | 333.01 | 332.76 | 332.46 | 332.13 | 332.37 | 332.65 | 333.21 | 332.78 | 332.06 | 333.62 |
| September-02-12 | 333.00 | 332.87 | 332.63 | 332.05 | 332.00 | 332.22 | 332.50 | 333.29 | 332.79 | 331.95 | 333.50 |
| September-12-12 | 333.30 | 333.12 | 332.77 | 332.05 | 332.21 | 332.48 | 332.80 | 333.48 | 332.98 | 332.16 | 333.74 |

| well | LiDAR elevation (m) | Depth BGL (m) | screen elevation (m) |
|---|---|---|---|
| MLP01A | 701.00 | 2.12 | 698.88 |
| MLP01B | 701.00 | 0.80 | 700.20 |
| MLP02A | 703.06 | 4.17 | 698.89 |
| MLP02B | 703.06 | 1.35 | 701.71 |
| MLP03A | 699.45 | 2.82 | 696.63 |
| MLP03B | 699.45 | 1.13 | 698.32 |
| MLP04A | 699.08 | 4.70 | 694.38 |
| MLP04B | 699.08 | 2.79 | 696.29 |
| MLP04C | 699.08 | 1.59 | 697.49 |
| MLP05A | 699.13 | 6.89 | 692.24 |
| MLP05B | 699.13 | 4.56 | 694.57 |
| MLP05C | 699.13 | 3.02 | 696.11 |
| MLP05D | 699.13 | 1.61 | 697.52 |
| MLP06A | 699.10 | 2.22 | 696.88 |
| MLP06B | 699.10 | 1.45 | 697.65 |
| MLP07A | 701.21 | 4.44 | 696.77 |
| MLP07B | 701.21 | 1.40 | 699.81 |
| MLP08A | 699.25 | 2.95 | 696.30 |
| MLP08B | 699.25 | 1.50 | 697.75 |
| MLP09A | 699.13 | 3.02 | 696.11 |
| MLP09B | 699.13 | 1.39 | 697.74 |
| MLP10A | 699.29 | 7.61 | 691.68 |
| MLP10B | 699.29 | 3.23 | 696.06 |
| MLP10C | 699.29 | 1.70 | 697.59 |
| MLP11A | 699.09 | 7.76 | 691.33 |
| MLP11B | 699.09 | 4.74 | 694.35 |
| MLP11C | 699.09 | 1.83 | 697.26 |
| MLP12A | 699.04 | 3.10 | 695.94 |
| MLP12B | 699.04 | 1.86 | 697.18 |
| MLP13A | 699.28 | 2.95 | 696.33 |
| MLP13B | 699.28 | 1.28 | 698.00 |

| water table wells | LiDAR elevation (m) |
|---|---|
| MLA | 698.94 |
| MLB | 698.98 |
| MLC | 699.12 |
| MLD | 699.03 |
| MLE | 698.94 |
| MLF | 699.25 |
| MLH | 699.12 |
| MLG | 698.71 |
| MLM | 698.90 |
| MLN | 699.07 |
| MLO | 699.28 |
| MLP | 699.33 |
| MLQ | 699.01 |
| MLR | 699.04 |
| MLS | 699.15 |
| MLT | 699.14 |
| MLU | 699.11 |
| MLV | 699.42 |

| | | | |
|---|---|---|---|
| MLP14A | 700.78 | 2.17 | 698.61 |
| MLP14B | 700.78 | 0.92 | 699.86 |
| MLP15A | 698.97 | 7.64 | 691.33 |
| MLP15B | 698.97 | 3.68 | 695.29 |
| MLP15C | 698.97 | 1.44 | 697.53 |
| MLP16A | 698.78 | 6.74 | 692.04 |
| MLP16B | 698.78 | 2.91 | 695.87 |
| MLP16C | 698.78 | 1.60 | 697.18 |
| MLP17A | 698.79 | 4.55 | 694.24 |
| MLP17B | 698.79 | 2.50 | 696.29 |
| MLP17C | 698.79 | 1.16 | 697.63 |
| MLP18A | 698.96 | 5.04 | 693.92 |
| MLP18B | 698.96 | 3.00 | 695.96 |
| MLP18C | 698.96 | 1.75 | 697.21 |
| MLP19A | 699.08 | 3.68 | 695.40 |
| MLP19B | 699.08 | 1.44 | 697.64 |

## ML Hydraulic Head (m)

| | Water Table Wells | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date | MLA | MLB | MLC | MLD | MLE | MLF | MLG | MLH | MLM |
| July-01-11 | 698.87 | 698.84 | 698.98 | 698.95 | 698.85 | 699.09 | 698.65 | 699.03 | 698.81 |
| August-07-11 | 698.89 | 698.82 | 698.96 | 698.96 | 698.85 | 699.05 | 698.67 | 699.08 | 698.78 |
| August-28-11 | 699.06 | | 698.87 | 698.91 | 698.81 | 699.02 | 698.81 | | 698.73 |
| October-04-11 | | | 698.83 | 698.86 | 698.76 | | | | |
| June-07-12 | | 698.98 | 699.12 | 698.97 | 698.88 | 699.09 | 698.88 | 699.12 | 698.78 |
| July-17-12 | 699.01 | 698.89 | 699.04 | 698.95 | 698.86 | 699.09 | 698.91 | 699.02 | 698.76 |
| August-04-12 | 699.08 | 698.96 | 699.10 | 699.01 | 698.93 | 699.15 | | | 698.82 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| September-08-12 | 699.12 | 699.01 | 699.15 | | 698.97 | 699.22 | 698.77 | | 698.89 |

| | Water Table Wells | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date | MLN | MLO | MLP | MLQ | MLR | MLS | MLT | MLU | MLV |
| July-01-11 | 698.95 | 699.12 | 699.19 | 698.93 | 698.98 | 699.04 | 699.13 | 698.99 | 699.23 |
| August-07-11 | 698.93 | 699.09 | 699.14 | 698.92 | 698.96 | 699.01 | 699.11 | 698.96 | 699.20 |
| August-28-11 | 698.87 | 699.05 | 699.10 | 698.74 | 698.90 | 698.95 | 699.06 | 698.90 | 699.15 |
| October-04-11 | 698.81 | 699.01 | 699.05 | 698.68 | 698.85 | 698.89 | 699.01 | 698.86 | 699.09 |
| June-07-12 | 698.94 | 698.99 | 699.15 | 698.93 | 698.95 | 699.01 | 699.21 | 698.98 | 699.20 |
| July-17-12 | 698.93 | 699.12 | 699.14 | | 698.95 | 699.00 | 699.14 | 698.96 | 699.20 |
| August-04-12 | 699.01 | 699.17 | 699.22 | | 699.02 | 699.07 | 699.21 | 699.03 | 699.26 |
| September-08-12 | 699.05 | 699.23 | 699.28 | 699.01 | 699.07 | 699.14 | 699.23 | 699.07 | 699.32 |

| | Shallow wells ~ 2 m | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | P1B | P2B | P3B | P4C | P5C | P5D | P6B | P7B | P8B | P9B |
| July-01-11 | 700.45 | 702.32 | | 698.81 | 699.01 | 698.72 | | | 699.00 | 698.90 |
| August-07-11 | 700.43 | 702.84 | 699.21 | 697.63 | 696.23 | 697.61 | 697.68 | | 697.96 | 697.87 |
| August-28-11 | 700.77 | 701.93 | 698.56 | 698.94 | 699.01 | 699.04 | 699.07 | | 699.04 | 699.00 |
| October-04-11 | 700.73 | 701.82 | 698.37 | 698.93 | 698.98 | 699.02 | 698.22 | | 699.04 | 698.98 |
| June-07-12 | 700.81 | 702.00 | 698.80 | 698.89 | 698.95 | 698.98 | 699.10 | 699.81 | 699.15 | 698.94 |
| July-17-12 | 700.78 | 702.00 | 698.52 | 698.91 | 698.68 | 698.69 | 699.06 | | 699.02 | 698.99 |
| August-04-12 | 700.77 | 702.24 | 698.37 | 698.95 | 699.02 | 699.04 | 697.91 | | 699.07 | 699.04 |
| September-08-12 | 699.10 | 701.19 | | 697.70 | 698.49 | 698.21 | | | 698.33 | 698.17 |

| Date | Shallow wells ~ 2 m | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | P10C | P11C | P12B | P13B | P14B | P15C | P16C | P17C | P18C | P19B |
| July-01-11 | 698.97 | 698.97 | 698.95 | 698.19 | | 698.75 | 698.45 | 698.77 | 698.90 | 698.84 |
| | 697.80 | 697.35 | 697.26 | 698.10 | 700.73 | 697.62 | 697.31 | 697.69 | 697.28 | 697.79 |
| August-28-11 | 699.08 | 699.00 | 698.96 | 699.18 | 699.91 | 698.88 | 698.65 | 698.73 | 698.89 | 698.93 |
| October-04-11 | 699.06 | 698.98 | 698.94 | 698.49 | | 698.86 | 698.63 | 698.71 | 698.86 | 698.90 |
| June-07-12 | 698.76 | 698.99 | 698.94 | 699.21 | | 698.82 | 698.61 | 698.74 | 697.87 | 698.87 |
| July-17-12 | 699.04 | 698.98 | 698.94 | 699.15 | | 698.82 | 698.62 | 698.68 | 698.82 | 698.89 |
| August-04-12 | 699.10 | 699.02 | 698.98 | 699.93 | | 698.89 | 698.67 | 698.78 | 698.91 | 698.94 |
| September-08-12 | 698.41 | 698.03 | 697.96 | 696.94 | | 697.89 | 697.66 | 698.09 | 697.94 | 697.88 |

| Date | Intermediate wells ~ 4 m | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | P1A | P2A | P3A | P4B | P5B | P6A | P7A | P8A | P9A | P10B |
| July-01-11 | | | | 697.40 | 698.92 | 697.59 | | 699.06 | 698.76 | 698.76 |
| August-07-11 | | 702.91 | | 696.44 | 694.77 | 696.90 | | 696.48 | 696.45 | 696.27 |
| August-28-11 | | 699.04 | | 698.93 | 698.93 | 699.08 | | 699.07 | 698.79 | 699.08 |
| October-04-11 | | | | 698.80 | 698.91 | 698.72 | | 699.07 | 698.79 | 699.07 |
| June-07-12 | | | 696.63 | 698.88 | 698.86 | 699.02 | | 698.99 | 699.02 | 697.97 |
| July-17-12 | 699.05 | | | 698.88 | 698.87 | 699.06 | | 699.04 | 698.76 | 699.07 |
| August-04-12 | | | | 698.72 | 698.93 | 698.27 | | 699.08 | 698.80 | 699.09 |
| September-08-12 | | | | 696.28 | 698.37 | 697.23 | | 698.36 | 697.78 | 698.17 |

| Date | Intermediate wells ~ 4 m | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | P11B | P12A | P13A | P14A | P15B | P16B | P17B | P18B | P19A |
| July-01-11 | 698.95 | | | | 698.83 | 698.57 | 698.65 | 696.53 | 698.81 |
| August-07-11 | 694.49 | 696.00 | 698.74 | | 695.42 | 696.07 | 696.40 | 696.31 | 695.66 |
| August-28-11 | 698.95 | 698.98 | 696.87 | | 698.84 | 698.58 | 698.68 | 698.61 | 698.82 |
| October-04-11 | 698.93 | 696.50 | 696.25 | | 698.85 | 698.57 | 698.68 | 697.38 | 698.82 |
| June-07-12 | 698.91 | 698.46 | 698.96 | | 698.60 | 698.49 | 698.92 | 698.68 | 696.41 |
| July-17-12 | 698.92 | 698.22 | 698.45 | | 698.81 | 698.54 | 698.66 | 698.41 | 698.77 |
| August-04-12 | 698.96 | 696.25 | 697.04 | | 698.78 | 698.57 | 698.71 | 697.35 | 698.82 |
| September-08-12 | 697.94 | | | | 697.93 | 697.70 | 697.92 | 695.12 | 697.71 |

| | Deep wells ~ 6 m | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Date | P4A | P5A | P10A | P11A | P15A | P16A | P17A | P18A |
| July-01-11 | | | | | | 692.09 | 698.12 | |
| August-07-11 | 698.80 | 698.09 | 697.73 | 697.14 | 695.26 | 696.67 | 694.92 | 698.65 |
| August-28-11 | 694.66 | 693.28 | 693.24 | 693.28 | 695.04 | 694.15 | 698.11 | 694.23 |
| October-04-11 | | 692.30 | 691.63 | | 691.62 | 691.89 | 698.11 | 693.95 |
| June-07-12 | | 697.55 | 696.54 | 696.82 | 698.27 | 697.37 | 698.06 | 694.96 |
| July-17-12 | 695.16 | 693.11 | 694.19 | 692.80 | 695.18 | 694.00 | 698.07 | 694.09 |
| August-04-12 | | 692.64 | 692.48 | 691.78 | 693.23 | 692.95 | 698.12 | 694.08 |
| September-08-12 | | | | | | 687.03 | 696.83 | |

## Appendix 3 Stable Water Isotopes

| ML 2011 | Isotopes d18O | | Isotopes d2H | | ML 2012 | Isotopes d18O | | | Isotopes d2H | | | Terrain Unit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Jun-11 | Aug-11 | Jun-11 | Aug-11 | Site | May-12 | Jul-12 | Sep-12 | May-12 | Jul-12 | Sep-12 | |
| MLP01B | -20.1 | x | -155.14 | x | MLP01B | -18.48 | -18.52 | -18.51 | -143.55 | -145.01 | -143.73 | Upland |
| MLP02B | -17.05 | -19.23 | -132.09 | -150.02 | MLP02B | -18.16 | -17.52 | -17.09 | -140.39 | -137.29 | -134.8 | Upland |
| MLP03B | x | -17.55 | x | -138.17 | MLP03B | -18.89 | -18.24 | -17.72 | -145.27 | -143.89 | -138.03 | Upland |
| MLP04C | x | -17.43 | x | -137.13 | MLP04C | -16.66 | -16.75 | -16.92 | -132.41 | -133.71 | -134.51 | Fen |
| MLP05D | x | x | x | x | MLP05D | -17.57 | -17.61 | -17.78 | -138.56 | -136.97 | -137.24 | Fen |
| MLP06B | x | -18.66 | x | -147.99 | MLP06B | -18.29 | -18.14 | -18.17 | -141.98 | -140.74 | -140.98 | Upland |
| MLP07B | x | -16.9 | x | -135.01 | MLP07B | -17.97 | x | -18.3 | -143.34 | x | -144.23 | Upland |
| MLP08B | -16.9 | -16.71 | -134.31 | -135.19 | MLP08B | -18.81 | -18.81 | -18.85 | -145.5 | -143.7 | -144.99 | Bog |
| MLP09B | -16.88 | -16.92 | -133.82 | -136.42 | MLP09B | -18.48 | -18.45 | -18.45 | -142.37 | -141.8 | -142.16 | Bog |
| MLP10C | x | -17.65 | x | -137.76 | MLP10C | -18.24 | -18.54 | -18.54 | -142.19 | -141.16 | -142.01 | Bog |
| MLP11C | -17.77 | -17.6 | -138.31 | -138.45 | MLP11C | -18.39 | -18.31 | -18.19 | -141.86 | -140.45 | -141.56 | Bog |
| MLP12B | -17.83 | -17.62 | -139.32 | -137.93 | MLP12B | -17.16 | -16.72 | -16.79 | -135.58 | -133.08 | -134.74 | Fen |
| MLP13B | -17.87 | -17.54 | -139.37 | -137.87 | MLP13B | -17.42 | -17.44 | -17.41 | -136.24 | -136.11 | -137.32 | Upland |
| MLP14B | x | -18.1 | x | -141.46 | MLP14B | -17.02 | -17.73 | -18.58 | -133.93 | -138.19 | -144.75 | Upland |
| MLP15C | x | -18.04 | x | -139.96 | MLP15C | -17.84 | -17.21 | -17.31 | -139.36 | -134.77 | -135.37 | Fen |
| MLP16C | x | -17.92 | x | -139.87 | MLP16C | -17.46 | -17.35 | -17.12 | -138.65 | -135.51 | -135.89 | Bog |
| MLP17C | x | -18 | x | -141.53 | MLP17C | -18.4 | -17.36 | -16.99 | -141.9 | -136.16 | -130.72 | Fen |
| MLP18C | -19.45 | -19.02 | -148.72 | -146.53 | MLP18C | -17.17 | -16.8 | -17.04 | -135.22 | -132.91 | -134.22 | Fen |
| MLP19B | -19.27 | -18.61 | -148.5 | -144 | MLP19B | -18.16 | -17.95 | -17.92 | -139.86 | -138.45 | -138.93 | Fen |
| MLP01A | -19.24 | -19.06 | -146.91 | -146.16 | MLP01A | -19.14 | x | x | -149.36 | x | x | Upland |
| MLP02A | -18.88 | -18.28 | -144.3 | -142.27 | MLP02A | -18.99 | -17.66 | x | -144.86 | -139.02 | x | Upland |
| MLP03A | x | -18.56 | x | -141.2 | MLP03A | -18.67 | x | x | -146.2 | x | x | Upland |
| MLP04B | -18.73 | -18.49 | -142.27 | -141.24 | MLP04B | -16.77 | -16.76 | -16.65 | -134.07 | -132.84 | -133.7 | Fen |
| MLP05C | -18.78 | -18.28 | -143.37 | -140.65 | MLP05C | -17.67 | -17.74 | -17.81 | -138.81 | -138.77 | -136.97 | Fen |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MLP06A | x | -18.13 | x | -140.46 | MLP06A | -18.44 | -18.11 | -18.18 | -141.36 | -140.66 | -140.4 | Upland |
| MLP07A | -18.34 | -18.26 | -141.31 | -139.82 | MLP07A | -18.18 | x | x | -142.76 | x | x | Upland |
| MLP08A | -18.78 | -18.36 | -144.19 | -139.96 | MLP08A | -19.32 | -19.43 | -19.42 | -148.36 | -147.31 | -146.95 | Bog |
| MLP09A | -18.46 | -17.38 | -144.42 | -136.89 | MLP09A | -19.16 | -19.18 | -19.15 | -146.7 | -145.68 | -147.19 | Bog |
| MLP10B | -17.04 | -17.08 | -133.98 | -135.75 | MLP10B | -18.33 | -18.68 | -18.63 | -141.34 | -141.6 | -142.36 | Bog |
| MLP11B | x | -17.78 | x | -138.2 | MLP11B | -18.41 | -18.24 | -18.26 | -141.27 | -139.94 | -141.51 | Bog |
| MLP12A | -16.73 | -17.51 | -128.07 | -136.46 | MLP12A | -17.29 | -17.23 | -17.13 | -137.38 | -135.91 | -136.43 | Fen |
| MLP13A | x | x | x | x | MLP13A | -17.75 | -17.56 | -17.59 | -137.05 | -136.59 | -137.75 | Upland |
| MLP14A | x | x | x | x | MLP14A | x | x | -17.37 | x | x | -135.51 | Upland |
| MLP15B | -17.11 | -17.51 | -134.75 | -138.84 | MLP15B | -17.33 | -17.28 | -17.32 | -136.64 | -135.4 | -136.09 | Fen |
| MLP16B | -17.19 | -17.28 | -136.29 | -135.52 | MLP16B | -18.2 | -18.21 | -17.98 | -140.85 | -140.6 | -141.14 | Bog |
| MLP17B | -16.65 | -17.31 | -128.68 | -133.88 | MLP17B | -16.92 | -16.97 | -16.86 | -132.8 | -133.18 | -133.55 | Fen |
| MLP18B | x | -18.64 | x | -141.92 | MLP18B | -16.65 | -16.35 | -16.83 | -132.3 | -132.01 | -132.43 | Fen |
| MLP19A | -17.96 | -18.18 | -140.08 | -140.09 | MLP19A | -18.14 | -18.1 | -18.12 | -140.23 | -139.4 | -140.04 | Fen |
| MLP04A | -17.2 | -17.48 | -134.62 | -135.58 | MLP04A | -16.33 | -16.49 | -16.47 | -132.47 | -130.89 | -133.39 | Fen |
| MLP05A | -16.08 | -17.15 | -123.91 | -132.99 | MLP05A | -17.71 | -17.87 | -17.17 | -138.51 | -139.42 | -133.54 | Fen |
| MLP05B | -17.06 | -17.32 | -133.38 | -134.08 | MLP05B | -17.75 | -17.78 | -17.83 | -138.76 | -138.83 | -138.25 | Fen |
| MLP10A | -17.23 | -17.63 | -136.2 | -136.78 | MLP10A | -18.52 | -18.59 | -18.51 | -142.45 | -142.66 | -141.83 | Bog |
| MLP11A | x | -17.85 | x | -139.41 | MLP11A | -18.44 | -18.27 | -18.19 | -141.48 | -140.94 | -142.21 | Bog |
| MLP15A | -17 | -16.71 | -135.19 | -133.62 | MLP15A | -17.65 | -17.51 | -17.59 | -139.33 | -139.27 | -138.67 | Fen |
| MLP16A | -16.84 | -17.1 | -132.68 | -134.98 | MLP16A | -18.59 | -18.71 | -18.59 | -143.47 | -143.14 | -142.67 | Bog |
| MLP17A | -18.2 | -17.92 | -140.91 | -138.57 | MLP17A | -16.95 | -17.03 | -16.84 | -133.84 | -134.43 | -133.87 | Fen |
| MLP18A | -18.21 | -17.89 | -140.38 | -137.31 | MLP18A | -16.46 | -16.31 | x | -132.83 | -133.09 | x | Fen |
| | | | | | | | | | | | | |
| MLA | -17.51 | -17.06 | -137.57 | -132.85 | MLA | -18.03 | -16.96 | -15.01 | -140.08 | -133.87 | -115.94 | Fen |
| MLB | -17.72 | -17.76 | -139.05 | -138.45 | MLB | -17.64 | -16.51 | -15.27 | -137.9 | -128.26 | -118.96 | Fen |
| MLC | -18.7 | -18.15 | -145.03 | -139.64 | MLC | -18.08 | -18.19 | -15.65 | -140.61 | -139.89 | -120.05 | Bog |
| MLD | -17.48 | -17.1 | -135.99 | -130.95 | MLD | -16.38 | -16.99 | -15.29 | -127.76 | -132.55 | -118.55 | Fen |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MLE | -16.92 | -16.92 | -134.32 | -131.98 | MLE | -16.62 | -16.33 | -16.74 | -132.29 | -130.18 | -132.99 | Fen |
| MLF | -17.99 | -17.89 | -139.59 | -136.18 | MLF | -17.79 | -17.77 | -15.67 | -137.93 | -135.84 | -118.84 | Bog |
| MLG | -17.94 | -16.31 | -140.78 | -125.85 | MLG | -17.63 | -17.25 | -15.86 | -136.11 | -135.54 | -124.17 | Fen |
| MLH | -17.86 | -17.25 | -140.47 | -133.11 | MLH | -17.41 | -15.37 | -15.67 | -136.85 | -119.9 | -121.2 | Fen |
| MLM | -17.23 | -17.13 | -134.4 | -133.11 | MLM | -17.37 | -17.17 | -14.86 | -137.11 | -134.99 | -116.89 | Bog |
| MLN | -18.29 | -17.05 | -143.62 | -132.78 | MLN | -17.37 | -16.98 | -15.52 | -136.75 | -135.16 | -120.24 | Fen |
| MLO | -18.39 | -18.1 | -142.66 | -137.91 | MLO | -18.04 | -18.21 | -15.16 | -139.51 | -139.74 | -114.56 | Bog |
| MLP | -18.21 | -17.68 | -141.6 | -136.78 | MLP | -18.11 | -17.44 | -15.07 | -140.09 | -133.72 | -115.11 | Bog |
| MLQ | -17.17 | -17.01 | -136.49 | -133.08 | MLQ | -17.48 | -16.96 | -16.42 | -137.93 | -134.84 | -128.03 | Fen |
| MLR | -17.99 | -17.95 | -141.33 | -137.36 | MLR | -17.92 | -18.28 | -15.38 | -139.73 | -138.1 | -117.03 | Fen |
| MLS | -18.55 | -18.37 | -144.19 | -144.83 | MLS | -18.15 | -18.13 | -15.87 | -140.22 | -140.22 | -121.75 | Fen |
| MLT | -18.24 | -18.03 | -142.04 | -136.51 | MLT | -18.17 | -16.68 | -15.77 | -140.7 | -127.95 | -122.41 | Bog |
| MLU | -17.92 | -17.91 | -138.77 | -144.67 | MLU | -18.21 | -18.34 | -18.12 | -140.2 | -138.46 | -138.72 | Fen |
| MLV | -18.7 | -18.03 | -143.8 | -153.53 | MLV | -18.25 | -16.87 | -15.19 | -140.8 | -130.73 | -115.08 | Bog |

| **JPH 2011** | **Isotopes d18O** | | **Isotopes d2H** | | **JPH 2012** | **Isotopes d18O** | | | **Isotopes d2H** | | | **Terrain unit** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Jun-11** | **Aug-11** | **Jun-11** | **Aug-11** | **Site** | **May-12** | **Jul-12** | **Sep-12** | **May-12** | **Jul-12** | **Sep-12** | |
| JPHP01A | -18.01 | -17.93 | -141.84 | -139.67 | JPHP01A | -17.89 | -18.51 | -18.01 | -140.3 | -139.54 | -139.07 | Upland |
| JPHP01B | -19.2 | -19.16 | -150.45 | -148.47 | JPHP01B | -18.79 | -18.79 | -18.95 | -146.94 | -147.13 | -147.1 | Upland |
| JPHP01C | -19.38 | -18.95 | -152.74 | -148.22 | JPHP01C | -19.31 | -18.96 | -19.56 | -151.15 | -149.49 | -152.45 | Upland |
| JPHP02A | -18.17 | -18.04 | -142.45 | -141.17 | JPHP02A | -17.93 | -18.58 | -17.97 | -148.88 | -140.66 | -140.4 | Upland |
| JPHP02B | -19.01 | -19 | -148.83 | -149.2 | JPHP02B | -19.1 | -19.62 | -19.07 | -140.62 | -149.04 | -148.02 | Upland |
| JPHP02C | -18.9 | -18.96 | -147.07 | -149.42 | JPHP02C | -19.17 | -19.8 | -19.06 | -149.32 | -151.29 | -149.24 | Upland |
| JPHP03A | -18.65 | -18.63 | -147.27 | -147.27 | JPHP03A | -18.6 | -18.67 | -18.57 | -145.98 | -146.93 | -145.48 | Upland |
| JPHP03B | -19.25 | -19.18 | -149.56 | -149.25 | JPHP03B | -19.2 | -19.66 | -18.91 | -149.07 | -149.6 | -147.59 | Upland |
| JPHP03C | -19.02 | -18.82 | -148.07 | -147.75 | JPHP03C | -19.76 | -20.52 | -19.65 | -154.31 | -155.73 | -154.38 | Upland |
| JPHP04A | -18.09 | -18.17 | -141.39 | -141.58 | JPHP04A | -18.06 | -18.13 | -17.91 | -140.94 | -140.62 | -140.2 | Upland |
| JPHP04B | -18.99 | -18.96 | -147.7 | -148.47 | JPHP04B | -19.08 | -19.26 | -19.27 | -149.51 | -150.4 | -150.84 | Upland |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JPHP04C | -19.22 | -18.76 | -150.41 | -146.52 | JPHP04C | -19.48 | -19.73 | -20.05 | -152.97 | -154.31 | -155.67 | Upland |
| JPHP05A | -18.31 | -18.33 | -143.85 | -142.68 | JPHP05A | -18.22 | -18.89 | -18.27 | -143.18 | -143.82 | -142.54 | Upland |
| JPHP05B | -19.11 | -19.01 | -149.76 | -147.98 | JPHP05B | -19.19 | -19.55 | -19.04 | -149.09 | -148.03 | -147.8 | Upland |
| JPHP05C | -19.15 | -18.73 | -151.63 | -147.4 | JPHP05C | -19.54 | -19.94 | -19.49 | -152.55 | -151.06 | -151.54 | Upland |
| JPHP06A | -18.4 | -18.37 | -144.43 | -145.42 | JPHP06A | -18.51 | -19.06 | -18.47 | -144.14 | -144.48 | -144.55 | Upland |
| JPHP06B | -18.7 | -18.67 | -147.1 | -147.68 | JPHP06B | -18.86 | -19.38 | -18.72 | -147.28 | -147.59 | -146.97 | Upland |
| JPHP06C | -18.81 | -18.94 | -147.94 | -148.95 | JPHP06C | -19.45 | -19.74 | -19.23 | -149.87 | -151.23 | -150.41 | Upland |
| JPHP07A | -18.26 | -18.21 | -143.84 | -143.01 | JPHP07A | -18.27 | -18.21 | -18.2 | -143.48 | -142.84 | -142.25 | Upland |
| JPHP07B | -18.9 | -18.95 | -147.97 | -148.45 | JPHP07B | -18.83 | -18.67 | -18.6 | -146.73 | -146.56 | -145.9 | Upland |
| JPHP07C | -18.81 | -18.76 | -147.89 | -148.2 | JPHP07C | -20.3 | -19.24 | -19.26 | -158.01 | -151.96 | -149.57 | Upland |
| JPHP08A | -19.08 | -18.94 | -148.25 | -149.15 | JPHP08A | -19.1 | -18.51 | -18.99 | -148.41 | -148.25 | -148.14 | Fen |
| JPHP08B | -18.2 | -18.11 | -142.31 | -141.57 | JPHP08B | -18.43 | -17.91 | -18.46 | -143.43 | -143.25 | -142.57 | Fen |
| JPHP08C | -17.14 | -18.34 | -135.11 | -143.8 | JPHP08C | -19.85 | -17.33 | -18.54 | -156.33 | -139.5 | -143.79 | Fen |
| JPHP09A | -18.82 | -18.54 | -147.27 | -146.49 | JPHP09A | -18.53 | -18.62 | -18.49 | -146.2 | -146.29 | -145.65 | Fen |
| JPHP09B | -17.93 | -17.82 | -141.16 | -140.63 | JPHP09B | -18.01 | -18.14 | -17.99 | -140.51 | -141.03 | -140.6 | Fen |
| JPHP09C | -19.95 | -18.48 | -155.23 | -146.27 | JPHP09C | -17.82 | -17.93 | -17.24 | -140.2 | -140.45 | -134.37 | Fen |
| JPHP10A | -18.43 | -18.38 | -144.4 | -144.84 | JPHP10A | -18.33 | -18.49 | -18.37 | -144.64 | -143.88 | -143.31 | Fen |
| JPHP10B | -17.91 | -17.98 | -140.83 | -142.35 | JPHP10B | -17.89 | -18.24 | -18.07 | -141.73 | -141.32 | -140.66 | Fen |
| JPHP10C | -19.05 | -18.68 | -150.03 | -145.76 | JPHP10C | -18.39 | -18.1 | -17.05 | -143.74 | -141.49 | -133.5 | Fen |
| JPHP11A | -17.91 | -17.96 | -140.53 | -140.58 | JPHP11A | -18.02 | -17.63 | -18.02 | -141.65 | -141.4 | -139.58 | Upland |
| JPHP11B | -18.37 | -18.47 | -144.99 | -145.38 | JPHP11B | -18.24 | -18.26 | -18.39 | -144.98 | -145 | -143.94 | Upland |
| JPHP11C | -18.78 | -18.87 | -146.69 | -148.53 | JPHP11C | -19 | -18.57 | -18.61 | -149.8 | -150.14 | -146.18 | Upland |
| | | | | | JPHP12 | | -17.61 | -18.76 | | -137.12 | -145.59 | Fen |
| JPHA | -16.33 | -17.39 | -128.46 | -137.75 | JPHA | -20.91 | -16.77 | -14.96 | -163.81 | -134.09 | -113.32 | Fen |
| JPHB | -18.46 | -17.93 | -143.96 | -140.93 | JPHB | -17.85 | -17.53 | -15.38 | -140.29 | -135.8 | -117.39 | Fen |
| JPHC | -18.78 | -17.47 | -146.21 | -139.32 | JPHC | -18.95 | | -17.03 | -148.4 | | -133.72 | Fen |
| JPHD | -17.74 | -18.01 | -137.32 | -142.86 | JPHD | -17.15 | -17.62 | -15.24 | -135.48 | -136.7 | -117.46 | Fen |
| JPHE | -18.76 | -18.55 | -145.91 | -144.79 | JPHE | -17.64 | -17.22 | -15.26 | -137.64 | -135.36 | -116.1 | Fen |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JPHF | -19.94 | -18.98 | -153.88 | -148.05 | JPHF | -18.66 | -17.16 | -14.7 | -147.2 | -134.2 | -112.13 | Fen |
| JPHG | -17.28 | -17.5 | -136.15 | -137.94 | JPHG | -18.18 | -16.98 | -15.26 | -143.51 | -132.02 | -118.7 | Fen |
| | | | | | JPH weir | -19.4 | -17.44 | -17.01 | -153.2 | -135.24 | -131.19 | Fen |
| | | | | | JPH open water | -15.89 | -17 | -15.5 | -135.04 | -135.63 | -117.6 | Fen |
| | | | | | rain collector | -19.76 | -18.71 | -15.78 | -153.49 | -143.73 | -119.35 | |

## Appendix 4 Water Level Loggers on a Daily Time Step

| **2011 ML** | **Water Table Loggers Depth Below Surface (mm)** | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DOY** | **MLA** | | | | | | | **MLB** | **MLC** | **MLD** | **MLE** | **MLF** | **MLG** | **MLH** | **MLM** | **MLN** | **MLO** | **MLP** |
| **169** | 78 | 168 | 163 | 121 | 111 | | 72 | | | | | | **MLQ** | **MLR** | **MLS** | **MLT** | **MLU** | **MLV** |
| **170** | 75 | 166 | 161 | 118 | 109 | | 76 | | | | | | | | | | | |
| **171** | 74 | 157 | 152 | 109 | 100 | | 78 | | | | | | | | | | | |
| **172** | 73 | 162 | 156 | 107 | 104 | | 83 | | | | | | | | | | | |
| **173** | 76 | 170 | 163 | 114 | 112 | | 91 | | | | | | | | | | | |
| **174** | 78 | 166 | 162 | 113 | 109 | | 97 | | | | | | | | | | | |
| **175** | 73 | 146 | 142 | 101 | 96 | | 100 | | | | | | | | | | | |
| **176** | 72 | 139 | 132 | 86 | 86 | | 93 | | | | | | | | | | | |
| **177** | 73 | 138 | 132 | 78 | 82 | | 74 | | | | | | | | | | | |
| **178** | 72 | 136 | 129 | 74 | 79 | 158 | 48 | | | | | | | | | | | |
| **179** | 71 | 141 | 132 | 80 | 85 | 166 | 53 | | | | | | | | | | | |
| **180** | 79 | 153 | 137 | 90 | 90 | 172 | 57 | 97 | 96 | 117 | 159 | 138 | | | | | | |
| **181** | 72 | 163 | 145 | 91 | 103 | 177 | 59 | 111 | 110 | 129 | 166 | 150 | 76 | 64 | 112 | 8 | 120 | 189 |
| **182** | 72 | 169 | 150 | 96 | 108 | 184 | 56 | 115 | 117 | 141 | 172 | 159 | 87 | 76 | 121 | 15 | 135 | 200 |
| **183** | 72 | 173 | 154 | 100 | 112 | 189 | 50 | 117 | 124 | 145 | 177 | 166 | 98 | 84 | 126 | 18 | 140 | 202 |
| **184** | 76 | 175 | 156 | 102 | 116 | 194 | 53 | 118 | 128 | 147 | 181 | 172 | 102 | 89 | 130 | 23 | 145 | 207 |
| **185** | 88 | 182 | 161 | 108 | 124 | 191 | 58 | 123 | 135 | 155 | 187 | 180 | 104 | 91 | 133 | 26 | 148 | 211 |
| **186** | 92 | 186 | 165 | 113 | 129 | 174 | 61 | 126 | 142 | 160 | 192 | 187 | 111 | 100 | 142 | 33 | 155 | 218 |
| **187** | 94 | 189 | 169 | 115 | 131 | 140 | 64 | 127 | 146 | 164 | 194 | 193 | 116 | 106 | 147 | 39 | 160 | 224 |
| **188** | 88 | 179 | 162 | 106 | 122 | 140 | 67 | 118 | 141 | 154 | 190 | 189 | 120 | 111 | 151 | 44 | 163 | 229 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **189** | 78 | 159 | 144 | 92 | 105 | 143 | 71 | 96 | 119 | 131 | 175 | 171 | 111 | 101 | 144 | 37 | 154 | 224 |
| **190** | 71 | 133 | 116 | 61 | 79 | 146 | 72 | 57 | 80 | 99 | 147 | 132 | 89 | 81 | 125 | 18 | 134 | 207 |
| **191** | 68 | 142 | 124 | 54 | 81 | 143 | 65 | 63 | 86 | 108 | 148 | 127 | 62 | 46 | 91 | -14 | 101 | 173 |
| **192** | 67 | 147 | 130 | 53 | 88 | 131 | 62 | 68 | 92 | 114 | 151 | 132 | 72 | 52 | 96 | -11 | 107 | 173 |
| **193** | 66 | 149 | 132 | 53 | 89 | 135 | 60 | 69 | 97 | 116 | 153 | 136 | 79 | 58 | 101 | -7 | 113 | 178 |
| **194** | 65 | 144 | 128 | 55 | 83 | 141 | 64 | 60 | 95 | 109 | 148 | 134 | 82 | 60 | 103 | -5 | 116 | 182 |
| **195** | 65 | 133 | 117 | 53 | 72 | 147 | 58 | 44 | 81 | 98 | 138 | 120 | 76 | 55 | 97 | -9 | 112 | 178 |
| **196** | 65 | 138 | 123 | 51 | 78 | 152 | 43 | 50 | 88 | 105 | 142 | 126 | 65 | 44 | 84 | -22 | 99 | 166 |
| **197** | 64 | 142 | 128 | 51 | 83 | 160 | 41 | 54 | 95 | 111 | 148 | 134 | 70 | 50 | 90 | -16 | 105 | 172 |
| **198** | 63 | 146 | 133 | 51 | 88 | 167 | 41 | 58 | 102 | 115 | 152 | 141 | 75 | 56 | 96 | -10 | 112 | 179 |
| **199** | 62 | 149 | 136 | 52 | 90 | 170 | 42 | 58 | 106 | 117 | 157 | 147 | 80 | 61 | 101 | -4 | 118 | 185 |
| **200** | 62 | 154 | 141 | 52 | 94 | 170 | 41 | 62 | 110 | 122 | 164 | 155 | 82 | 63 | 104 | 1 | 121 | 190 |
| **201** | 61 | 158 | 146 | 59 | 95 | 165 | 44 | 64 | 117 | 127 | 171 | 162 | 88 | 70 | 111 | 5 | 127 | 196 |
| **202** | 60 | 159 | 149 | 67 | 98 | 160 | 45 | 66 | 119 | 129 | 172 | 167 | 92 | 75 | 116 | 11 | 133 | 202 |
| **203** | 60 | 152 | 144 | 73 | 89 | 169 | 47 | 56 | 113 | 117 | 168 | 166 | 93 | 78 | 119 | 15 | 136 | 207 |
| **204** | 59 | 147 | 139 | 62 | 80 | 166 | 49 | 47 | 104 | 112 | 165 | 161 | 81 | 68 | 113 | 10 | 128 | 204 |
| **205** | 58 | 143 | 136 | 63 | 77 | 150 | 49 | 40 | 93 | 110 | 163 | 156 | 74 | 63 | 108 | 6 | 124 | 199 |
| **206** | 57 | 151 | 144 | 64 | 86 | 153 | 43 | 50 | 103 | 119 | 171 | 164 | 72 | 59 | 104 | 3 | 120 | 195 |
| **207** | 57 | 148 | 142 | 59 | 86 | 157 | 45 | 45 | 101 | 115 | 167 | 162 | 82 | 69 | 114 | 12 | 130 | 203 |
| **208** | 57 | 134 | 127 | 56 | 72 | 162 | 52 | 24 | 83 | 101 | 152 | 144 | 78 | 66 | 111 | 9 | 126 | 201 |
| **209** | 56 | 139 | 133 | 52 | 72 | 167 | 56 | 29 | 89 | 107 | 159 | 147 | 63 | 50 | 94 | -7 | 108 | 184 |
| **210** | 55 | 142 | 137 | 51 | 77 | 172 | 61 | 32 | 94 | 111 | 163 | 151 | 68 | 55 | 99 | -2 | 115 | 188 |
| **211** | 54 | 147 | 142 | 50 | 82 | 177 | 66 | 37 | 101 | 115 | 167 | 157 | 72 | 59 | 103 | 1 | 119 | 191 |
| **212** | 54 | 149 | 145 | 50 | 85 | 180 | 45 | 37 | 105 | 117 | 169 | 161 | 79 | 64 | 109 | 6 | 124 | 197 |
| **213** | 53 | 154 | 149 | 51 | 88 | 184 | 46 | 42 | 110 | 124 | 174 | 166 | 81 | 67 | 112 | 10 | 128 | 200 |
| **214** | 52 | 160 | 153 | 52 | 90 | 185 | 35 | 46 | 115 | 128 | 177 | 172 | 86 | 73 | 118 | 15 | 135 | 205 |
| **215** | 51 | 164 | 157 | 55 | 92 | 190 | 40 | 48 | 118 | 131 | 180 | 177 | 90 | 78 | 123 | 20 | 140 | 210 |
| **216** | 50 | 168 | 161 | 57 | 95 | 190 | 47 | 51 | 123 | 137 | 184 | 181 | 92 | 83 | 127 | 23 | 145 | 214 |
| **217** | 51 | 169 | 163 | 58 | 98 | 193 | 50 | 54 | 127 | 138 | 181 | 185 | 97 | 87 | 133 | 28 | 150 | 219 |
| **218** | 52 | 165 | 161 | 60 | 91 | 199 | 51 | 50 | 125 | 132 | 186 | 187 | 97 | 90 | 135 | 30 | 151 | 222 |
| **219** | 52 | 166 | 161 | 64 | 90 | 202 | 40 | 49 | 126 | 135 | 187 | 188 | 90 | 85 | 133 | 29 | 147 | 222 |
| **220** | 55 | 172 | 166 | 65 | 97 | 189 | | 54 | 131 | 142 | 189 | 192 | 91 | 87 | 133 | 31 | 149 | 223 |
| **221** | 63 | 175 | 170 | 68 | 101 | 183 | -193 | 59 | 135 | 147 | 195 | 196 | 98 | 94 | 141 | 35 | 156 | 227 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **222** | 63 | 181 | 169 | 86 | 108 | 185 | -238 | 80 | 140 | 150 | 211 | 204 | 102 | 98 | 146 | 38 | 158 | 231 |
| **223** | 49 | 151 | 144 | 80 | 104 | 179 | -241 | 52 | 143 | 156 | 184 | 200 | 105 | 101 | 158 | 44 | 165 | 239 |
| **224** | 41 | 138 | 139 | 68 | 86 | 185 | -225 | 22 | | 146 | 176 | 195 | 114 | 117 | 160 | 44 | 173 | 240 |
| **225** | 43 | 141 | 141 | 72 | 88 | 189 | -34 | 24 | | 148 | 180 | 195 | 99 | 94 | 150 | 36 | 161 | 232 |
| **226** | 34 | 130 | 136 | 61 | 77 | 193 | -285 | 13 | | 139 | 176 | 189 | 98 | 95 | 152 | 39 | 161 | 234 |
| **227** | 41 | 135 | 141 | 69 | 84 | 194 | -276 | 20 | | 148 | 183 | 193 | 89 | 87 | 144 | 31 | 153 | 227 |
| **228** | 48 | 141 | 145 | 76 | 89 | 193 | -214 | 25 | | 155 | 188 | 198 | 95 | 95 | 151 | 38 | 158 | 231 |
| **229** | 48 | 140 | 147 | 78 | 90 | 199 | -220 | 25 | | 157 | 190 | 202 | 101 | 102 | 157 | 44 | 163 | 237 |
| **230** | 45 | 137 | 145 | 86 | 94 | 198 | -191 | 26 | | 161 | 190 | 202 | 101 | 105 | 160 | 46 | 165 | 239 |
| **231** | | 132 | 143 | 73 | 84 | 202 | -240 | 14 | | 153 | 187 | 201 | 106 | 109 | 159 | 45 | 164 | 241 |
| **232** | | 146 | 157 | 77 | 84 | 214 | -210 | 17 | | 157 | 194 | 213 | 99 | 100 | 155 | 42 | 162 | 239 |
| **233** | | 154 | 153 | 84 | 89 | 218 | -223 | 22 | | 162 | 196 | 207 | 101 | 105 | 165 | 44 | 179 | 251 |
| **234** | | 157 | 156 | 89 | 92 | 220 | -216 | 26 | | 167 | 201 | 211 | 105 | 111 | 164 | 49 | 181 | 246 |
| **235** | | 159 | 162 | 94 | 95 | 223 | -194 | 29 | 153 | 171 | 205 | 215 | 109 | 117 | 169 | 54 | 187 | 250 |
| **236** | | | 235 | 100 | 95 | 227 | -147 | | 154 | 180 | 209 | 218 | 112 | 122 | 174 | 66 | 192 | 256 |
| **237** | -347 | | 239 | 105 | 153 | 230 | -169 | | 159 | 184 | 213 | 222 | 111 | 128 | 180 | 66 | 200 | 257 |
| **238** | -246 | | 242 | 108 | 116 | 234 | -144 | | 162 | 187 | 215 | 225 | 219 | 134 | 185 | 70 | 205 | 261 |
| **239** | -134 | | 245 | 113 | 120 | 237 | -108 | | 167 | 192 | 219 | 229 | 187 | 137 | 189 | 74 | 208 | 264 |
| **240** | -112 | | 246 | 113 | 123 | 239 | -101 | | 170 | 193 | 220 | 231 | 269 | 141 | 194 | 79 | 214 | 269 |
| **241** | -98 | | 248 | 117 | 125 | 242 | -23 | | 173 | 195 | 222 | 234 | 270 | 142 | 195 | 82 | 216 | 272 |
| **242** | -130 | | 251 | 123 | 128 | 246 | -93 | | 177 | 200 | 226 | 238 | 271 | 146 | 200 | 84 | 219 | 274 |
| **243** | -90 | | 254 | 126 | 131 | 251 | -109 | | 180 | 203 | 229 | 241 | 277 | 151 | 204 | 88 | 225 | 278 |
| **244** | -110 | | 256 | 130 | 133 | 254 | -89 | | 196 | 207 | 231 | 244 | 280 | 155 | 208 | 90 | 229 | 281 |
| **245** | -93 | | 259 | 135 | 134 | 258 | -40 | | 219 | 211 | 234 | 247 | 283 | 158 | 211 | 92 | 233 | 284 |
| **246** | -78 | | 262 | 135 | 133 | 263 | 23 | | 216 | 214 | 235 | 249 | 285 | 162 | 215 | 95 | 238 | 287 |
| **247** | -68 | | 266 | 142 | 137 | 264 | -85 | | 216 | 219 | 239 | 252 | 286 | 163 | 218 | 98 | 241 | 290 |
| **248** | -62 | | 271 | 149 | 145 | 265 | -118 | | 218 | 226 | 243 | 256 | 289 | 167 | 222 | 104 | 248 | 294 |
| **249** | -60 | | 276 | 155 | 152 | 269 | -140 | | 223 | 232 | 248 | 259 | 295 | 172 | 229 | 108 | 255 | 299 |
| **250** | -54 | | 281 | 161 | 163 | 271 | -121 | | 200 | 238 | 252 | 263 | 300 | 177 | 234 | 114 | 263 | 303 |
| **251** | -61 | | 285 | 166 | 169 | 272 | -63 | | 219 | 243 | 256 | 266 | 309 | 187 | 242 | 120 | 269 | 308 |
| **252** | -56 | | 290 | 173 | 174 | 266 | -59 | | 186 | 249 | 260 | 269 | 315 | 192 | 249 | 124 | 275 | 312 |
| **253** | -59 | | 284 | 167 | 171 | 235 | -37 | | 185 | 246 | 258 | 270 | 316 | 196 | 254 | 129 | 281 | 316 |
| **254** | -98 | | 288 | 173 | 175 | 236 | -103 | | 190 | 250 | 261 | 274 | 313 | 195 | 250 | 126 | 270 | 317 |

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| **255** | -65 | | 291 | 178 | 180 | 240 | -39 | | 193 | 255 | 264 | 277 | 322 | 198 | 255 | 128 | 274 | 318 |
| **256** | -55 | | 295 | 179 | 183 | 243 | -36 | | 194 | 257 | 266 | 279 | 328 | 205 | 261 | 133 | 282 | 323 |
| **257** | -88 | | 298 | 181 | 184 | 246 | -46 | | 198 | 260 | 268 | 279 | 336 | 207 | 264 | 133 | 284 | 325 |
| **258** | -69 | | 283 | 164 | 169 | 251 | -45 | | 203 | 245 | 259 | 275 | 339 | 207 | 266 | 138 | 286 | 326 |
| **259** | -73 | | 250 | 123 | 136 | 254 | -70 | | 207 | 215 | 227 | 247 | 322 | 190 | 248 | 124 | 259 | 319 |
| **260** | -89 | | 255 | 133 | 145 | 258 | -12 | | 210 | 220 | 229 | 246 | 284 | 152 | 208 | 92 | 205 | 287 |
| **261** | -111 | | 261 | 141 | 153 | 261 | -36 | | 215 | 225 | 235 | 249 | 288 | 160 | 215 | 96 | 217 | 287 |
| **262** | -77 | | 264 | 145 | 159 | 265 | 86 | | 219 | 229 | 238 | 252 | 295 | 167 | 222 | 102 | 228 | 292 |
| **263** | -36 | | 269 | 149 | 162 | 269 | 71 | | 224 | 232 | 241 | 254 | 299 | 173 | 227 | 105 | 235 | 295 |
| **264** | -50 | | 275 | 155 | 165 | 272 | 43 | | 228 | 239 | 246 | 257 | 304 | 175 | 231 | 108 | 240 | 298 |
| **265** | -82 | | 279 | 160 | 170 | 274 | 25 | | 229 | 243 | 250 | 261 | 307 | 179 | 237 | 113 | 250 | 303 |
| **266** | -18 | | 283 | 164 | 174 | 276 | | | 233 | 248 | 253 | 264 | 312 | 186 | 244 | 119 | 255 | 307 |
| **267** | -63 | | 287 | 169 | 175 | 279 | | | 233 | 251 | 257 | 266 | 316 | 192 | 248 | 123 | 262 | 311 |
| **268** | -50 | | 291 | 176 | 178 | 280 | | | 234 | 258 | 261 | 270 | 326 | 195 | 253 | 127 | 265 | 314 |
| **269** | -29 | | 295 | 178 | 183 | 281 | | | 230 | 262 | 265 | 273 | 327 | 199 | 260 | 131 | 274 | 319 |
| **270** | -34 | | 297 | 182 | 187 | 278 | | | 224 | 266 | 267 | 276 | 332 | 206 | 265 | 136 | 278 | 322 |
| **271** | -18 | | 299 | 187 | 189 | 272 | | | | 269 | 269 | 281 | 335 | 210 | 269 | 139 | 284 | 325 |
| **272** | -29 | | 301 | 188 | 189 | | | | | 270 | 270 | 281 | 337 | 215 | 272 | 143 | 285 | 329 |
| **273** | -13 | | 304 | 190 | 194 | | | | | 274 | 272 | 285 | 339 | 214 | 273 | 143 | 285 | 330 |
| **274** | -12 | | 304 | 190 | 194 | | | | | 275 | 273 | 285 | 344 | 285 | 285 | 315 | 435 | 255 |
| **275** | -19 | | 304 | 189 | 191 | | | | | 275 | 273 | 286 | 345 | 220 | 277 | 147 | 291 | 334 |
| **276** | | | 296 | 182 | 183 | | | | | 266 | 270 | 284 | 345 | 219 | 277 | 146 | 287 | 334 |
| **277** | | | 285 | 170 | 173 | | | | | 255 | 264 | 282 | 338 | 209 | 267 | 140 | 271 | 332 |

| **2012 ML** | **Water Table Loggers Depth Below Surface (mm)** | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DOY** | **MLA** | **MLB** | **MLC** | **MLD** | **MLE** | **MLF** | **MLG** | **MLH** | **MLM** | **MLN** | **MLO** | **MLP** | **MLQ** | **MLR** | **MLS** | **MLT** | **MLU** | **MLV** |
| **100** | | | | 170 | 186 | 258 | 60 | | 189 | 209 | 453 | 304 | 229 | 205 | 249 | 95 | 187 | 332 |
| **101** | | | | 167 | 152 | 243 | 78 | | 186 | 186 | 418 | 294 | 181 | 203 | 225 | 64 | 169 | 309 |
| **102** | | | | 165 | 126 | 221 | 92 | | 180 | 149 | 348 | 273 | 99 | 201 | 179 | 35 | 142 | 278 |
| **103** | | | | 159 | 105 | 208 | 46 | | 161 | 142 | 346 | 251 | 62 | 171 | 139 | 26 | 125 | 263 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **104** | 153 | 107 | 202 | -1 | 151 | 151 | 350 | 236 | 67 | 171 | 133 | 34 | 156 | 253 |
| **105** | 152 | 114 | 208 | -49 | 149 | 161 | 269 | 236 | 79 | 186 | 141 | 40 | 168 | 254 |
| **106** | 151 | 123 | 210 | -19 | 146 | 170 | 249 | 236 | 86 | 187 | 145 | 42 | 170 | 255 |
| **107** | 150 | 128 | 212 | -28 | 143 | 180 | 243 | 236 | 93 | 187 | 149 | 46 | 177 | 255 |
| **108** | 154 | 140 | 210 | 15 | 139 | 200 | 241 | 233 | 99 | 187 | 153 | 45 | 182 | 254 |
| **109** | 153 | 140 | 198 | 3 | 132 | 202 | 222 | 224 | 93 | 179 | 143 | 33 | 171 | 242 |
| **110** | 148 | 117 | 184 | 47 | 125 | 174 | 192 | 206 | 64 | 155 | 122 | 18 | 146 | 223 |
| **111** | 143 | 83 | 168 | -53 | 117 | 126 | 168 | 183 | 39 | 119 | 96 | 0 | 121 | 192 |
| **112** | 131 | 36 | 157 | -144 | 104 | 104 | 149 | 156 | 34 | 90 | 79 | -32 | 97 | 183 |
| **113** | 66 | 15 | 142 | -71 | 44 | 94 | 129 | 132 | 33 | 89 | 72 | -46 | 80 | 170 |
| **114** | 0 | 5 | 115 | -94 | 1 | 75 | 108 | 77 | 24 | 85 | 67 | -53 | 63 | 159 |
| **115** | -1 | 13 | 99 | -108 | 4 | 79 | 106 | 27 | 29 | 85 | 69 | -10 | 57 | 156 |
| **116** | -20 | 7 | 45 | -74 | -4 | 76 | 78 | -10 | 14 | 68 | 50 | -9 | 56 | 133 |
| **117** | -55 | -12 | 11 | -83 | -10 | 59 | 35 | -27 | 17 | 37 | 24 | -22 | 55 | 133 |
| **118** | -52 | -24 | -6 | -179 | -6 | 42 | 27 | -29 | 11 | 38 | 10 | -39 | 53 | 128 |
| **119** | -50 | -25 | -10 | -274 | 3 | 29 | 13 | -22 | 5 | 15 | 0 | -41 | 52 | 114 |
| **120** | -46 | -28 | -9 | -308 | 4 | 23 | 13 | -12 | 0 | -1 | 0 | -44 | 52 | 98 |
| **121** | -35 | -24 | -3 | -305 | 10 | 27 | 14 | -1 | 1 | -4 | 5 | -47 | 52 | 88 |
| **122** | -27 | -16 | 3 | -315 | 17 | 35 | 15 | 10 | 3 | -3 | 12 | -51 | 51 | 90 |
| **123** | -20 | -9 | 10 | -289 | 26 | 44 | 18 | 20 | 9 | 0 | 18 | -53 | 51 | 98 |
| **124** | -16 | -2 | 16 | -191 | 33 | 45 | 31 | 29 | 15 | 2 | 23 | -54 | 51 | 99 |
| **125** | -14 | 5 | 23 | -282 | 39 | 44 | 41 | 37 | 20 | 8 | 27 | -55 | 51 | 103 |
| **126** | -9 | 7 | 31 | -300 | 47 | 51 | 50 | 47 | 27 | 14 | 34 | -57 | 50 | 110 |
| **127** | -6 | 12 | 40 | -293 | 55 | 58 | 59 | 57 | 34 | 21 | 41 | -59 | 50 | 119 |
| **128** | -2 | 21 | 49 | -216 | 61 | 65 | 69 | 67 | 40 | 27 | 47 | -61 | 51 | 126 |
| **129** | 2 | 28 | 60 | -210 | 68 | 71 | 80 | 77 | 45 | 33 | 53 | -61 | 55 | 134 |
| **130** | 8 | 36 | 71 | -269 | 76 | 78 | 91 | 89 | 50 | 40 | 61 | -60 | 64 | 143 |
| **131** | 13 | 38 | 81 | -262 | 83 | 83 | 101 | 98 | 55 | 46 | 68 | -57 | 72 | 150 |
| **132** | 18 | 39 | 91 | -264 | 89 | 88 | 110 | 108 | 62 | 52 | 75 | -56 | 79 | 157 |
| **133** | 25 | 42 | 101 | -252 | 95 | 94 | 118 | 117 | 69 | 57 | 83 | -51 | 87 | 165 |
| **134** | 29 | 44 | 111 | -220 | 102 | 101 | 127 | 126 | 75 | 63 | 92 | -47 | 95 | 173 |

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| **135** | | | | 34 | 45 | 119 | -144 | | 106 | 105 | 134 | 133 | 78 | 66 | 98 | -44 | 101 | 179 |
| **136** | | | | 38 | 45 | 126 | -246 | | 109 | 108 | 142 | 140 | 82 | 69 | 102 | -40 | 105 | 184 |
| **137** | | | | 45 | 48 | 133 | -236 | | 114 | 113 | 148 | 147 | 87 | 75 | 109 | -35 | 112 | 191 |
| **138** | | | | 47 | 49 | 140 | -207 | | 117 | 115 | 152 | 153 | 88 | 78 | 113 | -33 | 114 | 195 |
| **139** | | | | 43 | 44 | 140 | -247 | | 114 | 111 | 153 | 154 | 82 | 76 | 110 | -36 | 112 | 195 |
| **140** | | | | 47 | 47 | 145 | -250 | | 115 | 117 | 157 | 158 | 86 | 82 | 116 | -30 | 118 | 200 |
| **141** | | | | 53 | 52 | 149 | -169 | | 119 | 121 | 172 | 163 | 90 | 86 | 121 | -29 | 123 | 205 |
| **142** | | | | 56 | 55 | 155 | -104 | | 122 | 123 | 295 | 168 | 91 | 90 | 126 | -25 | 126 | 209 |
| **143** | | | | 48 | 49 | 154 | -177 | | 117 | 121 | 292 | 167 | 84 | 86 | 122 | -30 | 122 | 207 |
| **144** | | | | 56 | 54 | 161 | -209 | | 123 | 127 | 297 | 173 | 90 | 94 | 130 | -24 | 128 | 213 |
| **145** | | | | 60 | 59 | 165 | -212 | | 127 | 131 | 300 | 178 | 92 | 98 | 135 | -23 | 129 | 217 |
| **146** | | | | 65 | 64 | 169 | -224 | | 131 | 135 | 303 | 183 | 95 | 104 | 140 | -22 | 132 | 222 |
| **147** | | | | 70 | 68 | 174 | -220 | | 135 | 139 | 306 | 188 | 97 | 109 | 147 | -21 | 137 | 227 |
| **148** | | | | 74 | 72 | 177 | -191 | | 142 | 143 | 309 | 194 | 102 | 115 | 153 | -23 | 142 | 232 |
| **149** | | | | 80 | 77 | 180 | -200 | | 148 | 147 | 311 | 199 | 106 | 120 | 160 | -25 | 149 | 237 |
| **150** | | | | 90 | 83 | 184 | -187 | | 154 | 150 | 313 | 206 | 110 | 126 | 167 | -27 | 155 | 243 |
| **151** | | | | 97 | 88 | 189 | -177 | | 159 | 152 | 314 | 212 | 113 | 133 | 173 | -23 | 157 | 249 |
| **152** | | | | 104 | 95 | 196 | -139 | | 165 | 162 | 317 | 218 | 121 | 141 | 181 | -20 | 178 | 254 |
| **153** | | | | 106 | 96 | 202 | -120 | | 169 | 164 | 318 | 223 | 124 | 144 | 184 | -21 | 183 | 258 |
| **154** | | | | 66 | 54 | 174 | -174 | | 138 | 130 | 296 | 193 | 84 | 105 | 149 | -58 | 138 | 226 |
| **155** | | | | 51 | 42 | 161 | -181 | | 121 | 122 | 287 | 178 | 72 | 89 | 136 | -75 | 124 | 213 |
| **156** | | | | 51 | 51 | 164 | -149 | | 122 | 125 | 288 | 181 | 75 | 91 | 138 | -70 | 127 | 215 |
| **157** | | | | 53 | 57 | 167 | -170 | | 124 | 128 | 290 | 184 | 80 | 94 | 142 | -71 | 131 | 217 |
| **158** | | | | 59 | 62 | 171 | -246 | | 129 | 132 | 292 | 188 | 85 | 100 | 147 | -65 | 136 | 222 |
| **160** | -75 | | | 71 | 69 | 181 | -238 | | 140 | 141 | 175 | 198 | | 112 | 155 | -52 | 143 | 233 |
| **161** | -54 | | | 76 | 73 | 184 | -229 | | 144 | 144 | 204 | 212 | | 117 | 162 | 12 | 147 | 247 |
| **162** | -52 | | | 79 | 76 | 190 | -213 | | 147 | 146 | 190 | 204 | | 121 | 167 | 4 | 150 | 242 |
| **163** | -49 | | | 84 | 83 | 192 | -216 | | 162 | 157 | 193 | 208 | | 137 | 172 | 11 | 172 | 246 |
| **164** | -57 | | | 79 | 70 | 190 | -222 | | 152 | 145 | 187 | 208 | | 119 | 168 | 7 | 162 | 245 |
| **165** | -63 | 88 | 87 | 73 | 64 | 188 | -228 | 142 | 148 | 141 | 182 | 205 | | 113 | 163 | 4 | 157 | 241 |
| **166** | -65 | 90 | 86 | 73 | 64 | 186 | -228 | 108 | 145 | 140 | 180 | 203 | | 113 | 162 | 6 | 157 | 240 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **167** | -59 | 98 | 93 | 81 | 71 | 192 | -219 | 115 | 151 | 148 | 188 | 209 | 121 | 171 | 16 | 167 | 247 |
| **168** | -56 | 102 | 98 | 85 | 75 | 196 | -212 | 118 | 154 | 151 | 192 | 212 | 123 | 174 | 20 | 171 | 252 |
| **169** | -63 | 95 | 94 | 79 | 68 | 194 | -218 | 114 | 151 | 144 | 187 | 211 | 117 | 170 | 16 | 164 | 250 |
| **170** | -69 | 90 | 89 | 73 | 62 | 190 | -226 | 108 | 145 | 140 | 181 | 207 | 111 | 164 | 12 | 159 | 245 |
| **171** | -76 | 85 | 83 | 68 | 57 | 188 | -233 | 105 | 141 | 137 | 176 | 204 | 107 | 160 | 8 | 155 | 240 |
| **172** | -75 | 87 | 83 | 71 | 60 | 186 | -231 | 106 | 140 | 141 | 178 | 202 | 110 | 163 | 10 | 159 | 241 |
| **173** | -65 | 97 | 91 | 80 | 71 | 192 | -218 | 115 | 147 | 150 | 187 | 208 | 119 | 173 | 21 | 172 | 249 |
| **174** | -58 | 104 | 98 | 86 | 78 | 197 | -206 | 122 | 153 | 155 | 193 | 213 | 125 | 181 | 28 | 182 | 255 |
| **175** | -53 | 110 | 103 | 94 | 85 | 203 | -195 | 128 | 157 | 161 | 195 | 218 | 131 | 187 | 34 | 191 | 260 |
| **176** | -49 | 114 | 108 | 99 | 90 | 207 | -188 | 132 | 160 | 164 | 196 | 222 | 136 | 192 | 38 | 195 | 265 |
| **177** | -50 | 118 | 110 | 102 | 92 | 209 | -187 | 135 | 164 | 166 | 197 | 225 | 135 | 194 | 41 | 199 | 268 |
| **178** | -41 | 124 | 116 | 108 | 98 | 213 | -177 | 141 | 168 | 170 | 201 | 229 | 140 | 200 | 46 | 207 | 273 |
| **179** | -34 | 129 | 122 | 111 | 105 | 218 | -165 | 146 | 171 | 175 | 205 | 234 | 148 | 206 | 53 | 211 | 278 |
| **180** | -27 | 135 | 126 | 116 | 109 | 222 | -156 | 151 | 175 | 178 | 210 | 238 | 153 | 212 | 58 | 217 | 281 |
| **181** | -21 | 142 | 131 | 121 | 117 | 227 | -147 | 157 | 180 | 187 | 215 | 243 | 160 | 219 | 65 | 225 | 286 |
| **182** | -18 | 146 | 135 | 127 | 121 | 230 | -140 | 161 | 185 | 190 | 219 | 247 | 164 | 223 | 67 | 228 | 290 |
| **183** | -41 | 121 | 116 | 103 | 95 | 215 | -170 | 143 | 168 | 169 | 202 | 232 | 141 | 201 | 45 | 194 | 273 |
| **184** | -58 | 107 | 98 | 91 | 82 | 199 | -194 | 131 | 151 | 159 | 191 | 215 | 126 | 186 | 31 | 176 | 256 |
| **185** | -73 | 93 | 86 | 75 | 65 | 188 | -216 | 117 | 137 | 145 | 177 | 203 | 112 | 171 | 17 | 159 | 243 |
| **186** | -130 | 40 | 30 | 6 | 8 | 126 | -289 | 57 | 79 | 94 | 125 | 133 | 49 | 106 | -45 | 89 | 179 |
| **187** | -124 | 48 | 33 | 6 | 20 | 108 | -294 | 59 | 80 | 96 | 117 | 109 | 52 | 101 | -50 | 92 | 164 |
| **188** | -117 | 55 | 35 | 13 | 25 | 99 | -293 | 62 | 79 | 97 | 110 | 103 | 57 | 100 | -55 | 96 | 161 |
| **189** | -113 | 56 | 33 | 17 | 25 | 96 | -289 | 62 | 84 | 96 | 105 | 104 | 59 | 99 | -61 | 97 | 161 |
| **190** | -104 | 61 | 35 | 26 | 31 | 101 | -280 | 67 | 93 | 100 | 110 | 114 | 63 | 105 | -59 | 103 | 168 |
| **191** | -97 | 64 | 38 | 35 | 36 | 111 | -272 | 71 | 101 | 103 | 117 | 125 | 66 | 110 | -53 | 111 | 176 |
| **192** | -91 | 68 | 42 | 44 | 42 | 120 | -262 | 76 | 108 | 107 | 124 | 136 | 69 | 116 | -46 | 117 | 184 |
| **193** | -85 | 72 | 49 | 52 | 49 | 130 | -249 | 83 | 118 | 113 | 131 | 147 | 74 | 123 | -35 | 126 | 192 |
| **194** | -79 | 77 | 56 | 60 | 55 | 139 | -243 | 89 | 125 | 118 | 136 | 156 | 80 | 131 | -26 | 132 | 200 |
| **195** | -75 | 83 | 62 | 68 | 62 | 148 | -232 | 96 | 134 | 124 | 146 | 167 | 88 | 139 | -15 | 140 | 209 |
| **196** | -73 | 86 | 68 | 74 | 67 | 155 | -224 | 100 | 139 | 127 | 148 | 174 | 91 | 145 | -9 | 146 | 215 |
| **197** | -72 | 87 | 71 | 74 | 69 | 158 | -219 | 102 | 142 | 129 | 151 | 181 | 93 | 148 | -5 | 149 | 219 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **198** | -67 | 90 | 75 | 77 | 73 | 165 | -208 | 106 | 147 | 132 | 157 | 187 | | 97 | 152 | 1 | 154 | 224 |
| **199** | -62 | 93 | 79 | 82 | 76 | 169 | -200 | 109 | 150 | 137 | 163 | 193 | | 100 | 157 | 6 | 160 | 229 |
| **200** | -83 | 75 | 63 | 61 | 54 | 158 | -127 | 99 | 134 | 130 | 148 | 179 | | 93 | 139 | -14 | 149 | 216 |
| **201** | -102 | 69 | 57 | 55 | 44 | 152 | | | 118 | 113 | 147 | 170 | | 74 | 131 | -17 | 129 | 208 |
| **202** | -97 | 76 | 64 | 63 | 50 | 158 | | | 124 | 119 | 154 | 177 | | 81 | 139 | -10 | 137 | 215 |
| **203** | -94 | 79 | 69 | 66 | 54 | 161 | | | 127 | 123 | 156 | 183 | | 84 | 142 | -8 | 139 | 219 |
| **204** | -91 | 83 | 73 | 71 | 58 | 165 | | | 131 | 126 | 161 | 188 | | 89 | 147 | -2 | 143 | 224 |
| **205** | -87 | 87 | 78 | 76 | 64 | 170 | | | 136 | 131 | 168 | 193 | | 93 | 152 | 5 | 147 | 229 |
| **206** | -116 | 60 | 53 | 45 | 38 | 141 | | | 121 | 103 | 142 | 169 | | 66 | 126 | -23 | 120 | 205 |
| **207** | -157 | 22 | 11 | -9 | -2 | 93 | | | 64 | 63 | 99 | 108 | | 20 | 77 | -70 | 70 | 153 |
| **208** | -151 | 30 | 16 | -7 | 9 | 84 | | | 65 | 66 | 94 | 93 | | 25 | 85 | -74 | 73 | 144 |
| **209** | -148 | 32 | 16 | -3 | 11 | 113 | | | 64 | 66 | 109 | 101 | | 26 | 75 | -64 | 74 | 157 |
| **210** | -149 | 30 | 12 | 14 | 8 | 75 | | | 67 | 62 | 100 | 89 | | 24 | 73 | -84 | 72 | 140 |
| **211** | -155 | 22 | 5 | 5 | 4 | 76 | | | 66 | 56 | 90 | 85 | | 18 | 65 | -91 | 65 | 136 |
| **212** | -121 | 46 | 36 | 13 | 10 | 83 | | | 73 | 62 | 96 | 101 | | 24 | 73 | -84 | 73 | 144 |
| **213** | -133 | 35 | 18 | 21 | 16 | 93 | | | 79 | 68 | 103 | 106 | | 29 | 80 | -75 | 80 | 153 |
| **214** | -128 | 40 | 24 | 28 | 21 | 101 | | | 89 | 72 | 110 | 115 | | 34 | 87 | -66 | 87 | 161 |
| **215** | -133 | 35 | 22 | 21 | 14 | 97 | | | 85 | 65 | 108 | 117 | | 29 | 83 | -67 | 84 | 160 |
| **216** | -141 | 29 | 16 | 15 | 6 | 99 | | | 77 | 60 | 104 | 114 | | 23 | 76 | -73 | 79 | 157 |
| **217** | -134 | 36 | 24 | | 8 | 102 | -23 | | 83 | 68 | 110 | 121 | 44 | 30 | 86 | -67 | 87 | 163 |
| **218** | -126 | 43 | 31 | | 12 | 109 | -18 | | 92 | 75 | 116 | 128 | 51 | 38 | 93 | -55 | 95 | 170 |
| **219** | -120 | 48 | 37 | | 16 | 114 | -11 | | 100 | 80 | 120 | 135 | 53 | 43 | 99 | -51 | 101 | 176 |
| **220** | -115 | 53 | 42 | | 19 | 118 | -5 | | 104 | 84 | 127 | 141 | 57 | 48 | 104 | -48 | 107 | 182 |
| **221** | -110 | 58 | 48 | | 22 | 127 | -3 | | 110 | 89 | 132 | 148 | 59 | 54 | 111 | -40 | 112 | 188 |
| **222** | -149 | 22 | 12 | | -9 | 93 | -26 | | 67 | 53 | 99 | 113 | 29 | 20 | 74 | -76 | 72 | 152 |
| **223** | -144 | 31 | 20 | | -1 | 96 | -29 | | 71 | 62 | 106 | 113 | 38 | 23 | 79 | -68 | 80 | 156 |
| **224** | -137 | 39 | 27 | | 5 | 102 | -27 | | 78 | 69 | 112 | 119 | 46 | 30 | 86 | -60 | 87 | 162 |
| **225** | -132 | 43 | 32 | | 9 | 107 | -24 | | 86 | 73 | 116 | 125 | 47 | 35 | 90 | -56 | 93 | 167 |
| **226** | -132 | 43 | 33 | | 7 | 108 | -24 | | 88 | 72 | 117 | 127 | 46 | 35 | 90 | -58 | 92 | 169 |
| **227** | -148 | 28 | 19 | | -8 | 94 | -32 | | 70 | 57 | 103 | 113 | 33 | 20 | 75 | -72 | 77 | 154 |
| **228** | -146 | 31 | 22 | | -3 | 95 | -31 | | 72 | 62 | 105 | 112 | 37 | 24 | 77 | -69 | 82 | 156 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **229** | -139 | 38 | 28 | 3 | 99 | -29 | 79 | 67 | 110 | 117 | 42 | 30 | 82 | -64 | 87 | 162 |
| **230** | -133 | 42 | 32 | 8 | 104 | -24 | 84 | 72 | 115 | 124 | 47 | 34 | 87 | -60 | 92 | 167 |
| **231** | -127 | 47 | 37 | 11 | 111 | -17 | 91 | 77 | 120 | 130 | 49 | 40 | 93 | -55 | 98 | 172 |
| **232** | -121 | 51 | 41 | 14 | 116 | -10 | 95 | 81 | 124 | 136 | 50 | 45 | 99 | -51 | 103 | 177 |
| **233** | -116 | 55 | 46 | 18 | 120 | -9 | 99 | 86 | 127 | 142 | 58 | 50 | 104 | -45 | 108 | 183 |
| **234** | -114 | 56 | 47 | 17 | 121 | -7 | 101 | 87 | 128 | 145 | 60 | 52 | 105 | -43 | 109 | 185 |
| **235** | -137 | 36 | 28 | -3 | 108 | -20 | 80 | 66 | 113 | 129 | 38 | 37 | 83 | -62 | 86 | 167 |
| **236** | -138 | 37 | 29 | 0 | 109 | -28 | 74 | 67 | 115 | 128 | 39 | 27 | 83 | -61 | 87 | 167 |
| **237** | -132 | 44 | 35 | 6 | 115 | -27 | 80 | 75 | 122 | 133 | 46 | 35 | 92 | -52 | 95 | 174 |
| **238** | -131 | 45 | 39 | 7 | 117 | -27 | 83 | 76 | 125 | 136 | 47 | 36 | 93 | -50 | 97 | 176 |
| **239** | -129 | 47 | 42 | 7 | 120 | -24 | 85 | 79 | 126 | 138 | 48 | 38 | 95 | -48 | 99 | 178 |
| **240** | -124 | 51 | 46 | 9 | 122 | -20 | 89 | 83 | 129 | 141 | 49 | 42 | 99 | -45 | 103 | 182 |
| **241** | -120 | 54 | 49 | 10 | 124 | -15 | 93 | 87 | 132 | 145 | 55 | 46 | 103 | -41 | 108 | 186 |
| **242** | -119 | 54 | 50 | 11 | 124 | -11 | 94 | 88 | 133 | 148 | 57 | 49 | 105 | -39 | 110 | 188 |
| **243** | -116 | 58 | 54 | 12 | 128 | -10 | 100 | 93 | 139 | 152 | 62 | 52 | 110 | -32 | 113 | 192 |
| **244** | -114 | 62 | 58 | 12 | 130 | -7 | 103 | 95 | 143 | 154 | 64 | 56 | 113 | -29 | 117 | 196 |
| **245** | -117 | 57 | 56 | 7 | 128 | -11 | 100 | 92 | 140 | 155 | 57 | 53 | 110 | -33 | 146 | 196 |
| **246** | -172 | 0 | -1 | -52 | 75 | -48 | 40 | 37 | 82 | 94 | 3 | 11 | 51 | -87 | 60 | 135 |
| **247** | -190 | -25 | -20 | -60 | 31 | -68 | 4 | 12 | 42 | 35 | -16 | -26 | 17 | -101 | 44 | 89 |
| **248** | -188 | -37 | -21 | -63 | 8 | -80 | -18 | -2 | 12 | 11 | -26 | -39 | 0 | -102 | 44 | 69 |
| **249** | -186 | -36 | -22 | -53 | 4 | -74 | -13 | 0 | 5 | 12 | -19 | -38 | -3 | -103 | 45 | 67 |
| **250** | -184 | -33 | -23 | -46 | 10 | -67 | -1 | 7 | 12 | 22 | -10 | -35 | 2 | -105 | 44 | 74 |
| **251** | -180 | -26 | -28 | -39 | 36 | -60 | 13 | 15 | 44 | 52 | -2 | -29 | 9 | -92 | 44 | 101 |
| **252** | -180 | -3 | -10 | -32 | 27 | -55 | 26 | 22 | 34 | 46 | 5 | -20 | 17 | -107 | 44 | 94 |
| **253** | -181 | -16 | -29 | -29 | 36 | -35 | 42 | 27 | 43 | 57 | 10 | -14 | 25 | -107 | 43 | 103 |
| **254** | -186 | -18 | -22 | -7 | 41 | -49 | 52 | 52 | 47 | 62 | 28 | 10 | 24 | -106 | 44 | 105 |
| **255** | -198 | -32 | -21 | -34 | 37 | -56 | 44 | 22 | 39 | 53 | -1 | -14 | 14 | -104 | 44 | 97 |
| **256** | -196 | -22 | -23 | -32 | 43 | -50 | 51 | 28 | 49 | 61 | 7 | -3 | 21 | -103 | 44 | 105 |

| JPH 2011 | Water Table Loggers Depth Below Surface (mm) | | | | | | | JPH 2012 | Water Table Loggers Depth Below Surface (mm) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DOY | JPH A | JPH B | JPH C | JPH D | JPH E | JPH F | JPH G | DOY | JPH A | JPH B | JPH C | JPH D | JPH E | JPH F | JPH G |
| 100 | | | | | | | | 100 | | | 412 | -54 | 415 | 313 | 631 |
| 101 | | | | | | | | 101 | | | 363 | -48 | 401 | 310 | 625 |
| 102 | | | | | | | | 102 | | | 260 | -52 | -33 | 308 | 609 |
| 103 | | | | | | | | 103 | | | 203 | -53 | -38 | 303 | 562 |
| 104 | | | | | | | | 104 | | | 202 | -56 | -36 | 303 | 520 |
| 105 | | | | | | | | 105 | | | 234 | -45 | -34 | 303 | 523 |
| 106 | | | | | | | | 106 | | | 265 | -42 | -35 | 303 | 534 |
| 107 | | | | | | | | 107 | | | 287 | -42 | -33 | 304 | 548 |
| 108 | | | | | | | | 108 | | | 284 | -42 | -33 | 304 | 551 |
| 109 | | | | | | | | 109 | | | 266 | -43 | -44 | 303 | 542 |
| 110 | | | | | | | | 110 | | | 226 | -43 | -57 | 303 | 486 |
| 111 | | | | | | | | 111 | | | 180 | -49 | -61 | 303 | 386 |
| 112 | | | | | | | | 112 | | | 136 | -58 | -60 | 302 | 266 |
| 113 | | | | | | | | 113 | | | 144 | -60 | -63 | 302 | 169 |
| 114 | | | | | | | | 114 | | | 143 | -59 | -55 | 302 | 229 |
| 115 | | | | | | | | 115 | | | 146 | -56 | -52 | 302 | 291 |
| 116 | | | | | | | | 116 | | | 160 | -51 | -43 | 302 | 292 |
| 117 | | | | | | | | 117 | | | 172 | -49 | -32 | 301 | 284 |
| 118 | | | | | | | | 118 | | | 162 | -46 | -40 | 299 | 287 |
| 119 | | | | | | | | 119 | | | 164 | -40 | -35 | 298 | 328 |
| 120 | | | | | | | | 120 | | | 178 | -33 | -29 | 298 | 365 |
| 121 | | | | | | | | 121 | | | 194 | -24 | -25 | 297 | 392 |
| 122 | | | | | | | | 122 | | | 209 | -14 | 0 | 297 | 409 |
| 123 | | | | | | | | 123 | | | 220 | -5 | 4 | 297 | 421 |
| 124 | | | | | | | | 124 | | | 223 | 8 | 11 | 295 | 429 |
| 125 | | | | | | | | 125 | | | 222 | 21 | 14 | 294 | 435 |
| 126 | | | | | | | | 126 | | | 225 | 41 | 21 | 293 | 440 |
| 127 | | | | | | | | 127 | | | 234 | 63 | 28 | 290 | 453 |
| 128 | | | | | | | | 128 | | | 234 | 79 | 35 | 287 | 457 |
| 129 | | | | | | | | 129 | | | 205 | 71 | 29 | 276 | 439 |
| 130 | | | | | | | | 130 | | | 231 | 90 | 44 | 278 | 466 |
| 131 | | | | | | | | 131 | | | 245 | 114 | 66 | 277 | 478 |
| 132 | | | | | | | | 132 | | | 254 | 133 | 82 | 275 | 487 |
| 133 | | | | | | | | 133 | | | 264 | 153 | 101 | 275 | 496 |
| 134 | | | | | | | | 134 | | | 269 | 172 | 119 | 273 | 504 |
| 135 | | | | | | | | 135 | | | 278 | 190 | 136 | 272 | 512 |
| 136 | | | | | | | | 136 | | | 278 | 202 | 143 | 268 | 517 |
| 137 | | | | | | | | 137 | | | 209 | 150 | 89 | 253 | 472 |
| 138 | | | | | | | | 138 | | | 232 | 176 | 111 | 252 | 497 |
| 139 | | | | | | | | 139 | | | 113 | 69 | 26 | 211 | 359 |
| 140 | | | | | | | | 140 | | | 86 | 12 | 10 | 218 | 373 |
| 141 | | | | | | | | 141 | | | 137 | 59 | 40 | 233 | 423 |
| 142 | | | | | | | | 142 | | | 183 | 109 | 68 | 239 | 443 |
| 143 | | | | | | | | 143 | | | 222 | 153 | 100 | 243 | 462 |
| 144 | | | | | | | | 144 | | | 252 | 187 | 131 | 247 | 479 |
| 145 | | | | | | | | 145 | | | 269 | 207 | 151 | 250 | 489 |
| 145 | | | | | | | | 145 | 345 | 330 | 292 | 236 | 181 | 250 | 507 |
| 146 | | | | | | | | 146 | 347 | 331 | 311 | 248 | 175 | 263 | 516 |

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| **147** | | | | | | | |
| **148** | | | | | | | |
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| **168** | | | | | | | |
| **169** | | | | | | | |
| **170** | | | | | | | |
| **171** | | | | | | | |
| **172** | 33 | 20 | 62 | -30 | 24 | 92 | 260 |
| **173** | 35 | 41 | 82 | -21 | 35 | 108 | 534 |
| **174** | 45 | 81 | 116 | 2 | 57 | 125 | 565 |
| **175** | 7 | 19 | 57 | -24 | 24 | 76 | 607 |
| **176** | -7 | -5 | 41 | -45 | 13 | 90 | 431 |
| **177** | 25 | 20 | 76 | -33 | 39 | 115 | 456 |
| **178** | 37 | 44 | 105 | -18 | 60 | 122 | 536 |
| **179** | 32 | 67 | 128 | 0 | 78 | 132 | 573 |
| **180** | 44 | 113 | 170 | 33 | 104 | 146 | 610 |
| **181** | 40 | 89 | 138 | 33 | 90 | 119 | 675 |
| **182** | 26 | 71 | 103 | 7 | 63 | 130 | 595 |
| **183** | 25 | 105 | 138 | 35 | 86 | 138 | 614 |
| **184** | 9 | 83 | 108 | 17 | 67 | 131 | 635 |
| **185** | 12 | 142 | 165 | 59 | 91 | 153 | 614 |
| **186** | 27 | 184 | 221 | 113 | 131 | 167 | 701 |
| **187** | 39 | 183 | 221 | 128 | 142 | 164 | 739 |
| **188** | 25 | 95 | 136 | 62 | 94 | 122 | 743 |
| **189** | 1 | 33 | 70 | -3 | 48 | 107 | 596 |
| **190** | -16 | -3 | 61 | -23 | 36 | 120 | 526 |
| **191** | -21 | -28 | 125 | 9 | 74 | 158 | 524 |
| **192** | -17 | -26 | 186 | 59 | 115 | 173 | 630 |
| **193** | -9 | 2 | 231 | 105 | 149 | 179 | 697 |
| **194** | 3 | 62 | 248 | 133 | 165 | 181 | 733 |
| **195** | 15 | 119 | 261 | 152 | 176 | 187 | 745 |
| **196** | 36 | 171 | 279 | 177 | 191 | 194 | 746 |
| **197** | 63 | 202 | 294 | 195 | 203 | 200 | 747 |
| **198** | 94 | 216 | 304 | 210 | 215 | 204 | 748 |

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| **147** | 348 | 346 | 333 | 271 | 196 | 263 | 523 |
| **148** | 348 | 354 | 353 | 291 | 218 | 268 | 535 |
| **149** | 348 | 356 | 371 | 309 | 238 | 273 | 547 |
| **150** | 348 | 357 | 390 | 329 | 260 | 280 | 561 |
| **151** | 349 | 357 | 405 | 345 | 278 | 285 | 573 |
| **152** | 353 | 357 | 417 | 358 | 294 | 288 | 584 |
| **153** | 357 | 358 | 425 | 368 | 307 | 291 | 595 |
| **154** | 345 | 324 | 351 | 299 | 253 | 257 | 552 |
| **155** | 342 | 328 | 255 | 203 | 155 | 243 | 514 |
| **156** | 348 | 356 | 323 | 277 | 208 | 264 | 555 |
| **157** | 348 | 357 | 370 | 324 | 252 | 276 | 576 |
| **158** | 353 | 357 | 416 | 372 | 300 | 288 | 599 |
| **159** | 357 | 357 | 436 | 398 | 334 | 294 | 617 |
| **160** | 357 | 357 | 438 | 406 | 348 | 296 | 631 |
| **161** | 357 | 358 | 438 | 408 | 352 | 297 | 644 |
| **162** | 357 | 358 | 439 | 415 | 366 | 298 | 658 |
| **163** | 352 | 357 | 387 | 332 | 287 | 290 | 607 |
| **164** | 357 | 357 | 431 | 388 | 331 | 297 | 649 |
| **165** | 357 | 357 | 437 | 403 | 346 | 297 | 666 |
| **166** | 357 | 359 | 439 | 415 | 364 | 298 | 680 |
| **167** | 357 | 362 | 438 | 415 | 376 | 298 | 690 |
| **168** | 343 | 325 | 254 | 185 | 168 | 253 | 516 |
| **169** | 231 | 221 | 113 | 66 | 58 | 192 | 413 |
| **170** | 267 | 248 | 151 | 110 | 72 | 220 | 439 |
| **171** | 328 | 301 | 231 | 201 | 127 | 250 | 477 |
| **172** | 347 | 338 | 309 | 271 | 196 | 272 | 506 |
| **173** | 347 | 353 | 364 | 313 | 256 | 287 | 533 |
| **174** | 348 | 357 | 404 | 346 | 302 | 296 | 561 |
| **175** | 352 | 357 | 424 | 365 | 333 | 298 | 584 |
| **176** | 345 | 329 | 316 | 249 | 237 | 280 | 517 |
| **177** | 349 | 356 | 401 | 339 | 310 | 297 | 569 |
| **178** | 342 | 327 | 371 | 309 | 293 | 279 | 560 |
| **179** | 343 | 336 | 307 | 241 | 223 | 287 | 526 |
| **180** | 347 | 357 | 398 | 337 | 306 | 298 | 574 |
| **181** | 352 | 357 | 428 | 379 | 350 | 298 | 606 |
| **182** | 352 | 356 | 393 | 331 | 309 | 296 | 598 |
| **183** | 351 | 356 | 400 | 350 | 316 | 298 | 606 |
| **184** | 347 | 334 | 394 | 344 | 324 | 285 | 607 |
| **185** | 89 | 25 | 55 | -17 | 7 | 52 | 99 |
| **186** | 62 | 7 | 45 | -26 | -1 | 16 | 185 |
| **187** | 38 | 42 | 75 | -5 | 21 | 76 | 271 |
| **188** | 40 | 90 | 104 | 12 | 38 | 113 | 313 |
| **189** | -44 | -17 | 139 | -9 | 58 | 128 | 347 |
| **190** | -56 | -97 | -19 | -95 | -24 | 96 | 371 |
| **191** | -58 | -97 | -24 | -91 | -103 | -58 | 278 |
| **192** | -75 | -110 | -36 | -91 | -106 | -76 | 174 |
| **193** | -75 | -108 | -32 | -96 | -105 | -70 | 13 |
| **194** | -74 | -105 | -28 | -100 | -103 | -66 | -52 |
| **195** | -74 | -106 | -27 | -100 | -103 | -63 | 37 |
| **196** | -74 | -103 | -25 | -100 | -101 | -57 | 176 |
| **197** | -75 | -106 | -26 | -100 | -97 | -53 | 248 |
| **198** | -69 | -105 | -28 | -103 | -93 | -50 | 277 |

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| **199** | 127 | 230 | 316 | 223 | 223 | 209 | 747 |
| **200** | 143 | 221 | 295 | 210 | 209 | 200 | 747 |
| **201** | 65 | 62 | 109 | 41 | 84 | 127 | 734 |
| **202** | 72 | 63 | 112 | 24 | 75 | 155 | 578 |
| **203** | 79 | 104 | 151 | 53 | 102 | 172 | 642 |
| **204** | 95 | 136 | 188 | 85 | 127 | 188 | 672 |
| **205** | 121 | 174 | 236 | 131 | 163 | 204 | 715 |
| **206** | 151 | 209 | 281 | 178 | 201 | 214 | 743 |
| **207** | 140 | 174 | 231 | 149 | 176 | 187 | 747 |
| **208** | 136 | 153 | 170 | 92 | 126 | 185 | 709 |
| **209** | 122 | 120 | 157 | 83 | 123 | 180 | 723 |
| **210** | 115 | 55 | 100 | 10 | 95 | 195 | 619 |
| **211** | 138 | 109 | 157 | 47 | 135 | 205 | 635 |
| **212** | 152 | 137 | 188 | 74 | 157 | 210 | 691 |
| **213** | 175 | 172 | 226 | 111 | 184 | 218 | 722 |
| **214** | 184 | 189 | 234 | 131 | 193 | 214 | 743 |
| **215** | 193 | 203 | 239 | 141 | 190 | 217 | 743 |
| **216** | 197 | 233 | 288 | 186 | 226 | 229 | 747 |
| **217** | 197 | 250 | 314 | 217 | 242 | 234 | 748 |
| **218** | 197 | 251 | 311 | 221 | 236 | 232 | 748 |
| **219** | 200 | 272 | 331 | 242 | 251 | 240 | 748 |
| **220** | 202 | 286 | 335 | 251 | 259 | 243 | 748 |
| **221** | 206 | 306 | 345 | 265 | 264 | 247 | 749 |
| **222** | 206 | 318 | 355 | 277 | 272 | 252 | 751 |
| **223** | 206 | 329 | 366 | 288 | 280 | 257 | 753 |
| **224** | 200 | 289 | 313 | 227 | 236 | 254 | 759 |
| **225** | 195 | 316 | 345 | 253 | 253 | 254 | 686 |
| **226** | 331 | 291 | 309 | 214 | 229 | 270 | 564 |
| **227** | 347 | 335 | 369 | 276 | 269 | 275 | 542 |
| **228** | 347 | 347 | 385 | 299 | 288 | 275 | 579 |
| **229** | 346 | 351 | 376 | 298 | 286 | 273 | 589 |
| **230** | 346 | 348 | 367 | 291 | 279 | 276 | 593 |
| **231** | 346 | 352 | 374 | 298 | 283 | 283 | 592 |
| **232** | 346 | 355 | 395 | 316 | 302 | 288 | 598 |
| **233** | 351 | 356 | 406 | 327 | 312 | 291 | 604 |
| **234** | 357 | 356 | 414 | 336 | 319 | 292 | 613 |
| **235** | 357 | 357 | 409 | 334 | 312 | 296 | 621 |
| **236** | 357 | 357 | 422 | 349 | 329 | 296 | 627 |
| **237** | 357 | 357 | 423 | 352 | 330 | 297 | 635 |
| **238** | 357 | 357 | 427 | 359 | 337 | 297 | 640 |
| **239** | 357 | 357 | 432 | 368 | 345 | 260 | 646 |
| **240** | 345 | 313 | 320 | 243 | 248 | 264 | 653 |
| **241** | 346 | 327 | 271 | 210 | 195 | 285 | 572 |
| **242** | 346 | 354 | 336 | 276 | 254 | 293 | 542 |
| **243** | 353 | 357 | 372 | 310 | 289 | 295 | 582 |
| **244** | 357 | 357 | 395 | 330 | 308 | 295 | 610 |
| **245** | 358 | 358 | 412 | 348 | 322 | 294 | 630 |
| **246** | 357 | 357 | 427 | 367 | 339 | 295 | 646 |
| **247** | 357 | 357 | 435 | 380 | 353 | 294 | 655 |
| **248** | 357 | 357 | 435 | 384 | 356 | 294 | 663 |
| **249** | 357 | 357 | 437 | 393 | 365 | 294 | 672 |
| **250** | 357 | 357 | 437 | 397 | 367 | 294 | 681 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **199** | -79 | -116 | -33 | -114 | -102 | -63 |
| **200** | -96 | -132 | -45 | -116 | -103 | -99 |
| **201** | -102 | -133 | -54 | -118 | -101 | -100 |
| **202** | -104 | -133 | -55 | -118 | -102 | -99 |
| **203** | -109 | -134 | -58 | -118 | -101 | -101 |
| **204** | -113 | -137 | -62 | -118 | -102 | -104 |
| **205** | -115 | -136 | -62 | -118 | -102 | -104 |
| **206** | -119 | -136 | -62 | -118 | -103 | -103 |
| **207** | -122 | -133 | -63 | -118 | -103 | -100 |
| **208** | -123 | -136 | -69 | -118 | -103 | -101 |
| **209** | -120 | -149 | -76 | -119 | -104 | -102 |
| **210** | -113 | -151 | -86 | -119 | -104 | -103 |
| **211** | -104 | -140 | -88 | -120 | -105 | -104 |
| **212** | -93 | -119 | -72 | -120 | -105 | -104 |
| **213** | -88 | -106 | -58 | -120 | -106 | -100 |
| **214** | -77 | -100 | -53 | -121 | -106 | -103 |
| **215** | -72 | -98 | -41 | -113 | -106 | -101 |
| **216** | -59 | -99 | -37 | -116 | -108 | -102 |
| **217** | -49 | -90 | -28 | -108 | -108 | -101 |
| **218** | -44 | -78 | -14 | -98 | -108 | -90 |
| **219** | -41 | -73 | 3 | -84 | -110 | -68 |
| **220** | -27 | -55 | 30 | -65 | -110 | -45 |
| **221** | -27 | -57 | 33 | -64 | -111 | -35 |
| **222** | -11 | -45 | 54 | -51 | -75 | -14 |
| **223** | 0 | -13 | 83 | -26 | -37 | 25 |
| **224** | 2 | 41 | 111 | -5 | -20 | 60 |
| **225** | 18 | 79 | 121 | 12 | -3 | 74 |
| **226** | 42 | 110 | 131 | 24 | 2 | 84 |
| **227** | 66 | 155 | 168 | 58 | 19 | 106 |
| **228** | 89 | 186 | 201 | 96 | 36 | 123 |
| **229** | 113 | 207 | 227 | 130 | 58 | 135 |
| **230** | 146 | 235 | 260 | 168 | 90 | 151 |
| **231** | 178 | 258 | 292 | 201 | 121 | 165 |
| **232** | 208 | 276 | 312 | 223 | 147 | 174 |
| **233** | 222 | 276 | 303 | 219 | 150 | 172 |
| **234** | 172 | 182 | 211 | 137 | 98 | 126 |
| **235** | 146 | 133 | 132 | 53 | 37 | 123 |
| **236** | 185 | 202 | 202 | 117 | 76 | 159 |
| **237** | 210 | 233 | 246 | 162 | 109 | 171 |
| **238** | 242 | 267 | 285 | 200 | 142 | 182 |
| **239** | 276 | 295 | 322 | 236 | 174 | 189 |
| **240** | 307 | 310 | 342 | 257 | 193 | 195 |
| **241** | 328 | 316 | 346 | 261 | 200 | 198 |
| **242** | 344 | 327 | 353 | 268 | 203 | 203 |
| **243** | 345 | 339 | 364 | 280 | 217 | 209 |
| **244** | 345 | 339 | 358 | 274 | 215 | 207 |
| **245** | 118 | 58 | 96 | 27 | 30 | 74 |
| **246** | 14 | -42 | 4 | -72 | -59 | -28 |
| **247** | -30 | -79 | -19 | -94 | -68 | -34 |
| **248** | -45 | -95 | -27 | -101 | -98 | -66 |
| **249** | -56 | -104 | -41 | -114 | -98 | -84 |
| **250** | -60 | -104 | -44 | -120 | -98 | -88 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **251** | 357 | 357 | 437 | 402 | 372 | 295 | 689 |
| **252** | 357 | 357 | 438 | 408 | 378 | 294 | 697 |
| **253** | 358 | 359 | 438 | 410 | 380 | 294 | 706 |
| **254** | 358 | 362 | 436 | 392 | 358 | 294 | 714 |
| **255** | 359 | 360 | 437 | 393 | 352 | 294 | 712 |
| **256** | 359 | 366 | 437 | 402 | 358 | 294 | 720 |
| **257** | 359 | 367 | 438 | 409 | 366 | 294 | 724 |
| **258** | 358 | 363 | 416 | 370 | 329 | 259 | 728 |
| **259** | 349 | 322 | 228 | 159 | 165 | 239 | 702 |
| **260** | 328 | 269 | 162 | 108 | 111 | 274 | 537 |
| **261** | 347 | 319 | 252 | 210 | 179 | 290 | 470 |
| **262** | 347 | 345 | 304 | 253 | 234 | 293 | 519 |
| **263** | 347 | 354 | 338 | 278 | 270 | 294 | 544 |
| **264** | 349 | 357 | 364 | 298 | 297 | 294 | 564 |
| **265** | 358 | 358 | 379 | 310 | 313 | 295 | 584 |
| **266** | 358 | 358 | 392 | 323 | 325 | 295 | 601 |
| **267** | 358 | 358 | 403 | 333 | 334 | 295 | 617 |
| **268** | 358 | 358 | 413 | 344 | 343 | 295 | 634 |
| **269** | 359 | 358 | 420 | 353 | 349 | 295 | 650 |
| **270** | 359 | 358 | 427 | 359 | 351 | 295 | 666 |
| **271** | 359 | 358 | 431 | 364 | 352 | 295 | 681 |
| **272** | 359 | 358 | 433 | 371 | 355 | 296 | 692 |
| **273** | 359 | 359 | 436 | 383 | 361 | 296 | 700 |
| **274** | 359 | 359 | 437 | 389 | 362 | 295 | 712 |
| **275** | 359 | 359 | 437 | 390 | 360 | 295 | 722 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **251** | -56 | -102 | -43 | -119 | -97 | -87 |
| **252** | -52 | -97 | -43 | -117 | -97 | -84 |
| **253** | -56 | -100 | -46 | -118 | -97 | -87 |
| **254** | -106 | -145 | -59 | -122 | -95 | -128 |
| **255** | -122 | -154 | -79 | -121 | -93 | -141 |
| **256** | -123 | -157 | -83 | -121 | -92 | -143 |

## Appendix 5 Meteorological Station

| ML Fen 2011 | | | | | | Ground/Water temperature | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DOY | Wind Speed ($ms^{-1}$) Daily Mean | Wind Direction (°) Daily Mean | Air Temp. (°C) Daily Mean | Relative Humidity (%) Daily Mean | Precip (mm) Daily Total | ~10 cm below (°C) daily Average | ~20 cm below (°C) daily Average | ~40 cm below (°C) daily Average | Net Radiation $W(m^{2})^{-1}$ Daily Mean | Air Pressure (Kpa) Daily Mean |
| **159** | 0.20 | 70.37 | 14.15 | 50.52 | 0.00 | 13.49 | 15.16 | 15.08 | 48.54 | 93.72 |
| **160** | 0.20 | 92.84 | 15.62 | 50.76 | 0.00 | 13.77 | 17.28 | 17.17 | 149.01 | 93.35 |
| **161** | 0.20 | 119.46 | 16.95 | 48.64 | 1.02 | 14.60 | 17.85 | 17.34 | 71.22 | 92.97 |
| **162** | 1.15 | 136.60 | 13.75 | 57.53 | 2.03 | 11.09 | 14.68 | 13.89 | 183.04 | 92.86 |
| **163** | 1.46 | 225.30 | 13.14 | 53.41 | 0.00 | 5.92 | 8.80 | 8.26 | 96.85 | 92.76 |
| **164** | 1.11 | 181.18 | 14.92 | 54.38 | 0.00 | 6.06 | 8.91 | 8.13 | 108.28 | 92.69 |
| **165** | 1.46 | 161.67 | 13.93 | 72.16 | 11.94 | 6.23 | 9.45 | 8.27 | 53.58 | 92.87 |
| **166** | 2.92 | 247.77 | 12.55 | 90.22 | 14.48 | 6.46 | 9.82 | 8.70 | 12.88 | 92.75 |
| **167** | 3.80 | 258.29 | 12.75 | 88.95 | 10.92 | 6.68 | 9.82 | 8.98 | 32.10 | 92.77 |
| **168** | 3.44 | 298.90 | 13.03 | 83.66 | 1.52 | 6.86 | 9.96 | 9.24 | 74.39 | 93.10 |
| **169** | 3.95 | 259.13 | 13.02 | 88.94 | 3.30 | 7.02 | 10.12 | 9.45 | 9.48 | 92.64 |
| **170** | 4.12 | 276.47 | 14.07 | 81.42 | 2.79 | 7.17 | 10.03 | 9.60 | 51.60 | 92.79 |
| **171** | 3.88 | 302.80 | 14.11 | 86.53 | 1.02 | 7.30 | 10.29 | 9.69 | 28.13 | 92.97 |
| **172** | 1.99 | 176.92 | 15.72 | 75.51 | 7.37 | 7.43 | 10.57 | 9.88 | 79.43 | 93.06 |
| **173** | 1.84 | 200.63 | 16.34 | 53.33 | 0.00 | 7.58 | 10.77 | 10.20 | 146.00 | 93.22 |
| **174** | 2.71 | 131.94 | 20.28 | 42.99 | 0.00 | 7.73 | 11.05 | 10.34 | 176.43 | 92.81 |
| **175** | 2.84 | 150.22 | 15.28 | 76.33 | 6.60 | 7.90 | 11.35 | 10.67 | 16.33 | 92.43 |
| **176** | 2.59 | 234.67 | 10.37 | 92.65 | 18.29 | 8.10 | 11.16 | 10.81 | 16.00 | 92.34 |
| **177** | 2.98 | 146.98 | 11.52 | 71.94 | 1.02 | 8.23 | 10.89 | 10.57 | 101.23 | 92.98 |
| **178** | 2.81 | 113.24 | 8.75 | 78.79 | 6.35 | 8.29 | 10.58 | 10.49 | 54.01 | 93.19 |
| **179** | 2.30 | 168.80 | 14.14 | 74.56 | 0.00 | 8.32 | 10.60 | 10.30 | 148.15 | 92.30 |
| **180** | 3.15 | 248.65 | 17.69 | 64.19 | 2.29 | 8.35 | 11.25 | 10.86 | 153.57 | 91.58 |
| **181** | 4.10 | 274.54 | 14.89 | 57.38 | 0.00 | 8.48 | 11.68 | 11.39 | 172.46 | 92.11 |
| **182** | 4.36 | 251.64 | 12.84 | 55.06 | 0.00 | 8.65 | 11.53 | 11.44 | 162.80 | 92.80 |
| **183** | 3.83 | 247.18 | 15.76 | 45.32 | 0.00 | 8.77 | 11.33 | 11.20 | 141.26 | 93.06 |
| **184** | 3.08 | 194.11 | 16.10 | 62.04 | 1.02 | 8.85 | 11.42 | 11.15 | 86.08 | 92.70 |
| **185** | 5.32 | 273.52 | 14.62 | 49.56 | 0.00 | 8.92 | 11.41 | 11.18 | 174.90 | 93.16 |
| **186** | 4.35 | 272.61 | 16.65 | 44.95 | 0.00 | 8.98 | 11.27 | 11.14 | 121.48 | 93.54 |
| **187** | 2.28 | 262.06 | 17.68 | 50.73 | 0.00 | 9.03 | 11.37 | 11.13 | 176.87 | 93.65 |
| **188** | 1.84 | 139.45 | 16.70 | 68.56 | 0.00 | 9.09 | 11.85 | 11.37 | 100.08 | 93.25 |
| **189** | 4.41 | 124.74 | 16.28 | 68.86 | 8.13 | 9.22 | 12.22 | 11.68 | 94.89 | 91.76 |
| **190** | 3.25 | 134.30 | 13.45 | 88.66 | 27.69 | 9.38 | 12.21 | 11.90 | 11.35 | 91.89 |
| **191** | 3.34 | 70.44 | 14.29 | 77.32 | 0.76 | 9.51 | 12.24 | 11.84 | 84.25 | 93.12 |
| **192** | 1.99 | 141.95 | 14.95 | 57.92 | 0.00 | 9.58 | 12.21 | 11.85 | 166.92 | 93.92 |
| **193** | 2.24 | 151.66 | 13.76 | 66.66 | 0.00 | 9.65 | 12.26 | 11.97 | 95.48 | 93.75 |
| **194** | 1.04 | 125.49 | 16.51 | 71.14 | 0.00 | 9.71 | 12.29 | 11.95 | 72.51 | 93.07 |
| **195** | 2.08 | 145.34 | 16.71 | 82.47 | 9.91 | 9.78 | 12.68 | 12.24 | 66.07 | 92.32 |
| **196** | 2.65 | 251.01 | 15.85 | 70.58 | 0.25 | 9.90 | 13.09 | 12.50 | 111.45 | 91.91 |
| **197** | 1.53 | 200.51 | 15.80 | 73.64 | 0.00 | 10.03 | 13.20 | 12.76 | 95.87 | 92.63 |
| **198** | 1.96 | 145.66 | 18.50 | 62.39 | 0.00 | 10.17 | 13.38 | 13.01 | 176.42 | 93.32 |
| **199** | 2.68 | 186.30 | 19.41 | 69.69 | 1.78 | 10.31 | 13.77 | 13.42 | 112.80 | 92.88 |
| **200** | 3.42 | 261.27 | 17.59 | 61.78 | 0.00 | 10.48 | 14.04 | 13.71 | 166.28 | 92.47 |
| **201** | 3.51 | 283.90 | 15.06 | 64.27 | 0.00 | 10.66 | 13.91 | 13.76 | 84.57 | 92.37 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **202** | 2.51 | 197.86 | 14.41 | 71.05 | 0.00 | 10.78 | 13.64 | 13.51 | 125.65 | 92.67 |
| **203** | 3.52 | 127.03 | 13.50 | 86.67 | 2.29 | 10.85 | 13.61 | 13.46 | 52.56 | 93.15 |
| **204** | 2.95 | 160.31 | 12.41 | 87.56 | 5.59 | 10.92 | 13.38 | 13.35 | 52.08 | 93.12 |
| **205** | 2.15 | 232.07 | 13.97 | 84.85 | 6.10 | 10.94 | 13.43 | 13.21 | 80.50 | 93.25 |
| **206** | 3.63 | 254.60 | 18.58 | 57.78 | 0.00 | 10.97 | 13.58 | 13.28 | 155.00 | 92.93 |
| **207** | 2.77 | 274.51 | 18.32 | 57.69 | 0.00 | 11.02 | 13.65 | 13.45 | 154.38 | 92.47 |
| **208** | 2.85 | 271.80 | 13.80 | 83.28 | 17.53 | 11.09 | 13.71 | 13.57 | 44.13 | 92.63 |
| **209** | 3.52 | 263.80 | 14.55 | 69.37 | 0.25 | 11.18 | 13.60 | 13.42 | 87.30 | 93.12 |
| **210** | 3.07 | 249.35 | 13.81 | 69.66 | 1.02 | 11.21 | 13.37 | 13.26 | 47.59 | 92.96 |
| **211** | 2.71 | 239.36 | 15.09 | 62.98 | 0.00 | 11.22 | 13.20 | 13.09 | 138.40 | 93.19 |
| **212** | 2.56 | 217.18 | 15.74 | 69.28 | 1.27 | 11.20 | 13.27 | 13.11 | 89.33 | 92.86 |
| **213** | 4.37 | 266.81 | 13.96 | 66.37 | 0.00 | 11.22 | 13.33 | 13.25 | 84.21 | 92.90 |
| **214** | 3.55 | 267.75 | 15.68 | 56.16 | 0.00 | 11.24 | 13.16 | 13.07 | 134.11 | 93.03 |
| **215** | 2.55 | 273.29 | 14.24 | 67.45 | 0.51 | 11.24 | 13.08 | 12.97 | 122.80 | 93.10 |
| **216** | 1.97 | 246.93 | 15.79 | 62.66 | 0.00 | 11.24 | 13.04 | 12.91 | 136.85 | 93.39 |
| **217** | 2.12 | 148.28 | 16.79 | 60.85 | 0.00 | 11.24 | 13.25 | 12.97 | 131.32 | 93.28 |
| **218** | 2.41 | 185.79 | 13.86 | 83.73 | 1.52 | 11.28 | 13.42 | 13.11 | 6.13 | 93.01 |
| **219** | 2.39 | 288.30 | 11.84 | 88.70 | 2.29 | 11.34 | 12.99 | 13.07 | 28.74 | 92.98 |
| **220** | 1.64 | 250.85 | 16.62 | 68.72 | 0.00 | 11.32 | 12.88 | 12.82 | 143.68 | 93.33 |
| **221** | 1.80 | 180.14 | 16.76 | 67.26 | 0.00 | 11.29 | 13.31 | 12.85 | 119.36 | 93.11 |
| **222** | 1.90 | 228.88 | 14.49 | 68.42 | 0.00 | 11.33 | 13.34 | 13.05 | 117.58 | 93.01 |
| **223** | 1.54 | 98.87 | 14.78 | 64.22 | 0.00 | 11.38 | 13.15 | 13.05 | 113.33 | 93.27 |
| **224** | 2.35 | 203.35 | 17.03 | 65.22 | 2.29 | 11.41 | 13.16 | 12.95 | 100.90 | 93.47 |
| **225** | 2.00 | 131.99 | 16.33 | 73.71 | 4.57 | 11.43 | 13.40 | 12.97 | 85.51 | 93.27 |
| **226** | 2.60 | 153.50 | 17.66 | 74.79 | 2.29 | 11.48 | 13.64 | 13.10 | 120.70 | 92.81 |
| **227** | 3.33 | 276.82 | 13.48 | 71.78 | 4.32 | 11.56 | 13.91 | 13.32 | 77.30 | 92.77 |
| **228** | 3.99 | 269.22 | 12.81 | 64.68 | 0.00 | 11.65 | 13.44 | 13.25 | 119.83 | 92.97 |
| **229** | 3.78 | 273.40 | 12.64 | 65.16 | 0.00 | 11.66 | 13.09 | 12.98 | 118.69 | 92.99 |
| **230** | 2.58 | 282.02 | 9.64 | 83.10 | 2.03 | 11.61 | 12.82 | 12.76 | 52.91 | 93.27 |
| **231** | 2.21 | 236.89 | 10.84 | 76.98 | 2.54 | 11.55 | 12.50 | 12.55 | 67.68 | 93.46 |
| **232** | 1.89 | 195.20 | 12.47 | 71.31 | 0.00 | 11.46 | 12.33 | 12.35 | 66.98 | 93.27 |
| **233** | 2.88 | 193.25 | 18.66 | 62.25 | 0.00 | 11.38 | 12.53 | 12.23 | 105.03 | 92.50 |
| **234** | 2.72 | 252.55 | 19.47 | 54.95 | 0.00 | 11.34 | 12.95 | 12.33 | 95.63 | 92.17 |
| **235** | 4.66 | 275.51 | 15.19 | 63.75 | 0.25 | 11.38 | 12.99 | 12.60 | 74.58 | 92.45 |
| **236** | 3.30 | 236.75 | 14.76 | 57.08 | 0.00 | 11.42 | 12.61 | 12.56 | 73.63 | 92.94 |
| **237** | 4.15 | 279.22 | 12.35 | 60.53 | 0.00 | 11.40 | 12.34 | 12.46 | 86.18 | 93.23 |
| **238** | 1.96 | 229.08 | 13.49 | 63.36 | 0.00 | 11.34 | 11.95 | 12.08 | 81.24 | 93.81 |
| **239** | 2.30 | 235.82 | 16.80 | 56.47 | 0.00 | 11.24 | 12.05 | 11.91 | 86.37 | 93.35 |
| **240** | 2.14 | 249.65 | 14.71 | 59.48 | 0.00 | 11.19 | 12.16 | 11.96 | 112.28 | 93.49 |
| **241** | 2.61 | 215.79 | 15.49 | 70.94 | 0.00 | 11.16 | 12.28 | 12.00 | 26.10 | 92.73 |
| **242** | 3.56 | 274.98 | 11.97 | 73.53 | 0.00 | 11.17 | 12.22 | 11.99 | 79.81 | 92.70 |
| **243** | 3.50 | 284.19 | 9.18 | 72.83 | 0.00 | 11.16 | 11.95 | 11.76 | 70.87 | 93.18 |
| **244** | 1.67 | 237.26 | 9.71 | 65.06 | 0.00 | 11.11 | 11.47 | 11.46 | 86.36 | 93.08 |
| **245** | 1.82 | 168.42 | 9.20 | 70.19 | 0.00 | 11.00 | 11.27 | 11.26 | 80.84 | 93.27 |
| **246** | 2.32 | 206.14 | 8.99 | 73.00 | 0.00 | 10.89 | 11.01 | 11.12 | 78.71 | 93.95 |
| **247** | 4.00 | 218.27 | 16.12 | 54.56 | 0.00 | 10.78 | 11.04 | 10.99 | 83.39 | 93.01 |
| **248** | 3.35 | 254.39 | 16.76 | 53.31 | 0.00 | 10.71 | 11.29 | 11.06 | 88.22 | 92.80 |
| **249** | 3.50 | 249.56 | 18.53 | 50.75 | 0.00 | 10.69 | 11.46 | 11.28 | 87.96 | 93.46 |
| **250** | 2.89 | 235.61 | 20.57 | 45.92 | 0.00 | 10.71 | 11.70 | 11.37 | 92.22 | 93.89 |
| **251** | 1.75 | 224.51 | 19.68 | 54.56 | 0.00 | 10.75 | 11.88 | 11.55 | 100.64 | 94.11 |
| **252** | 2.79 | 228.36 | 20.45 | 52.35 | 0.00 | 10.80 | 12.06 | 11.60 | 93.29 | 93.84 |
| **253** | 2.24 | 247.44 | 15.70 | 51.03 | 0.00 | 10.87 | 12.16 | 11.70 | 82.12 | 93.74 |

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|---|---|---|---|---|---|---|---|---|---|---|
| **254** | 1.89 | 232.50 | 10.38 | 73.36 | 1.52 | 10.93 | 11.86 | 11.56 | 14.23 | 93.68 |
| **255** | 3.12 | 223.43 | 8.27 | 75.35 | 0.25 | 10.92 | 11.27 | 11.32 | 55.46 | 93.94 |
| **256** | 1.34 | 123.28 | 2.73 | 63.44 | 0.25 | 10.83 | 10.69 | 10.77 | 61.63 | 94.77 |
| **257** | 3.37 | 163.66 | 6.00 | 49.81 | 0.00 | 10.67 | 10.00 | 10.25 | 66.47 | 94.05 |
| **258** | 2.45 | 163.51 | 10.74 | 51.50 | 0.00 | 10.45 | 9.60 | 10.13 | 55.64 | 92.73 |
| **259** | 3.41 | 195.62 | 9.32 | 88.49 | 9.65 | 10.25 | 9.90 | 10.11 | -4.53 | 91.79 |
| **260** | 5.42 | 276.44 | 8.99 | 84.04 | 7.37 | 10.14 | 10.01 | 10.05 | 27.35 | 92.27 |
| **261** | 2.95 | 264.42 | 8.96 | 76.22 | 0.00 | 10.08 | 10.03 | 9.92 | 55.05 | 92.77 |
| **262** | 2.47 | 263.77 | 8.08 | 74.17 | 1.02 | 10.02 | 9.94 | 9.85 | 55.30 | 93.12 |
| **263** | 2.01 | 226.30 | 9.29 | 73.27 | 0.00 | 9.95 | 9.63 | 9.79 | 58.27 | 93.83 |
| **264** | 4.11 | 174.45 | 13.16 | 51.53 | 0.00 | 9.86 | 9.51 | 9.68 | 46.76 | 92.98 |
| **265** | 3.41 | 244.15 | 13.85 | 45.88 | 0.00 | 9.78 | 9.69 | 9.75 | 41.05 | 92.65 |
| **266** | 2.95 | 200.34 | 15.48 | 57.73 | 0.00 | 9.73 | 9.70 | 9.75 | 29.55 | 92.47 |
| **267** | 1.79 | 228.26 | 12.67 | 58.28 | 0.00 | 9.71 | 9.95 | 9.77 | 56.61 | 92.98 |
| **268** | 4.09 | 161.16 | 18.51 | 51.27 | 0.00 | 9.70 | 9.93 | 9.74 | 44.86 | 92.13 |
| **269** | 3.73 | 248.07 | 12.11 | 51.20 | 0.00 | 9.71 | 10.21 | 9.82 | 41.91 | 92.28 |
| **270** | 2.99 | 242.01 | 11.46 | 47.94 | 0.00 | 9.73 | 9.82 | 9.71 | 37.34 | 92.24 |
| **271** | 3.56 | 287.93 | 7.87 | 68.68 | 0.00 | 9.70 | 9.45 | 9.52 | 8.17 | 93.54 |
| **272** | 3.10 | 183.31 | 6.97 | 69.67 | 0.00 | 9.62 | 9.04 | 9.27 | 34.71 | 93.97 |
| **273** | 3.82 | 226.25 | 10.55 | 49.32 | 0.00 | 9.49 | 8.80 | 9.18 | 29.29 | 92.49 |
| **274** | 2.29 | 232.60 | 7.21 | 51.23 | 0.00 | 9.37 | 8.79 | 9.08 | 35.52 | 93.41 |
| **275** | 2.65 | 123.96 | 5.47 | 77.30 | 0.00 | 9.26 | 8.60 | 8.79 | -3.90 | 93.81 |
| **276** | 3.83 | 128.89 | 4.89 | 90.62 | 0.25 | 9.16 | 8.42 | 8.73 | 10.40 | 93.52 |

| **ML Bog 2011** | | | | | | Ground/Water temperature | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DOY | Wind Speed ($ms^{-1}$) Daily Mean | Wind Direction (°) Daily Mean | Air Temp. (°C) Daily Mean | Relative Humidity (%) Daily Mean | Precip (mm) Daily Total | ~10 cm below (°C) daily Average | ~20 cm below (°C) daily Average | ~40 cm below (°C) daily Average | Net Radiation $W(m^{2})^{-1}$ Daily Mean | Air Pressure (Kpa) Daily Mean |
| **159** | 0.20 | 125.32 | 13.92 | 51.76 | 0.25 | 6.66 | 10.99 | 5.95 | 113.29 | 93.75 |
| **160** | 0.20 | 108.34 | 16.24 | 48.64 | 0.00 | 5.63 | 10.20 | 4.57 | 176.99 | 93.33 |
| **161** | 0.20 | 159.87 | 16.61 | 51.84 | 0.76 | 5.98 | 11.74 | 4.82 | 85.83 | 92.97 |
| **162** | 0.99 | 162.71 | 13.46 | 56.79 | 2.54 | 6.37 | 11.93 | 5.12 | 211.47 | 92.88 |
| **163** | 1.05 | 169.29 | 13.48 | 52.72 | 0.00 | 6.72 | 11.61 | 5.37 | 112.95 | 92.76 |
| **164** | 0.89 | 191.39 | 15.22 | 54.97 | 0.00 | 6.90 | 11.92 | 5.51 | 133.50 | 92.71 |
| **165** | 1.09 | 194.09 | 13.76 | 75.16 | 13.97 | 7.11 | 12.86 | 5.73 | 68.44 | 92.89 |
| **166** | 2.08 | 291.90 | 12.46 | 92.16 | 16.00 | 7.34 | 12.96 | 6.07 | 28.83 | 92.76 |
| **167** | 2.60 | 283.83 | 12.66 | 90.74 | 10.41 | 7.47 | 12.83 | 6.27 | 37.92 | 92.80 |
| **168** | 2.15 | 177.42 | 13.21 | 84.69 | 2.29 | 7.49 | 12.59 | 6.43 | 89.63 | 93.12 |
| **169** | 2.70 | 305.50 | 12.97 | 90.09 | 3.30 | 7.50 | 12.04 | 6.59 | 17.29 | 92.64 |
| **170** | 2.70 | 253.95 | 14.21 | 82.53 | 2.79 | 7.47 | 11.58 | 6.71 | 59.10 | 92.82 |
| **171** | 2.37 | 148.17 | 14.14 | 87.60 | 1.52 | 7.44 | 12.14 | 6.77 | 37.81 | 92.99 |
| **172** | 1.24 | 141.56 | 15.37 | 75.78 | 9.65 | 7.49 | 12.10 | 6.88 | 90.25 | 93.09 |
| **173** | 1.29 | 187.53 | 16.61 | 52.90 | 0.00 | 7.51 | 11.57 | 7.05 | 169.87 | 93.23 |
| **174** | 1.88 | 108.08 | 20.84 | 42.06 | 0.00 | 7.50 | 13.22 | 7.12 | 203.26 | 92.79 |
| **175** | 1.76 | 138.20 | 14.79 | 80.29 | 8.64 | 7.60 | 12.64 | 7.23 | 24.50 | 92.45 |
| **176** | 1.77 | 208.43 | 10.24 | 94.28 | 15.24 | 7.69 | 10.34 | 7.37 | 28.30 | 92.33 |
| **177** | 2.50 | 205.25 | 11.61 | 70.65 | 1.02 | 7.65 | 10.00 | 7.37 | 115.33 | 93.06 |
| **178** | 1.80 | 94.22 | 8.78 | 81.41 | 7.87 | 7.59 | 8.93 | 7.39 | 65.91 | 93.16 |
| **179** | 1.54 | 149.71 | 14.97 | 72.86 | 0.00 | 7.47 | 10.33 | 7.34 | 171.37 | 92.24 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **180** | 2.02 | 222.79 | 17.71 | 64.65 | 1.52 | 7.44 | 11.10 | 7.43 | 185.32 | 91.61 |
| **181** | 2.91 | 246.07 | 15.00 | 54.84 | 0.00 | 7.52 | 11.23 | 7.61 | 197.90 | 92.18 |
| **182** | 2.93 | 229.30 | 12.98 | 54.26 | 0.00 | 7.64 | 10.57 | 7.69 | 188.90 | 92.85 |
| **183** | 2.44 | 214.85 | 16.08 | 44.85 | 0.00 | 7.70 | 10.71 | 7.64 | 168.67 | 93.07 |
| **184** | 2.37 | 195.68 | 16.09 | 63.74 | 1.27 | 7.73 | 10.86 | 7.59 | 99.49 | 92.70 |
| **185** | 3.57 | 242.32 | 14.84 | 47.04 | 0.00 | 7.78 | 11.70 | 7.56 | 207.03 | 93.22 |
| **186** | 2.97 | 245.08 | 17.03 | 44.37 | 0.00 | 7.86 | 11.71 | 7.57 | 148.88 | 93.57 |
| **187** | 1.64 | 229.16 | 18.00 | 50.37 | 0.00 | 7.94 | 13.26 | 7.56 | 200.90 | 93.65 |
| **188** | 1.46 | 129.27 | 16.96 | 69.44 | 0.00 | 8.08 | 14.15 | 7.65 | 115.10 | 93.20 |
| **189** | 2.82 | 102.42 | 16.11 | 70.02 | 10.67 | 8.29 | 14.26 | 7.82 | 102.81 | 91.71 |
| **190** | 2.99 | 247.13 | 13.41 | 91.21 | 30.99 | 8.49 | 11.96 | 8.02 | 19.42 | 91.95 |
| **191** | 2.42 | 95.65 | 13.92 | 78.00 | 0.51 | 8.58 | 11.37 | 8.16 | 93.93 | 93.22 |
| **192** | 1.36 | 121.42 | 14.93 | 57.52 | 0.00 | 8.62 | 11.11 | 8.33 | 186.26 | 93.95 |
| **193** | 1.51 | 130.16 | 14.14 | 66.44 | 0.00 | 8.59 | 10.57 | 8.40 | 113.10 | 93.73 |
| **194** | 0.74 | 120.93 | 16.70 | 71.76 | 0.00 | 8.54 | 11.17 | 8.40 | 84.53 | 93.05 |
| **195** | 1.40 | 130.98 | 16.60 | 83.93 | 11.43 | 8.56 | 12.05 | 8.45 | 76.76 | 92.28 |
| **196** | 1.89 | 224.06 | 15.95 | 70.56 | 0.25 | 8.67 | 12.19 | 8.59 | 134.07 | 91.94 |
| **197** | 1.05 | 190.66 | 15.66 | 74.35 | 0.00 | 8.79 | 12.43 | 8.72 | 113.97 | 92.70 |
| **198** | 1.41 | 127.47 | 19.23 | 60.60 | 0.00 | 8.89 | 13.38 | 8.84 | 201.15 | 93.33 |
| **199** | 1.83 | 165.07 | 19.30 | 71.39 | 1.52 | 9.02 | 13.99 | 8.97 | 131.27 | 92.85 |
| **200** | 2.33 | 232.26 | 17.58 | 60.28 | 0.00 | 9.20 | 14.37 | 9.14 | 196.82 | 92.48 |
| **201** | 2.65 | 256.51 | 15.11 | 63.93 | 0.00 | 9.38 | 13.22 | 9.28 | 97.46 | 92.38 |
| **202** | 1.81 | 178.81 | 14.76 | 72.06 | 0.00 | 9.47 | 13.89 | 9.30 | 144.12 | 92.72 |
| **203** | 2.34 | 104.58 | 13.51 | 87.12 | 3.56 | 9.54 | 13.09 | 9.33 | 60.79 | 93.16 |
| **204** | 1.75 | 138.80 | 12.37 | 89.05 | 4.32 | 9.60 | 13.06 | 9.35 | 62.71 | 93.13 |
| **205** | 1.58 | 209.03 | 14.11 | 85.44 | 7.11 | 9.64 | 13.70 | 9.37 | 93.42 | 93.26 |
| **206** | 2.46 | 229.75 | 18.94 | 56.76 | 0.00 | 9.70 | 14.52 | 9.46 | 181.65 | 92.91 |
| **207** | 2.09 | 248.67 | 18.52 | 57.20 | 0.00 | 9.78 | 14.99 | 9.56 | 176.19 | 92.47 |
| **208** | 2.10 | 244.16 | 13.68 | 85.33 | 16.76 | 9.85 | 13.37 | 9.64 | 61.71 | 92.68 |
| **209** | 2.37 | 231.99 | 14.67 | 68.58 | 0.00 | 9.91 | 12.55 | 9.69 | 98.91 | 93.14 |
| **210** | 2.05 | 222.83 | 13.60 | 71.31 | 0.51 | 9.92 | 12.22 | 9.70 | 58.85 | 92.97 |
| **211** | 1.90 | 204.90 | 15.67 | 60.88 | 0.00 | 9.89 | 13.25 | 9.67 | 162.44 | 93.20 |
| **212** | 1.84 | 206.27 | 15.78 | 70.51 | 1.02 | 9.87 | 13.40 | 9.67 | 105.20 | 92.86 |
| **213** | 3.09 | 235.79 | 14.13 | 65.22 | 0.00 | 9.89 | 12.79 | 9.71 | 103.09 | 92.92 |
| **214** | 2.38 | 237.72 | 16.05 | 54.82 | 0.00 | 9.89 | 13.69 | 9.70 | 155.37 | 93.04 |
| **215** | 2.05 | 253.65 | 14.33 | 68.70 | 0.25 | 9.86 | 13.59 | 9.68 | 144.18 | 93.13 |
| **216** | 1.34 | 209.70 | 16.17 | 60.32 | 0.00 | 9.84 | 13.97 | 9.67 | 157.77 | 93.40 |
| **217** | 1.48 | 126.17 | 16.92 | 61.34 | 0.00 | 9.85 | 14.48 | 9.68 | 148.97 | 93.28 |
| **218** | 1.68 | 171.32 | 13.52 | 85.68 | 1.52 | 9.91 | 13.58 | 9.74 | 12.44 | 93.00 |
| **219** | 1.84 | 264.95 | 12.02 | 89.83 | 2.29 | 9.95 | 11.98 | 9.77 | 37.78 | 93.01 |
| **220** | 1.23 | 231.93 | 16.76 | 68.11 | 0.00 | 9.86 | 14.08 | 9.66 | 168.46 | 93.35 |
| **221** | 1.35 | 181.42 | 16.65 | 67.67 | 0.00 | 9.92 | 15.06 | 9.69 | 139.39 | 93.10 |
| **222** | 1.57 | 236.30 | 14.21 | 69.33 | 0.00 | 10.04 | 14.56 | 9.82 | 133.27 | 93.03 |
| **223** | 1.05 | 100.98 | 15.29 | 63.60 | 0.00 | 10.10 | 13.80 | 9.86 | 119.63 | 93.30 |
| **224** | 1.56 | 182.45 | 17.24 | 65.76 | 2.03 | 10.10 | 13.92 | 9.83 | 120.78 | 93.49 |
| **225** | 1.46 | 145.42 | 16.23 | 76.16 | 5.08 | 10.18 | 15.19 | 9.86 | 106.36 | 93.26 |
| **226** | 1.93 | 174.47 | 17.83 | 75.28 | 4.06 | 10.34 | 15.70 | 9.96 | 141.62 | 92.80 |
| **227** | 2.29 | 247.72 | 13.30 | 71.37 | 2.29 | 10.50 | 15.22 | 10.13 | 90.59 | 92.81 |
| **228** | 2.76 | 240.39 | 13.05 | 63.61 | 0.00 | 10.57 | 13.14 | 10.22 | 133.21 | 92.99 |
| **229** | 2.61 | 247.39 | 12.72 | 65.49 | 0.00 | 10.45 | 13.01 | 10.13 | 135.69 | 93.01 |
| **230** | 1.89 | 252.00 | 9.78 | 83.48 | 1.78 | 10.38 | 12.40 | 10.02 | 65.35 | 93.31 |
| **231** | 1.52 | 207.77 | 10.59 | 78.76 | 2.54 | 10.27 | 11.88 | 9.89 | 86.62 | 93.47 |

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|---|---|---|---|---|---|---|---|---|---|---|
| **232** | 1.31 | 170.77 | 12.77 | 71.42 | 0.00 | 10.15 | 11.67 | 9.77 | 76.81 | 93.25 |
| **233** | 1.92 | 169.77 | 18.99 | 61.58 | 0.00 | 10.08 | 13.66 | 9.70 | 123.43 | 92.47 |
| **234** | 1.88 | 226.89 | 19.62 | 54.19 | 0.00 | 10.21 | 14.65 | 9.78 | 109.36 | 92.17 |
| **235** | 3.24 | 246.01 | 15.10 | 63.55 | 0.25 | 10.44 | 14.03 | 9.93 | 90.27 | 92.53 |
| **236** | 2.24 | 208.33 | 15.09 | 56.09 | 0.00 | 10.54 | 12.60 | 9.98 | 89.28 | 92.94 |
| **237** | 2.97 | 250.28 | 12.18 | 61.43 | 0.00 | 10.48 | 12.01 | 9.92 | 101.37 | 93.30 |
| **238** | 1.42 | 191.39 | 13.98 | 61.82 | 0.00 | 10.38 | 11.42 | 9.81 | 102.08 | 93.82 |
| **239** | 1.62 | 209.83 | 16.84 | 56.75 | 0.00 | 10.24 | 12.18 | 9.71 | 100.45 | 93.36 |
| **240** | 1.59 | 226.16 | 14.83 | 59.18 | 0.00 | 10.25 | 12.74 | 9.70 | 127.57 | 93.51 |
| **241** | 1.80 | 187.99 | 15.48 | 71.47 | 0.00 | 10.33 | 13.34 | 9.71 | 32.43 | 92.76 |
| **242** | 2.50 | 244.14 | 12.22 | 73.42 | 0.00 | 10.43 | 12.61 | 9.75 | 94.99 | 92.71 |
| **243** | 2.60 | 254.38 | 9.33 | 72.89 | 0.00 | 10.44 | 11.91 | 9.73 | 82.58 | 93.19 |
| **244** | 1.20 | 198.76 | 9.33 | 65.73 | 0.00 | 10.35 | 10.67 | 9.64 | 106.44 | 93.11 |
| **245** | 1.50 | 209.66 | 9.17 | 70.67 | 0.00 | 10.13 | 10.98 | 9.48 | 92.57 | 93.26 |
| **246** | 1.46 | 183.89 | 8.68 | 73.37 | 0.00 | 9.98 | 10.48 | 9.35 | 98.48 | 93.97 |
| **247** | 2.51 | 190.30 | 16.15 | 54.67 | 0.00 | 9.82 | 10.76 | 9.22 | 101.07 | 93.04 |
| **248** | 2.29 | 226.48 | 16.99 | 52.69 | 0.00 | 9.83 | 11.48 | 9.21 | 105.24 | 92.81 |
| **249** | 2.33 | 221.36 | 18.66 | 50.30 | 0.00 | 9.96 | 12.15 | 9.26 | 109.45 | 93.47 |
| **250** | 2.01 | 209.65 | 20.79 | 45.49 | 0.00 | 10.13 | 12.80 | 9.34 | 110.92 | 93.89 |
| **251** | 1.19 | 185.26 | 19.60 | 55.75 | 0.00 | 10.32 | 13.48 | 9.43 | 119.48 | 94.13 |
| **252** | 1.86 | 205.94 | 20.70 | 52.34 | 0.00 | 10.49 | 13.78 | 9.53 | 110.67 | 93.87 |
| **253** | 1.75 | 239.95 | 15.78 | 51.43 | 0.00 | 10.64 | 13.71 | 9.63 | 99.45 | 93.75 |
| **254** | 1.39 | 209.68 | 10.48 | 73.99 | 1.52 | 10.74 | 12.54 | 9.67 | 26.71 | 93.69 |
| **255** | 2.60 | 245.44 | 8.51 | 75.18 | 0.25 | 10.65 | 11.17 | 9.57 | 68.49 | 93.94 |
| **256** | 1.06 | 125.56 | 2.72 | 63.51 | 0.25 | 10.39 | 9.97 | 9.37 | 82.26 | 94.78 |
| **257** | 2.40 | 138.44 | 5.95 | 50.24 | 0.00 | 10.00 | 7.77 | 9.08 | 86.43 | 94.10 |
| **258** | 1.84 | 140.49 | 10.86 | 50.35 | 0.00 | 9.56 | 7.41 | 8.75 | 68.67 | 92.77 |
| **259** | 2.09 | 170.48 | 9.26 | 89.47 | 8.64 | 9.29 | 9.34 | 8.59 | 3.41 | 91.81 |
| **260** | 3.74 | 246.73 | 8.97 | 85.56 | 7.37 | 9.20 | 9.54 | 8.59 | 36.37 | 92.26 |
| **261** | 2.11 | 237.37 | 9.07 | 76.06 | 0.00 | 9.16 | 9.69 | 8.60 | 68.58 | 92.78 |
| **262** | 1.79 | 228.08 | 8.23 | 73.89 | 0.76 | 9.14 | 9.43 | 8.59 | 76.67 | 93.11 |
| **263** | 1.37 | 189.55 | 9.15 | 73.77 | 0.25 | 9.06 | 8.85 | 8.51 | 75.77 | 93.85 |
| **264** | 2.90 | 146.12 | 13.00 | 52.74 | 0.00 | 8.91 | 9.09 | 8.37 | 57.51 | 93.01 |
| **265** | 2.37 | 215.54 | 13.91 | 45.60 | 0.00 | 8.83 | 9.59 | 8.30 | 48.82 | 92.65 |
| **266** | 2.08 | 171.00 | 15.37 | 58.29 | 0.00 | 8.85 | 9.57 | 8.31 | 35.56 | 92.48 |
| **267** | 1.31 | 212.49 | 12.74 | 58.14 | 0.00 | 8.86 | 10.43 | 8.33 | 73.82 | 92.99 |
| **268** | 2.82 | 136.97 | 18.38 | 51.98 | 0.00 | 8.92 | 11.73 | 8.35 | 55.11 | 92.17 |
| **269** | 2.65 | 223.47 | 12.31 | 51.06 | 0.00 | 9.02 | 11.28 | 8.38 | 52.03 | 92.29 |
| **270** | 2.08 | 214.72 | 11.58 | 47.39 | 0.00 | 9.13 | 9.39 | 8.42 | 46.42 | 92.24 |
| **271** | 2.65 | 259.67 | 8.04 | 67.96 | 0.00 | 9.03 | 8.81 | 8.30 | 13.88 | 93.52 |
| **272** | 2.13 | 159.07 | 6.84 | 70.71 | 0.00 | 8.81 | 8.00 | 8.14 | 46.20 | 94.02 |
| **273** | 2.75 | 195.48 | 10.59 | 49.26 | 0.00 | 8.53 | 7.03 | 7.96 | 33.21 | 92.50 |
| **274** | 1.68 | 216.44 | 7.24 | 51.26 | 0.00 | 8.33 | 7.96 | 7.85 | 43.16 | 93.41 |
| **275** | 1.70 | 100.37 | 5.45 | 77.13 | 0.25 | 8.21 | 7.20 | 7.76 | 0.26 | 93.82 |
| **276** | 2.42 | 107.40 | 4.86 | 90.44 | 0.00 | 8.06 | 6.36 | 7.66 | 11.33 | 93.56 |

**ML Fen 2012**

| DOY | Wind Speed ($ms^{-1}$) Daily Mean | Wind Direction (°) Daily Mean | Air Temp (°C) Daily Mean | Relative Humidity (%) Daily Mean | Precip (mm) Daily Total | Ground/Water temperature ~10 cm below (°C) daily Average | ~20 cm below (°C) daily Average | ~40 cm below (°C) daily Average | Net Radiation $W(m^{2})^{-1}$ Daily Mean | Air Pressure (Kpa) Daily Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| **160** | 2.15 | 106.42 | 16.04 | 42.78 | 0.00 | 8.77 | 10.30 | 11.69 | 168.06 | 92.82 |
| **161** | 2.32 | 85.88 | 16.16 | 51.71 | 0.00 | 8.91 | 10.75 | 12.27 | 125.38 | 92.38 |
| **162** | 3.66 | 70.36 | 11.40 | 72.97 | 0.00 | 9.10 | 10.76 | 12.86 | 84.39 | 92.87 |
| **163** | 1.52 | 157.89 | 11.92 | 58.49 | 0.00 | 8.99 | 9.91 | 9.61 | 122.25 | 93.38 |
| **164** | 2.62 | 182.77 | 13.91 | 83.52 | 4.06 | 8.97 | 10.82 | 12.59 | 67.62 | 92.88 |
| **165** | 1.82 | 164.66 | 13.14 | 87.39 | 3.30 | 9.27 | 11.44 | 13.86 | 83.28 | 92.58 |
| **166** | 3.58 | 293.25 | 12.68 | 70.47 | 0.25 | 9.59 | 11.45 | 13.54 | 158.13 | 92.79 |
| **167** | 1.69 | 232.94 | 11.56 | 60.66 | 0.51 | 9.62 | 10.88 | 12.30 | 140.95 | 93.42 |
| **168** | 2.75 | 163.34 | 12.84 | 59.79 | 1.02 | 9.51 | 10.77 | 12.73 | 100.78 | 92.92 |
| **169** | 1.97 | 233.97 | 12.47 | 84.86 | 2.54 | 9.46 | 10.81 | 11.56 | 48.16 | 91.77 |
| **170** | 2.32 | 281.20 | 12.59 | 83.62 | 2.03 | 9.56 | 11.14 | 12.71 | 90.19 | 92.01 |
| **171** | 2.44 | 244.71 | 11.75 | 88.88 | 3.05 | 9.74 | 11.49 | 13.06 | 77.33 | 92.82 |
| **172** | 2.37 | 229.72 | 14.02 | 60.49 | 0.25 | 9.85 | 11.26 | 12.60 | 171.48 | 93.48 |
| **173** | 1.53 | 154.44 | 15.03 | 45.60 | 0.00 | 9.84 | 11.13 | 12.24 | 196.49 | 93.73 |
| **174** | 2.08 | 161.73 | 16.49 | 48.29 | 0.00 | 9.88 | 11.56 | 13.86 | 147.09 | 93.50 |
| **175** | 2.34 | 94.62 | 16.95 | 46.38 | 0.00 | 10.00 | 11.79 | 13.86 | 191.09 | 93.65 |
| **176** | 3.00 | 139.11 | 16.32 | 62.40 | 0.51 | 10.11 | 11.96 | 14.12 | 49.42 | 93.67 |
| **177** | 2.69 | 228.74 | 19.43 | 60.49 | 0.00 | 10.19 | 12.04 | 13.72 | 154.26 | 92.90 |
| **178** | 2.58 | 273.93 | 19.39 | 44.31 | 0.00 | 10.39 | 12.62 | 15.53 | 192.14 | 92.33 |
| **179** | 4.31 | 297.76 | 15.74 | 60.93 | 1.52 | 10.59 | 12.66 | 15.28 | 141.85 | 91.95 |
| **180** | 3.90 | 272.84 | 16.67 | 52.03 | 0.00 | 10.68 | 12.45 | 14.29 | 183.60 | 92.78 |
| **181** | 1.40 | 215.26 | 14.33 | 64.29 | 0.25 | 10.64 | 12.04 | 14.31 | 78.65 | 92.99 |
| **182** | 2.32 | 228.33 | 18.86 | 52.58 | 0.00 | 10.54 | 11.94 | 14.39 | 171.36 | 92.98 |
| **183** | 2.15 | 197.26 | 14.76 | 83.99 | 16.51 | 10.56 | 12.28 | 15.44 | 16.26 | 92.77 |
| **184** | 2.76 | 252.36 | 16.51 | 59.18 | 0.00 | 10.82 | 12.36 | 14.11 | 138.93 | 92.92 |
| **185** | 2.72 | 100.32 | 13.37 | 84.37 | 41.91 | 10.92 | 12.58 | 14.39 | 21.54 | 92.27 |
| **186** | 4.14 | 255.07 | 14.85 | 75.31 | 8.89 | 11.33 | 12.38 | 12.30 | 84.48 | 91.78 |
| **187** | 2.95 | 234.52 | 15.40 | 67.79 | 0.00 | 11.53 | 12.74 | 12.99 | 149.55 | 93.27 |
| **188** | 1.98 | 192.04 | 14.56 | 65.67 | 2.03 | 11.80 | 13.16 | 14.34 | 119.68 | 93.75 |
| **189** | 1.16 | 209.21 | 18.38 | 50.25 | 0.00 | 11.88 | 13.25 | 14.07 | 195.13 | 94.07 |
| **190** | 2.31 | 163.49 | 22.22 | 49.49 | 0.00 | 12.30 | 14.66 | 16.47 | 180.09 | 94.02 |
| **191** | 1.93 | 196.61 | 25.25 | 51.55 | 0.00 | 12.87 | 15.54 | 17.47 | 185.11 | 93.71 |
| **192** | 2.77 | 197.56 | 25.31 | 52.92 | 0.00 | 13.49 | 16.47 | 19.19 | 175.06 | 93.19 |
| **193** | 2.65 | 271.86 | 20.90 | 47.35 | 0.00 | 13.89 | 16.20 | 18.74 | 151.26 | 93.30 |
| **194** | 3.37 | 228.33 | 21.33 | 40.45 | 0.00 | 13.88 | 15.58 | 16.84 | 169.95 | 93.38 |
| **195** | 1.50 | 221.21 | 15.80 | 51.08 | 0.00 | 13.72 | 14.87 | 14.80 | 165.04 | 93.98 |
| **196** | 2.19 | 149.65 | 18.95 | 57.92 | 0.00 | 13.47 | 14.75 | 15.95 | 151.99 | 93.65 |
| **197** | 2.27 | 94.18 | 19.17 | 74.47 | 0.00 | 13.47 | 15.22 | 17.14 | 60.20 | 93.46 |
| **198** | 1.37 | 214.46 | 18.16 | 67.70 | 0.00 | 13.53 | 15.09 | 16.90 | 125.98 | 93.51 |
| **199** | 3.72 | 176.77 | 19.74 | 68.11 | 0.00 | 13.57 | 15.25 | 17.17 | 168.22 | 93.00 |
| **200** | 2.64 | 204.53 | 17.87 | 81.71 | 19.05 | 13.72 | 15.55 | 16.52 | 77.93 | 92.57 |
| **201** | 4.90 | 279.16 | 14.34 | 74.17 | 0.25 | 13.96 | 15.46 | 16.98 | 76.18 | 93.24 |
| **202** | 1.68 | 235.18 | 18.19 | 59.55 | 0.00 | 13.69 | 14.57 | 14.80 | 185.90 | 93.91 |
| **203** | 2.52 | 126.18 | 19.22 | 69.47 | 2.03 | 13.60 | 15.20 | 16.42 | 122.90 | 93.21 |
| **204** | 2.03 | 226.32 | 18.13 | 79.31 | 0.00 | 13.78 | 15.42 | 17.33 | 121.86 | 93.42 |
| **205** | 1.95 | 117.27 | 19.74 | 61.75 | 0.00 | 13.88 | 15.43 | 16.97 | 137.83 | 93.41 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **206** | 2.52 | 99.19 | 17.32 | 84.83 | 44.96 | 14.03 | 15.87 | 17.10 | 49.57 | 92.90 |
| **207** | 1.86 | 153.07 | 17.75 | 83.26 | 6.60 | 14.65 | 16.07 | 16.44 | 62.15 | 93.40 |
| **208** | 0.94 | 181.26 | 16.98 | 80.72 | 1.27 | 14.99 | 16.40 | 17.32 | 54.99 | 93.64 |
| **209** | 1.63 | 216.33 | 17.96 | 73.21 | 0.00 | 15.02 | 16.38 | 17.22 | 132.86 | 93.25 |
| **210** | 1.08 | 187.25 | 16.65 | 82.18 | 9.65 | 15.24 | 16.89 | 18.44 | 66.48 | 93.27 |
| **211** | 1.28 | 207.98 | 17.70 | 79.00 | 0.00 | 15.41 | 16.99 | 17.96 | 113.68 | 93.46 |
| **212** | 2.54 | 257.49 | 20.75 | 56.92 | 0.00 | 15.66 | 17.59 | 20.00 | 168.20 | 93.26 |
| **213** | 3.17 | 273.47 | 18.11 | 60.38 | 0.00 | 15.78 | 17.52 | 20.56 | 117.54 | 93.19 |
| **214** | 2.95 | 270.90 | 17.20 | 55.50 | 0.00 | 15.54 | 16.79 | 18.48 | 148.56 | 93.28 |
| **215** | 2.46 | 290.03 | 12.92 | 87.98 | 9.40 | 15.33 | 16.38 | 18.27 | 9.25 | 93.28 |
| **216** | 1.45 | 210.31 | 16.36 | 74.02 | 0.00 | 15.04 | 15.95 | 15.63 | 111.80 | 93.51 |
| **217** | 3.52 | 248.77 | 18.81 | 65.06 | 0.00 | 15.21 | 16.77 | 18.98 | 125.06 | 93.21 |
| **218** | 2.93 | 276.67 | 15.01 | 58.95 | 0.00 | 15.19 | 16.20 | 17.73 | 149.32 | 93.48 |
| **219** | 1.19 | 172.19 | 16.72 | 57.33 | 0.00 | 14.82 | 15.49 | 15.57 | 148.08 | 93.75 |
| **220** | 2.15 | 93.05 | 18.91 | 57.47 | 0.00 | 14.79 | 16.27 | 17.17 | 152.00 | 93.73 |
| **221** | 3.05 | 144.85 | 20.19 | 59.17 | 14.22 | 14.97 | 16.28 | 16.69 | 147.64 | 93.68 |
| **222** | 3.79 | 250.77 | 16.67 | 74.04 | 11.94 | 15.18 | 16.38 | 17.46 | 66.10 | 93.35 |
| **223** | 3.25 | 261.17 | 16.42 | 51.71 | 0.00 | 15.07 | 15.78 | 16.94 | 124.15 | 93.54 |
| **224** | 3.93 | 284.72 | 13.68 | 61.16 | 0.25 | 14.81 | 15.57 | 17.15 | 118.63 | 93.64 |
| **225** | 1.61 | 250.01 | 13.00 | 69.46 | 0.25 | 14.39 | 14.73 | 14.98 | 129.12 | 94.01 |
| **226** | 2.85 | 174.39 | 14.74 | 75.53 | 10.67 | 14.18 | 14.94 | 15.60 | 48.63 | 93.34 |
| **227** | 2.86 | 204.41 | 11.67 | 87.19 | 2.79 | 14.20 | 14.68 | 15.26 | 8.31 | 93.36 |
| **228** | 2.22 | 278.77 | 11.35 | 69.38 | 0.00 | 13.80 | 13.74 | 13.78 | 113.63 | 94.03 |
| **229** | 2.52 | 243.21 | 16.16 | 60.05 | 0.00 | 13.48 | 14.16 | 15.07 | 110.83 | 93.53 |
| **230** | 2.29 | 243.94 | 17.48 | 58.79 | 0.00 | 13.64 | 14.65 | 15.72 | 110.54 | 93.60 |
| **231** | 2.01 | 169.62 | 18.50 | 56.08 | 0.00 | 13.81 | 14.68 | 15.39 | 139.62 | 93.76 |
| **232** | 2.74 | 202.86 | 20.69 | 57.15 | 0.00 | 13.92 | 15.12 | 15.83 | 126.82 | 93.33 |
| **233** | 2.09 | 140.20 | 20.12 | 64.26 | 0.00 | 14.16 | 15.47 | 16.42 | 110.15 | 93.24 |
| **234** | 1.69 | 165.16 | 20.03 | 65.87 | 11.68 | 14.35 | 15.77 | 16.77 | 104.22 | 92.96 |
| **235** | 1.94 | 251.40 | 14.83 | 91.46 | 5.59 | 14.61 | 15.93 | 16.76 | 10.25 | 92.86 |
| **236** | 2.97 | 277.83 | 15.76 | 76.43 | 0.25 | 14.58 | 15.53 | 15.61 | 109.84 | 92.75 |
| **237** | 2.56 | 248.91 | 12.79 | 72.96 | 0.51 | 14.57 | 15.50 | 16.44 | 68.64 | 92.69 |
| **238** | 2.93 | 305.75 | 12.05 | 89.72 | 1.52 | 14.30 | 14.71 | 14.84 | 10.44 | 92.81 |
| **239** | 1.03 | 208.07 | 14.28 | 71.93 | 0.00 | 13.96 | 14.29 | 14.45 | 89.94 | 93.46 |
| **240** | 2.84 | 182.13 | 17.08 | 66.21 | 0.00 | 13.78 | 14.42 | 14.43 | 98.02 | 93.24 |
| **241** | 1.47 | 231.35 | 17.91 | 61.35 | 0.00 | 13.80 | 14.60 | 14.87 | 99.65 | 92.85 |
| **242** | 3.55 | 258.45 | 14.20 | 68.99 | 1.27 | 13.88 | 14.80 | 15.22 | 75.46 | 92.53 |
| **243** | 3.69 | 278.68 | 9.91 | 77.12 | 0.00 | 13.80 | 14.11 | 14.11 | 48.71 | 93.11 |
| **244** | 1.38 | 174.81 | 10.69 | 72.56 | 0.00 | 13.34 | 13.24 | 13.06 | 109.96 | 93.50 |
| **245** | 3.57 | 103.45 | 13.30 | 79.56 | 13.46 | 12.98 | 13.22 | 12.95 | 28.41 | 92.77 |
| **246** | 4.48 | 296.33 | 11.67 | 94.55 | 46.99 | 12.92 | 13.18 | 13.05 | 0.41 | 91.97 |
| **247** | 5.78 | 290.61 | 9.99 | 82.40 | 11.68 | 12.62 | 12.70 | 12.50 | 35.94 | 92.60 |
| **248** | 3.33 | 298.10 | 10.57 | 89.88 | 3.05 | 12.16 | 11.96 | 11.86 | 13.82 | 93.17 |
| **249** | 1.45 | 195.28 | 11.80 | 78.60 | 0.00 | 11.85 | 12.33 | 11.94 | 67.85 | 93.38 |
| **250** | 2.03 | 211.95 | 12.93 | 68.52 | 0.00 | 11.95 | 12.51 | 12.64 | 101.83 | 93.64 |
| **251** | 2.84 | 224.42 | 12.76 | 62.08 | 0.00 | 12.28 | 12.97 | 13.60 | 79.73 | 93.77 |
| **252** | 3.14 | 183.67 | 13.03 | 67.04 | 0.00 | 11.82 | 12.36 | 13.32 | 90.24 | 93.60 |
| **253** | 1.81 | 133.05 | 15.99 | 63.78 | 0.00 | 12.24 | 13.51 | 14.57 | 69.41 | 92.46 |
| **254** | 3.90 | 270.36 | 10.30 | 86.12 | 14.22 | 12.73 | 13.35 | 15.32 | 7.65 | 91.81 |
| **255** | 6.46 | 304.33 | 7.37 | 65.47 | 3.05 | 11.68 | 10.91 | 11.21 | 0.87 | 92.30 |
| **256** | 2.98 | 281.88 | 3.72 | 69.48 | 0.00 | 10.61 | 9.83 | 9.29 | -15.78 | 93.47 |

**ML Bog 2012**

| DOY | Wind Speed ($ms^{-1}$) Daily Mean | Wind Direction (°) Daily Mean | Air Temp (°C) Daily Mean | Relative Humidity (%) Daily Mean | Precip (mm) Daily Total | Ground/Water temperature ~10 cm below (°C) daily Average | ~20 cm below (°C) daily Average | ~40 cm below (°C) daily Average | Net Radiation $W(m^{2})^{-1}$ Daily Mean | Air Pressure (Kpa) Daily Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| **160** | 3.23 | 87.21 | 13.10 | 77.43 | 0.25 | 4.33 | 5.49 | 6.30 | 61.06 | 92.85 |
| **161** | 3.95 | 90.80 | 16.23 | 69.25 | 0.25 | 4.44 | 5.55 | 6.54 | 113.37 | 92.40 |
| **162** | 2.69 | 142.43 | 16.19 | 48.98 | 0.25 | 4.62 | 5.91 | 7.12 | 180.90 | 92.86 |
| **163** | 1.39 | 103.02 | 16.10 | 43.38 | 0.00 | 4.84 | 6.10 | 7.08 | 175.51 | 93.40 |
| **164** | 1.64 | 95.37 | 16.09 | 52.04 | 0.00 | 5.03 | 6.23 | 7.45 | 131.48 | 92.90 |
| **165** | 3.17 | 161.39 | 11.61 | 73.40 | 0.00 | 5.22 | 6.51 | 7.76 | 88.81 | 92.60 |
| **166** | 1.00 | 143.82 | 11.65 | 58.91 | 0.00 | 5.38 | 6.53 | 7.51 | 125.99 | 92.80 |
| **167** | 1.80 | 183.39 | 13.92 | 83.43 | 4.83 | 5.48 | 6.74 | 8.22 | 78.43 | 93.42 |
| **168** | 1.20 | 144.42 | 13.21 | 87.82 | 4.06 | 5.63 | 7.18 | 8.72 | 86.89 | 92.98 |
| **169** | 2.74 | 278.34 | 12.87 | 70.67 | 0.25 | 5.81 | 7.45 | 8.63 | 167.06 | 91.79 |
| **170** | 1.29 | 237.53 | 11.45 | 61.97 | 0.25 | 5.96 | 7.39 | 8.14 | 149.85 | 92.01 |
| **171** | 1.78 | 147.47 | 12.67 | 60.09 | 0.00 | 6.04 | 7.26 | 8.11 | 100.54 | 92.81 |
| **172** | 1.38 | 215.17 | 12.37 | 85.46 | 3.81 | 6.10 | 7.28 | 8.33 | 52.36 | 93.48 |
| **173** | 1.69 | 266.03 | 12.61 | 83.71 | 1.52 | 6.18 | 7.53 | 8.70 | 90.36 | 93.75 |
| **174** | 2.07 | 279.50 | 11.80 | 89.27 | 3.56 | 6.28 | 7.81 | 9.02 | 75.40 | 93.52 |
| **175** | 1.92 | 248.19 | 13.89 | 61.84 | 0.00 | 6.40 | 7.88 | 8.75 | 176.97 | 93.65 |
| **176** | 1.09 | 163.01 | 15.29 | 44.98 | 0.00 | 6.48 | 7.82 | 8.61 | 206.04 | 93.70 |
| **177** | 1.51 | 169.08 | 16.06 | 49.69 | 0.00 | 6.57 | 7.88 | 8.93 | 153.40 | 92.93 |
| **178** | 1.45 | 78.08 | 16.94 | 47.05 | 0.00 | 6.65 | 7.99 | 9.07 | 198.76 | 92.36 |
| **179** | 1.90 | 120.57 | 16.26 | 61.87 | 0.51 | 6.75 | 8.27 | 9.62 | 51.02 | 91.96 |
| **180** | 1.83 | 207.67 | 19.56 | 59.97 | 0.00 | 6.86 | 8.58 | 10.17 | 156.59 | 92.79 |
| **181** | 1.81 | 251.48 | 19.58 | 44.34 | 0.00 | 7.04 | 9.06 | 10.69 | 197.93 | 93.00 |
| **182** | 3.30 | 285.29 | 15.71 | 60.51 | 1.02 | 7.25 | 9.32 | 10.56 | 146.16 | 93.00 |
| **183** | 2.84 | 251.12 | 17.07 | 50.74 | 0.00 | 7.40 | 9.34 | 10.36 | 188.44 | 92.78 |
| **184** | 0.99 | 197.35 | 14.23 | 63.82 | 0.00 | 7.51 | 9.35 | 10.26 | 78.56 | 92.93 |
| **185** | 1.55 | 208.75 | 18.92 | 52.21 | 0.00 | 7.56 | 9.40 | 10.36 | 176.15 | 92.32 |
| **186** | 1.56 | 201.68 | 14.61 | 84.90 | 15.75 | 7.64 | 9.65 | 10.75 | 22.79 | 91.76 |
| **187** | 1.96 | 232.60 | 16.67 | 58.76 | 0.00 | 7.75 | 9.57 | 10.37 | 141.27 | 93.27 |
| **188** | 1.86 | 97.36 | 13.21 | 84.74 | 40.89 | 7.81 | 9.55 | 10.36 | 24.94 | 93.76 |
| **189** | 3.55 | 273.92 | 14.70 | 76.80 | 8.89 | 7.89 | 9.55 | 9.83 | 95.60 | 94.08 |
| **190** | 2.10 | 216.19 | 15.54 | 67.04 | 0.00 | 7.96 | 9.39 | 9.47 | 157.98 | 94.04 |
| **191** | 1.33 | 183.81 | 14.40 | 66.71 | 1.78 | 8.03 | 9.27 | 9.29 | 128.14 | 93.74 |
| **192** | 0.88 | 197.20 | 17.98 | 52.16 | 0.00 | 8.10 | 9.13 | 9.15 | 207.92 | 93.21 |
| **193** | 1.52 | 148.48 | 22.23 | 49.01 | 0.00 | 8.14 | 9.17 | 9.26 | 187.84 | 93.31 |
| **194** | 1.40 | 178.09 | 25.41 | 50.90 | 0.00 | 8.21 | 9.52 | 9.74 | 193.99 | 93.39 |
| **195** | 2.03 | 177.74 | 25.70 | 51.43 | 0.00 | 8.36 | 10.08 | 10.48 | 181.29 | 93.99 |
| **196** | 1.98 | 247.27 | 21.31 | 46.43 | 0.00 | 8.57 | 10.64 | 11.14 | 156.63 | 93.67 |
| **197** | 2.37 | 222.27 | 21.61 | 39.35 | 0.00 | 8.77 | 10.96 | 11.53 | 174.43 | 93.47 |
| **198** | 1.21 | 223.66 | 15.93 | 50.20 | 0.00 | 8.93 | 11.04 | 11.46 | 170.37 | 93.54 |
| **199** | 1.43 | 137.75 | 18.62 | 57.90 | 0.00 | 9.02 | 10.95 | 11.48 | 155.85 | 93.03 |
| **200** | 1.44 | 87.91 | 19.18 | 74.48 | 0.00 | 9.10 | 11.12 | 11.90 | 62.98 | 92.59 |
| **201** | 1.04 | 200.17 | 18.04 | 67.92 | 0.00 | 9.19 | 11.24 | 11.93 | 131.11 | 93.24 |
| **202** | 2.47 | 156.42 | 19.88 | 67.37 | 0.00 | 9.29 | 11.41 | 12.28 | 170.75 | 93.93 |
| **203** | 1.80 | 184.33 | 17.88 | 82.51 | 19.81 | 9.41 | 11.75 | 12.70 | 80.76 | 93.24 |
| **204** | 3.50 | 255.34 | 14.42 | 73.62 | 0.25 | 9.55 | 11.91 | 12.23 | 69.87 | 93.42 |
| **205** | 1.20 | 212.41 | 18.26 | 59.50 | 0.00 | 9.63 | 11.60 | 11.78 | 191.96 | 93.43 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **206** | 1.66 | 109.35 | 19.31 | 68.68 | 2.29 | 9.66 | 11.72 | 12.39 | 126.36 | 92.91 |
| **207** | 1.43 | 205.28 | 18.22 | 78.30 | 0.00 | 9.75 | 11.96 | 12.62 | 125.58 | 93.39 |
| **208** | 1.28 | 106.24 | 19.57 | 62.08 | 0.00 | 9.85 | 12.04 | 12.59 | 141.83 | 93.66 |
| **209** | 1.89 | 127.33 | 17.25 | 85.46 | 41.91 | 9.94 | 12.22 | 12.88 | 55.47 | 93.27 |
| **210** | 1.62 | 218.32 | 17.71 | 83.87 | 5.59 | 10.08 | 12.39 | 12.42 | 65.38 | 93.28 |
| **211** | 0.62 | 170.85 | 16.64 | 81.22 | 0.76 | 10.24 | 12.26 | 12.07 | 61.56 | 93.47 |
| **212** | 1.14 | 199.07 | 17.69 | 73.46 | 0.00 | 10.35 | 12.06 | 11.84 | 138.34 | 93.28 |
| **213** | 0.78 | 186.57 | 16.34 | 83.18 | 10.41 | 10.41 | 11.97 | 11.76 | 71.07 | 93.20 |
| **214** | 0.92 | 191.28 | 17.42 | 79.34 | 0.00 | 10.44 | 11.97 | 11.80 | 119.76 | 93.30 |
| **215** | 1.83 | 233.18 | 20.92 | 56.41 | 0.00 | 10.48 | 12.05 | 11.91 | 177.78 | 93.30 |
| **216** | 2.24 | 246.62 | 18.17 | 60.04 | 0.00 | 10.53 | 12.25 | 12.12 | 122.87 | 93.52 |
| **217** | 2.17 | 246.14 | 17.47 | 53.57 | 0.00 | 10.60 | 12.38 | 12.25 | 155.77 | 93.23 |
| **218** | 1.82 | 267.92 | 12.85 | 87.79 | 7.11 | 10.64 | 12.42 | 12.27 | 9.90 | 93.48 |
| **219** | 1.07 | 208.13 | 16.30 | 74.81 | 0.25 | 10.66 | 12.35 | 12.17 | 119.67 | 93.76 |
| **220** | 2.44 | 224.93 | 18.82 | 64.86 | 0.00 | 10.66 | 12.41 | 12.29 | 126.81 | 93.74 |
| **221** | 2.26 | 260.67 | 15.12 | 58.75 | 0.00 | 10.69 | 12.51 | 12.36 | 152.56 | 93.71 |
| **222** | 0.87 | 163.79 | 16.43 | 57.52 | 0.00 | 10.71 | 12.42 | 12.23 | 152.21 | 93.36 |
| **223** | 1.45 | 92.39 | 19.05 | 57.74 | 0.00 | 10.70 | 12.48 | 12.45 | 157.28 | 93.56 |
| **224** | 1.99 | 126.53 | 20.37 | 57.61 | 0.00 | 10.73 | 12.62 | 12.61 | 154.52 | 93.65 |
| **225** | 2.63 | 228.24 | 16.67 | 74.79 | 25.91 | 10.78 | 12.85 | 12.79 | 68.89 | 94.02 |
| **226** | 2.29 | 239.00 | 16.55 | 50.67 | 0.00 | 10.86 | 12.78 | 12.46 | 129.87 | 93.38 |
| **227** | 2.88 | 262.01 | 13.80 | 60.19 | 0.25 | 10.90 | 12.63 | 12.26 | 121.03 | 93.34 |
| **228** | 1.24 | 241.18 | 12.88 | 69.61 | 0.00 | 10.90 | 12.41 | 11.97 | 133.49 | 94.05 |
| **229** | 1.93 | 153.56 | 14.49 | 76.08 | 10.16 | 11.22 | 12.25 | 11.84 | 49.89 | 93.55 |
| **230** | 2.46 | 260.07 | 11.61 | 88.57 | 2.54 | 12.33 | 12.23 | 11.80 | 11.90 | 93.60 |
| **231** | 1.65 | 258.33 | 11.18 | 69.52 | 0.00 | 13.55 | 12.06 | 11.50 | 118.54 | 93.78 |
| **232** | 1.68 | 220.47 | 16.04 | 60.10 | 0.00 | 17.01 | 11.86 | 11.30 | 119.90 | 93.35 |
| **233** | 1.77 | 249.05 | 17.54 | 58.51 | 0.00 | 18.48 | 11.88 | 11.41 | 114.18 | 93.26 |
| **234** | 1.28 | 155.03 | 17.88 | 57.51 | 0.00 | 19.49 | 11.97 | 11.51 | 145.88 | 92.98 |
| **235** | 1.93 | 183.20 | 20.92 | 55.83 | 0.00 | 22.36 | 12.12 | 11.81 | 129.23 | 92.87 |
| **236** | 1.31 | 118.47 | 20.09 | 63.83 | 0.00 | 20.98 | 12.41 | 12.17 | 114.38 | 92.76 |
| **237** | 1.19 | 164.95 | 19.93 | 66.06 | 12.70 | 22.02 | 12.67 | 12.47 | 111.89 | 92.71 |
| **238** | 1.45 | 243.60 | 14.60 | 92.10 | 4.57 | 15.17 | 12.96 | 12.62 | 14.47 | 92.81 |
| **239** | 2.10 | 255.26 | 15.90 | 76.11 | 0.00 | 19.03 | 12.92 | 12.45 | 108.32 | 93.46 |
| **240** | 1.87 | 230.13 | 12.82 | 72.28 | 0.51 | 15.07 | 12.91 | 12.37 | 75.65 | 93.27 |
| **241** | 2.39 | 289.14 | 11.90 | 89.91 | 1.78 | 12.67 | 12.74 | 12.12 | 12.11 | 92.87 |
| **242** | 0.75 | 178.53 | 13.93 | 72.26 | 0.00 | 15.22 | 12.57 | 11.89 | 93.72 | 92.54 |
| **243** | 1.90 | 160.04 | 16.72 | 66.92 | 0.00 | 16.72 | 12.45 | 11.81 | 105.62 | 93.11 |
| **244** | 1.09 | 217.48 | 17.74 | 62.63 | 0.00 | 18.37 | 12.47 | 11.91 | 108.02 | 93.52 |
| **245** | 2.51 | 243.20 | 14.20 | 69.11 | 1.27 | 14.96 | 12.56 | 12.03 | 72.83 | 92.81 |
| **246** | 2.66 | 255.64 | 10.01 | 76.56 | 0.00 | 10.59 | 12.44 | 11.65 | 49.00 | 91.98 |
| **247** | 0.93 | 150.02 | 10.40 | 72.39 | 0.00 | 12.81 | 12.08 | 11.06 | 117.22 | 92.61 |
| **248** | 2.26 | 83.90 | 13.16 | 79.88 | 10.67 | 13.21 | 11.91 | 11.14 | 30.31 | 93.18 |
| **249** | 3.78 | 288.06 | 11.52 | 95.37 | 44.70 | 11.63 | 11.98 | 11.28 | 1.89 | 93.38 |
| **250** | 4.12 | 267.06 | 9.98 | 82.96 | 9.14 | 12.09 | 11.92 | 11.10 | 80.53 | 93.66 |
| **251** | 2.74 | 276.79 | 10.35 | 90.37 | 2.54 | 10.78 | 11.81 | 10.93 | 18.83 | 93.77 |
| **252** | 1.21 | 203.71 | 11.49 | 79.64 | 0.00 | 13.14 | 11.69 | 10.80 | 74.13 | 93.64 |
| **253** | 1.30 | 189.05 | 12.60 | 69.04 | 0.00 | 14.11 | 11.66 | 10.78 | 112.36 | 92.50 |
| **254** | 2.26 | 224.15 | 12.74 | 61.64 | 0.00 | 13.28 | 11.72 | 10.84 | 87.13 | 91.83 |
| **255** | 1.93 | 168.26 | 12.52 | 67.80 | 0.00 | 12.99 | 11.72 | 10.71 | 99.91 | 92.32 |
| **256** | 1.17 | 117.84 | 15.89 | 63.81 | 0.00 | 15.41 | 11.66 | 10.62 | 78.37 | 93.49 |

**JPH Upland 2012**

| DOY | Wind Speed ($ms^{-1}$) Daily Mean | Wind Direction (°) Daily Mean | Air Temp (°C) Daily Mean | Relative Humidity (%) Daily Mean | Precip (mm) Daily Total | Ground/Water temperature ~10 cm below (°C) daily Average | ~20 cm below (°C) daily Average | ~40 cm below (°C) daily Average | Net Radiation $W(m^{2})^{-1}$ Daily Mean | Air Pressure (Kpa) Daily Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| **160** | 0.43 | 170.15 | 18.35 | 42.48 | 0.00 | 11.51 | 11.28 | 13.19 | 85.47 | 66.89 |
| **161** | 0.47 | 168.00 | 16.99 | 58.62 | 0.00 | 11.61 | 11.38 | 13.27 | 71.90 | 67.50 |
| **162** | 0.68 | 177.03 | 13.28 | 67.52 | 0.00 | 11.73 | 11.51 | 13.01 | 37.98 | 70.37 |
| **163** | 0.33 | 156.61 | 12.68 | 50.67 | 0.00 | 11.12 | 10.88 | 11.79 | 79.50 | 70.20 |
| **164** | 0.36 | 153.13 | 12.96 | 76.57 | 5.08 | 11.09 | 10.82 | 12.21 | 39.72 | 71.34 |
| **165** | 0.31 | 174.84 | 15.71 | 69.13 | 0.25 | 11.23 | 10.95 | 12.69 | 49.12 | 71.62 |
| **166** | 0.39 | 213.78 | 14.58 | 72.56 | 1.27 | 11.49 | 11.20 | 12.85 | 35.24 | 71.16 |
| **167** | 0.37 | 188.68 | 12.48 | 64.30 | 0.00 | 11.22 | 10.97 | 11.87 | 48.74 | 70.97 |
| **168** | 0.41 | 160.33 | 13.47 | 64.61 | 3.56 | 10.92 | 10.74 | 11.75 | 55.41 | 70.38 |
| **169** | 0.36 | 168.72 | 14.16 | 84.76 | 16.00 | 11.15 | 10.97 | 12.35 | 34.78 | 71.43 |
| **170** | 0.28 | 185.10 | 14.02 | 90.97 | 8.38 | 11.58 | 11.30 | 12.91 | 22.60 | 72.21 |
| **171** | 0.37 | 205.85 | 13.36 | 82.84 | 1.78 | 11.74 | 11.44 | 12.83 | 23.49 | 72.33 |
| **172** | 0.51 | 180.27 | 14.75 | 55.35 | 0.00 | 11.55 | 11.27 | 12.55 | 92.31 | 70.85 |
| **173** | 0.39 | 180.65 | 16.40 | 47.28 | 0.00 | 11.46 | 11.19 | 12.45 | 94.73 | 68.29 |
| **174** | 0.53 | 181.12 | 19.33 | 44.23 | 0.00 | 11.74 | 11.48 | 13.24 | 83.16 | 67.18 |
| **175** | 0.50 | 177.34 | 17.85 | 46.04 | 0.00 | 12.01 | 11.79 | 13.33 | 90.82 | 67.60 |
| **176** | 0.40 | 162.51 | 18.19 | 49.95 | 0.00 | 12.07 | 11.85 | 13.29 | 51.56 | 67.57 |
| **177** | 0.40 | 174.91 | 20.05 | 67.87 | 5.08 | 12.53 | 12.29 | 14.56 | 78.96 | 67.89 |
| **178** | 0.53 | 185.12 | 21.48 | 48.83 | 0.00 | 13.25 | 12.93 | 15.36 | 92.51 | 66.96 |
| **179** | 0.43 | 209.27 | 17.39 | 65.86 | 6.35 | 13.37 | 13.09 | 14.81 | 61.49 | 67.63 |
| **180** | 0.58 | 209.66 | 19.58 | 56.71 | 0.25 | 13.55 | 13.29 | 15.16 | 89.98 | 68.53 |
| **181** | 0.41 | 179.26 | 17.48 | 59.48 | 0.00 | 13.57 | 13.31 | 14.77 | 54.49 | 68.19 |
| **182** | 0.50 | 177.16 | 20.66 | 53.24 | 0.00 | 13.54 | 13.31 | 14.97 | 94.28 | 67.35 |
| **183** | 0.24 | 182.78 | 17.14 | 77.90 | 4.32 | 13.75 | 13.51 | 14.91 | 9.39 | 69.21 |
| **184** | 0.47 | 189.12 | 18.94 | 59.55 | 0.00 | 13.56 | 13.32 | 14.84 | 87.96 | 69.30 |
| **185** | 0.34 | 174.46 | 17.80 | 69.16 | 11.18 | 13.70 | 13.44 | 14.89 | 42.49 | 68.30 |
| **186** | 0.78 | 199.25 | 14.45 | 90.01 | 29.46 | 13.81 | 13.59 | 14.47 | -1.35 | 71.55 |
| **187** | 0.43 | 206.16 | 16.71 | 69.26 | 0.25 | 13.46 | 13.23 | 14.32 | 73.32 | 70.36 |
| **188** | 0.40 | 180.38 | 16.47 | 71.89 | 0.51 | 13.71 | 13.45 | 14.89 | 67.36 | 69.98 |
| **189** | 0.39 | 177.24 | 19.40 | 56.64 | 0.00 | 13.73 | 13.54 | 14.95 | 88.01 | 68.77 |
| **190** | 0.42 | 172.96 | 23.29 | 48.57 | 0.00 | 14.02 | 13.83 | 15.75 | 78.89 | 67.20 |
| **191** | 0.44 | 179.29 | 26.23 | 48.18 | 0.00 | 14.68 | 14.50 | 16.93 | 90.73 | 66.13 |
| **192** | 0.45 | 173.82 | 23.64 | 67.25 | 14.48 | 15.37 | 15.19 | 17.58 | 70.23 | 65.89 |
| **193** | 0.35 | 203.13 | 21.49 | 61.76 | 0.00 | 15.55 | 15.31 | 17.12 | 71.64 | 68.67 |
| **194** | 0.51 | 184.86 | 20.43 | 47.90 | 0.00 | 15.45 | 15.20 | 16.73 | 48.11 | 67.76 |
| **195** | 0.39 | 187.87 | 17.28 | 50.36 | 0.00 | 15.03 | 14.79 | 15.78 | 60.11 | 67.73 |
| **196** | 0.37 | 168.42 | 21.07 | 48.08 | 0.00 | 14.70 | 14.48 | 15.78 | 71.48 | 67.41 |
| **197** | 0.39 | 164.26 | 18.11 | 71.14 | 0.00 | 14.79 | 14.58 | 15.84 | 31.31 | 68.80 |
| **198** | 0.31 | 177.28 | 19.11 | 60.26 | 0.00 | 14.56 | 14.36 | 15.59 | 59.29 | 68.52 |
| **199** | 0.56 | 164.76 | 21.46 | 60.71 | 0.00 | 14.65 | 14.46 | 16.02 | 62.63 | 67.23 |
| **200** | 0.34 | 153.35 | 18.66 | 82.61 | 11.94 | 14.92 | 14.70 | 16.20 | 21.15 | 68.72 |
| **201** | 0.58 | 216.75 | 14.91 | 88.53 | 7.87 | 14.69 | 14.48 | 15.32 | 4.43 | 71.70 |
| **202** | 0.38 | 193.59 | 18.84 | 61.37 | 0.00 | 14.34 | 14.15 | 15.19 | 79.27 | 69.74 |
| **203** | 0.26 | 175.23 | 18.17 | 71.62 | 0.25 | 14.40 | 14.20 | 15.26 | 16.14 | 69.53 |
| **204** | 0.29 | 180.59 | 19.45 | 73.15 | 0.00 | 14.36 | 14.18 | 15.51 | 41.23 | 69.63 |
| **205** | 0.40 | 171.09 | 20.69 | 64.12 | 0.00 | 14.59 | 14.42 | 15.97 | 74.46 | 68.29 |

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|---|---|---|---|---|---|---|---|---|---|---|
| **206** | 0.38 | 186.22 | 19.32 | 72.29 | 0.00 | 14.86 | 14.69 | 16.13 | 27.04 | 69.08 |
| **207** | 0.38 | 195.41 | 21.47 | 69.35 | 0.00 | 14.93 | 14.76 | 16.38 | 55.32 | 69.08 |
| **208** | 0.42 | 174.82 | 20.87 | 65.69 | 0.00 | 15.14 | 14.97 | 16.61 | 74.04 | 68.17 |
| **209** | 0.34 | 187.20 | 20.77 | 68.87 | 0.00 | 15.27 | 15.13 | 16.63 | 64.30 | 68.08 |
| **210** | 0.39 | 165.58 | 20.90 | 61.36 | 0.00 | 15.31 | 15.21 | 16.56 | 65.18 | 67.93 |
| **211** | 0.24 | 172.93 | 18.03 | 69.78 | 0.00 | 15.16 | 15.06 | 15.93 | 23.29 | 69.17 |
| **212** | 0.50 | 192.19 | 21.77 | 56.74 | 0.00 | 14.91 | 14.81 | 15.92 | 61.77 | 68.30 |
| **213** | 0.33 | 175.40 | 19.29 | 63.14 | 0.76 | 14.94 | 14.87 | 15.92 | 39.47 | 67.88 |
| **214** | 0.32 | 175.84 | 18.14 | 68.32 | 0.00 | 14.81 | 14.72 | 15.61 | 48.35 | 68.84 |
| **215** | 0.25 | 172.09 | 16.01 | 84.06 | 2.79 | 14.70 | 14.60 | 15.37 | 12.08 | 70.75 |
| **216** | 0.38 | 168.87 | 16.49 | 72.54 | 0.00 | 14.37 | 14.27 | 15.10 | 66.40 | 70.66 |
| **217** | 0.53 | 189.95 | 20.06 | 57.06 | 0.00 | 14.56 | 14.42 | 15.74 | 44.38 | 69.13 |
| **218** | 0.64 | 220.06 | 17.13 | 52.93 | 0.00 | 14.44 | 14.30 | 14.92 | 52.13 | 68.59 |
| **219** | 0.30 | 174.63 | 16.83 | 56.80 | 0.00 | 14.04 | 13.95 | 14.50 | 50.01 | 68.50 |
| **220** | 0.37 | 161.14 | 19.87 | 59.91 | 0.51 | 14.17 | 14.08 | 15.22 | 39.47 | 68.19 |
| **221** | 0.46 | 167.82 | 20.56 | 50.87 | 0.00 | 14.17 | 14.09 | 15.00 | 46.26 | 67.52 |
| **222** | 0.38 | 177.00 | 18.58 | 81.10 | 4.57 | 14.35 | 14.29 | 15.49 | 1.24 | 69.31 |
| **223** | 0.46 | 184.40 | 18.32 | 56.51 | 0.00 | 14.30 | 14.23 | 15.14 | 45.07 | 69.68 |
| **224** | 0.54 | 213.93 | 14.61 | 58.49 | 0.00 | 14.06 | 14.00 | 14.36 | 26.75 | 70.24 |
| **225** | 0.33 | 192.22 | 14.80 | 61.41 | 0.00 | 13.58 | -- | 13.84 | 45.76 | 70.34 |
| **226** | 0.30 | 157.16 | 14.59 | 79.73 | 3.81 | 13.38 | -- | 13.60 | 8.28 | 70.52 |
| **227** | 0.59 | 221.40 | 13.69 | 78.23 | 0.25 | 13.42 | -- | 13.93 | 12.24 | 72.06 |
| **228** | 0.38 | 193.34 | 12.29 | 67.73 | 0.00 | 12.99 | -- | 12.88 | 42.60 | 70.58 |
| **229** | 0.20 | 160.70 | 16.60 | 80.79 | 0.00 | 12.83 | 13.07 | 13.46 | 37.67 | 69.98 |
| **230** | 0.20 | 178.68 | 17.20 | 81.47 | 0.76 | 13.18 | 13.61 | 14.24 | 42.96 | 69.31 |
| **231** | 0.20 | 157.67 | 17.46 | 72.68 | 0.00 | 13.27 | 13.59 | 14.02 | 47.59 | 68.07 |
| **232** | 0.20 | 173.29 | 20.84 | 65.09 | 0.00 | 13.43 | 13.96 | 14.63 | 47.06 | 67.59 |
| **233** | 0.20 | 161.51 | 17.73 | 71.66 | 0.00 | 13.67 | 14.15 | 14.53 | 24.72 | 67.83 |
| **234** | 0.20 | 177.73 | 19.88 | 80.43 | 1.52 | 13.72 | 14.29 | 14.92 | 32.63 | 68.45 |
| **235** | 0.20 | 182.51 | 16.10 | 95.00 | 10.92 | 14.03 | 14.57 | 15.10 | 3.86 | 70.21 |
| **236** | 0.20 | 194.72 | 17.05 | 89.52 | 0.76 | 14.09 | 14.52 | 15.05 | 29.82 | 71.67 |
| **237** | 0.20 | 196.77 | 14.69 | 86.03 | 0.00 | 13.91 | 14.09 | 14.35 | 24.55 | 70.94 |
| **238** | 0.20 | 220.07 | 14.52 | 93.31 | 0.00 | 13.74 | 13.89 | 14.22 | 2.28 | 71.52 |
| **239** | 0.20 | 173.05 | 16.07 | 79.90 | 0.00 | 13.56 | 13.69 | 14.02 | 42.74 | 70.94 |
| **240** | 0.20 | 157.93 | 16.89 | 78.40 | 0.00 | 13.43 | 13.62 | 13.97 | 32.85 | 69.89 |
| **241** | 0.20 | 172.25 | 18.06 | 73.82 | 0.00 | 13.57 | 13.87 | 14.35 | 37.26 | 69.26 |
| **242** | 0.20 | 192.68 | 16.07 | 85.38 | 0.25 | 13.75 | 14.02 | 14.52 | 17.03 | 70.54 |
| **243** | 0.20 | 219.76 | 12.62 | 91.04 | 0.25 | 13.49 | 13.48 | 13.62 | 3.72 | 71.02 |
| **244** | 0.20 | 187.56 | 13.98 | 77.68 | 0.00 | 13.07 | 13.03 | 13.13 | 37.47 | 71.36 |
| **245** | 0.20 | 177.19 | 12.98 | 91.59 | 1.52 | 12.70 | 12.64 | 12.66 | -2.41 | 71.18 |
| **246** | 0.20 | 212.83 | 13.57 | 96.56 | 20.57 | 12.72 | 12.82 | 13.06 | 2.74 | 71.03 |
| **247** | 0.20 | 232.35 | 11.49 | 96.69 | 20.57 | 12.67 | 12.63 | 12.68 | 4.22 | 69.47 |
| **248** | 0.20 | 218.20 | 14.03 | 94.20 | 0.00 | 12.41 | 12.44 | 12.69 | 27.45 | 69.55 |
| **249** | 0.20 | 154.41 | 13.35 | 86.95 | 0.25 | 12.49 | 12.55 | 12.77 | 40.81 | 70.43 |
| **250** | 0.20 | 181.35 | 12.26 | 82.86 | 0.00 | 12.12 | 12.01 | 11.90 | 34.30 | 70.07 |
| **251** | 0.20 | 175.79 | 12.24 | 87.18 | 0.76 | 11.94 | 11.98 | 11.96 | 35.70 | 70.17 |
| **252** | 0.20 | 168.18 | 11.76 | 82.95 | 0.00 | 11.67 | 11.61 | 11.47 | 21.99 | 69.79 |
| **253** | 0.20 | 153.93 | 13.18 | 84.72 | 0.00 | 11.60 | 11.69 | 11.73 | 19.78 | 70.41 |
| **254** | 0.20 | 204.09 | 12.23 | 92.53 | 16.00 | 11.75 | 11.92 | 11.98 | 4.60 | 70.63 |
| **255** | 0.20 | 237.25 | 8.27 | 96.67 | 23.11 | 11.56 | 11.35 | 11.03 | -3.21 | 68.77 |
| **256** | 0.20 | 202.07 | 6.65 | 89.58 | 0.00 | 10.75 | 10.35 | 9.87 | 18.05 | 68.00 |

**JPH Fen 2012**

| DOY | Wind Speed ($ms^{-1}$) Daily Mean | Wind Direction (°) Daily Mean | Air Temp (°C) Daily Mean | Relative Humidity (%) Daily Mean | Precip (mm) Daily Total | Ground/Water temperature ~10 cm below (°C) daily Average | ~20 cm below (°C) daily Average | ~40 cm below (°C) daily Average | Net Radiation $W(m^{2})^{-1}$ Daily Mean | Air Pressure (Kpa) Daily Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| **160** | 0.43 | 174.72 | 18.04 | 44.07 | 0.00 | 7.29 | 7.56 | 7.83 | 128.71 | 96.95 |
| **161** | 0.47 | 177.26 | 16.67 | 60.51 | 0.00 | 7.23 | 7.58 | 7.73 | 106.66 | 96.54 |
| **162** | 0.68 | 188.95 | 12.94 | 68.39 | 0.00 | 7.32 | 7.74 | 7.80 | 75.29 | 97.11 |
| **163** | 0.33 | 175.87 | 12.67 | 52.01 | 0.00 | 7.36 | 7.37 | 7.77 | 128.22 | 97.54 |
| **164** | 0.36 | 180.35 | 12.80 | 77.36 | 6.35 | 7.09 | 7.45 | 7.44 | 68.76 | 97.14 |
| **165** | 0.31 | 188.69 | 15.72 | 69.60 | 0.00 | 7.24 | 7.62 | 7.61 | 102.99 | 96.69 |
| **166** | 0.39 | 194.69 | 14.23 | 74.25 | 2.03 | 7.49 | 7.89 | 7.89 | 68.97 | 96.81 |
| **167** | 0.37 | 185.09 | 12.09 | 66.39 | 0.00 | 7.65 | 7.70 | 8.04 | 101.85 | 97.58 |
| **168** | 0.41 | 176.72 | 13.21 | 65.93 | 4.32 | 7.39 | 7.47 | 7.71 | 90.77 | 97.09 |
| **169** | 0.36 | 188.02 | 14.33 | 84.32 | 16.26 | 7.31 | 7.76 | 7.65 | 61.61 | 95.80 |
| **170** | 0.28 | 178.99 | 14.00 | 91.54 | 8.38 | 7.70 | 8.34 | 8.11 | 44.77 | 96.07 |
| **171** | 0.37 | 204.93 | 13.05 | 84.06 | 2.54 | 8.12 | 8.68 | 8.71 | 43.41 | 96.92 |
| **172** | 0.51 | 193.64 | 14.37 | 56.40 | 0.25 | 8.26 | 8.49 | 8.75 | 162.53 | 97.60 |
| **173** | 0.39 | 179.90 | 16.27 | 47.87 | 0.00 | 8.30 | 8.37 | 8.68 | 164.47 | 97.82 |
| **174** | 0.53 | 186.00 | 19.07 | 45.60 | 0.00 | 8.25 | 8.50 | 8.58 | 148.76 | 97.53 |
| **175** | 0.50 | 156.42 | 17.20 | 48.78 | 0.00 | 8.46 | 8.66 | 8.83 | 157.52 | 97.86 |
| **176** | 0.40 | 176.98 | 18.11 | 50.48 | 0.00 | 8.53 | 8.67 | 8.88 | 74.41 | 97.82 |
| **177** | 0.40 | 183.77 | 20.19 | 67.70 | 7.62 | 8.48 | 9.09 | 8.84 | 135.57 | 96.88 |
| **178** | 0.53 | 183.70 | 21.07 | 50.30 | 0.00 | 9.16 | 9.74 | 9.65 | 164.63 | 96.24 |
| **179** | 0.43 | 190.12 | 17.09 | 68.67 | 9.65 | 9.57 | 9.76 | 10.05 | 87.54 | 95.82 |
| **180** | 0.58 | 183.35 | 19.70 | 55.15 | 0.25 | 9.51 | 10.00 | 10.02 | 133.11 | 96.59 |
| **181** | 0.41 | 187.41 | 17.15 | 61.48 | 0.00 | 9.79 | 9.98 | 10.28 | 98.31 | 96.94 |
| **182** | 0.50 | 184.67 | 20.46 | 54.75 | 0.00 | 9.64 | 9.90 | 10.04 | 157.36 | 96.90 |
| **183** | 0.24 | 183.59 | 16.92 | 79.53 | 5.33 | 9.75 | 10.09 | 10.18 | 19.09 | 96.74 |
| **184** | 0.47 | 185.70 | 18.99 | 59.33 | 0.00 | 9.72 | 10.02 | 10.14 | 161.58 | 96.80 |
| **185** | 0.34 | 185.58 | 17.78 | 70.00 | 13.46 | 9.88 | 10.16 | 10.29 | 61.94 | 96.42 |
| **186** | 0.78 | 188.40 | 14.37 | 90.58 | 37.08 | 9.89 | 10.39 | 10.34 | 9.11 | 95.79 |
| **187** | 0.43 | 179.30 | 16.58 | 70.12 | 0.51 | 9.87 | 10.20 | 10.33 | 143.50 | 97.23 |
| **188** | 0.40 | 188.37 | 16.23 | 73.22 | 0.76 | 10.01 | 10.79 | 10.57 | 102.28 | 97.81 |
| **189** | 0.39 | 176.19 | 19.14 | 58.79 | 0.00 | 10.52 | 11.09 | 11.14 | 162.12 | 98.11 |
| **190** | 0.42 | 179.89 | 23.16 | 49.74 | 0.00 | 10.84 | 11.66 | 11.50 | 156.64 | 98.03 |
| **191** | 0.44 | 183.06 | 26.14 | 49.46 | 0.00 | 11.40 | 12.26 | 12.40 | 167.98 | 97.65 |
| **192** | 0.45 | 179.89 | 23.34 | 68.98 | 17.53 | 11.67 | 12.55 | 12.43 | 109.38 | 97.12 |
| **193** | 0.35 | 189.34 | 21.31 | 60.92 | 0.00 | 12.09 | 12.64 | 12.77 | 136.36 | 97.14 |
| **194** | 0.51 | 181.71 | 19.91 | 52.58 | 0.00 | 12.09 | 12.63 | 12.65 | 119.10 | 97.30 |
| **195** | 0.39 | 182.18 | 17.06 | 53.44 | 0.00 | 12.13 | 12.53 | 12.61 | 126.25 | 98.01 |
| **196** | 0.37 | 178.91 | 20.92 | 50.00 | 0.00 | 12.03 | 12.44 | 12.43 | 141.38 | 97.66 |
| **197** | 0.39 | 192.34 | 17.66 | 74.66 | 0.00 | 12.07 | 12.71 | 12.49 | 53.00 | 97.64 |
| **198** | 0.31 | 169.98 | 18.89 | 62.21 | 0.00 | 12.35 | 12.74 | 12.77 | 110.03 | 97.56 |
| **199** | 0.56 | 180.34 | 21.53 | 62.17 | 0.00 | 12.34 | 12.89 | 12.75 | 122.79 | 96.95 |
| **200** | 0.34 | 181.52 | 18.56 | 83.29 | 17.02 | 12.60 | 13.28 | 13.06 | 37.06 | 96.54 |
| **201** | 0.58 | 188.40 | 15.13 | 87.25 | 7.87 | 12.92 | 13.20 | 13.37 | 18.00 | 97.02 |
| **202** | 0.38 | 188.58 | 18.79 | 62.07 | 0.00 | 12.67 | 12.87 | 13.02 | 154.46 | 97.91 |
| **203** | 0.26 | 191.72 | 18.16 | 72.09 | 0.25 | 12.45 | 12.85 | 12.80 | 26.97 | 97.36 |
| **204** | 0.29 | 177.51 | 19.21 | 75.22 | 0.00 | 12.45 | 12.71 | 12.78 | 76.80 | 97.37 |
| **205** | 0.40 | 174.20 | 20.44 | 67.37 | 0.00 | 12.33 | 12.71 | 12.66 | 146.65 | 97.51 |

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|---|---|---|---|---|---|---|---|---|---|---|
| **206** | 0.38 | 200.12 | 19.02 | 76.48 | 0.00 | 12.41 | 12.96 | 12.77 | 56.33 | 97.05 |
| **207** | 0.38 | 191.99 | 21.15 | 72.49 | 0.51 | 12.67 | 13.13 | 13.06 | 111.20 | 97.41 |
| **208** | 0.42 | 196.26 | 20.60 | 69.76 | 0.00 | 12.80 | 13.31 | 13.19 | 143.53 | 97.66 |
| **209** | 0.34 | 186.14 | 20.58 | 73.86 | 0.00 | 12.97 | 13.51 | 13.38 | 108.09 | 97.23 |
| **210** | 0.39 | 185.44 | 20.69 | 64.87 | 0.00 | 13.16 | 13.67 | 13.59 | 124.53 | 97.29 |
| **211** | 0.24 | 178.62 | 17.74 | 74.13 | 0.00 | 13.28 | 13.72 | 13.70 | 36.45 | 97.50 |
| **212** | 0.50 | 189.53 | 21.41 | 60.17 | 0.00 | 13.27 | 13.57 | 13.64 | 145.91 | 97.12 |
| **213** | 0.33 | 177.06 | 19.01 | 67.43 | 0.76 | 13.16 | 13.63 | 13.52 | 84.64 | 97.09 |
| **214** | 0.32 | 182.89 | 18.07 | 70.47 | 0.00 | 13.28 | 13.67 | 13.66 | 95.53 | 97.22 |
| **215** | 0.25 | 173.95 | 15.85 | 86.40 | 3.56 | 13.28 | 13.67 | 13.61 | 18.18 | 97.26 |
| **216** | 0.38 | 174.97 | 16.56 | 71.68 | 0.00 | 13.31 | 13.52 | 13.64 | 123.85 | 97.57 |
| **217** | 0.53 | 184.65 | 20.09 | 57.66 | 0.00 | 13.13 | 13.57 | 13.42 | 93.34 | 97.10 |
| **218** | 0.64 | 200.46 | 16.65 | 58.06 | 0.00 | 13.33 | 13.73 | 13.69 | 130.03 | 97.40 |
| **219** | 0.30 | 180.20 | 16.59 | 61.92 | 0.25 | 13.34 | 13.62 | 13.67 | 110.66 | 97.84 |
| **220** | 0.37 | 166.94 | 19.48 | 62.83 | 0.51 | 13.21 | 13.60 | 13.51 | 115.81 | 97.84 |
| **221** | 0.46 | 181.91 | 20.23 | 53.82 | 0.00 | 13.37 | 13.76 | 13.73 | 129.14 | 97.79 |
| **222** | 0.38 | 189.92 | 18.73 | 80.04 | 5.59 | 13.43 | 13.90 | 13.78 | 5.76 | 97.21 |
| **223** | 0.46 | 186.98 | 18.30 | 55.89 | 0.00 | 13.59 | 13.87 | 13.95 | 120.75 | 97.40 |
| **224** | 0.54 | 188.30 | 14.38 | 60.93 | 0.00 | 13.51 | 13.77 | 13.86 | 66.97 | 97.58 |
| **225** | 0.33 | 196.94 | 14.54 | 65.16 | 0.00 | 13.34 | 13.35 | 13.58 | 114.96 | 98.08 |
| **226** | 0.30 | 171.36 | 14.53 | 80.95 | 3.56 | 13.04 | 13.08 | 13.28 | 28.51 | 97.37 |
| **227** | 0.59 | 196.28 | 13.46 | 79.62 | 0.25 | 12.75 | 12.93 | 12.96 | 32.25 | 97.48 |
| **228** | 0.38 | 203.18 | 12.69 | 65.11 | 0.00 | 12.68 | 12.55 | 12.93 | 113.28 | 98.07 |
| **229** | 0.20 | 182.25 | 18.11 | 59.57 | 0.25 | 12.26 | 12.36 | 12.40 | 97.55 | 97.45 |
| **230** | 0.20 | 180.02 | 17.47 | 66.98 | 0.76 | 12.32 | 12.63 | 12.57 | 104.02 | 97.62 |
| **231** | 0.20 | 163.14 | 18.67 | 59.04 | 0.00 | 12.59 | 12.71 | 12.90 | 114.50 | 97.76 |
| **232** | 0.20 | 187.28 | 21.85 | 54.91 | 0.00 | 12.55 | 12.80 | 12.82 | 107.58 | 97.25 |
| **233** | 0.20 | 169.07 | 18.43 | 62.32 | 0.00 | 12.76 | 13.02 | 13.13 | 59.45 | 97.30 |
| **234** | 0.20 | 180.09 | 20.54 | 69.61 | 2.54 | 12.72 | 13.00 | 13.06 | 89.55 | 96.98 |
| **235** | 0.20 | 183.68 | 16.41 | 91.21 | 12.70 | 12.86 | 13.24 | 13.24 | 4.75 | 96.89 |
| **236** | 0.20 | 178.24 | 16.99 | 79.80 | 0.76 | 12.90 | 13.22 | 13.28 | 67.78 | 96.65 |
| **237** | 0.20 | 200.31 | 14.00 | 79.66 | 0.00 | 12.95 | 13.02 | 13.38 | 54.16 | 96.66 |
| **238** | 0.20 | 217.11 | 14.17 | 85.75 | 0.00 | 12.66 | 12.77 | 12.93 | 21.59 | 96.81 |
| **239** | 0.20 | 180.39 | 15.54 | 73.61 | 0.00 | 12.51 | 12.59 | 12.77 | 95.51 | 97.52 |
| **240** | 0.20 | 176.70 | 18.10 | 68.10 | 0.00 | 12.40 | 12.47 | 12.64 | 68.74 | 97.25 |
| **241** | 0.20 | 175.54 | 18.23 | 65.28 | 0.00 | 12.34 | 12.52 | 12.62 | 79.46 | 96.77 |
| **242** | 0.20 | 177.83 | 16.28 | 70.61 | 0.51 | 12.38 | 12.65 | 12.68 | 45.16 | 96.39 |
| **243** | 0.20 | 180.51 | 12.53 | 76.33 | 0.25 | 12.43 | 12.45 | 12.73 | 25.40 | 97.02 |
| **244** | 0.20 | 180.01 | 13.21 | 70.50 | 0.00 | 12.12 | 12.13 | 12.33 | 84.42 | 97.62 |
| **245** | 0.20 | 184.82 | 13.40 | 85.16 | 1.78 | 11.92 | 11.84 | 12.11 | 15.70 | 97.09 |
| **246** | 0.20 | 203.02 | 13.42 | 95.64 | 22.86 | 11.64 | 11.88 | 11.81 | 6.32 | 96.01 |
| **247** | 0.20 | 185.50 | 10.53 | 94.78 | 24.38 | 11.71 | 11.88 | 11.96 | 9.62 | 96.48 |
| **248** | 0.20 | 176.27 | 13.27 | 87.88 | 0.00 | 11.60 | 11.66 | 11.78 | 45.80 | 97.15 |
| **249** | 0.20 | 163.90 | 12.41 | 77.02 | 0.51 | 11.50 | 11.71 | 11.70 | 74.19 | 97.51 |
| **250** | 0.20 | 181.87 | 13.21 | 70.68 | 0.00 | 11.54 | 11.52 | 11.75 | 71.33 | 97.66 |
| **251** | 0.20 | 191.28 | 12.40 | 76.03 | 0.76 | 11.19 | 11.26 | 11.30 | 56.89 | 97.81 |
| **252** | 0.20 | 180.70 | 13.47 | 67.87 | 0.00 | 11.10 | 11.08 | 11.23 | 55.65 | 97.56 |
| **253** | 0.20 | 154.26 | 14.51 | 76.24 | 0.00 | 10.83 | 10.90 | 10.91 | 64.08 | 96.54 |
| **254** | 0.20 | 186.89 | 12.01 | 88.81 | 19.05 | 10.78 | 10.98 | 10.89 | 11.57 | 95.68 |
| **255** | 0.20 | 144.13 | 7.62 | 91.83 | 27.69 | 10.88 | 10.99 | 11.02 | -5.95 | 96.20 |
| **256** | 0.20 | 206.23 | 7.26 | 68.53 | 0.00 | 10.77 | 10.66 | 10.87 | 46.94 | 97.63 |