The relationship among micro-topographic variation, water table depth and biogeochemistry in an ombrotrophic bog

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Abstract

Peatlands store 30% of global terrestrial organic carbon. At the Mer Bleue research site in southern Canada (45.40° N, 75.50° W), it has been shown that changes in water storage affect carbon fluxes in and out of the peatland. Mer Bleue has a distinct hummock – hollow surface topography. The micro-topographical features affect the temporal and spatial variations in water table. Sampling the temporal and spatial variations on two separate plots with varying degrees of micro-topographic relief took place during the 2010 field season. Each plot has 100 manual observation wells in a 2 x 2 metre grid that have been sampled every 2-3 weeks and several transects of 4-7 automatic capacitance data loggers, continuously recording water levels every 15 minutes. The continuous water table measurements were situated to maximize the difference in elevation between adjacent hummocks and hollows. Our results indicate that the spatial pattern of the water table at any given time is a subdued reflection of the surface topography – i.e. greater depth under hummocks than hollows. The continuous water table measurements show that the variations in water table are synchronized, despite differences in surface micro-topography. When combined with the surface elevation the patterns in time and space can be used to provide a tempo-spatial ecologically meaningful measure of water storage, explain the feedbacks between moisture and peat accumulation, and suggest a basis for scaling point measurements to account for topographic variations.

Résumé

Les tourbières contiennent 30% du carbone organique terrestre au monde. Au site de recherche Mer Bleue à Ottawa (45.40° N, 75.50° W), on a montré que les flux de carbone sont contrôlés par des fluctuations de stockage total du tourbières. La nappe phréatique indique la rétention d'humidité. La tourbière à Mer Bleue a une microtopographie distincte de buttes et creux. Les caractéristiques des micro-topographique affectent les variations temporelles et spatiales de la nappe phréatique. L'échantillonnage a eu lieu entre Juin et Décembre 2010, en deux parcelles à des degrés divers de l'allégement de micro-topographiques. Chaque parcelle dispose de 100 puits d'observation dans un manuel de 2 x 2 mètres de grille qui ont été échantillonnés tous les 2-3 semaines et plusieurs transects de 4-7 automatique des enregistreurs de données capacitive, enregistrement en continu des niveaux d'eau toutes les 15 minutes. Les mesures en continu de la nappe phréatique se trouvaient à maximiser la différence d'altitude entre les buttes et les creux adjacents. Les résultats indiquent que la répartition spatiale de la nappe phréatique à un moment donné est un reflet modéré de la topographie de surface. Les mesures en continu de la nappe phréatique montrent que les variations de la nappe phréatique sont synchronisés, malgré les différences de surface micro-topographie. Lorsqu'il est combiné avec l'élévation de la surface des modèles dans le temps et l'espace peut être utilisé pour fournir une mesure tempo-spatiale écologiquement significatives de stockage de l'eau, expliquent les rétroactions entre l'accumulation d'humidité et de la tourbe, et de proposer une base pour l'extension des mesures ponctuelles pour tenir compte des variations topographiques.

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CHAPTER 1 – INTRODUCTION

At northern latitudes, peatlands represent a significant proportion of the total land area, and on a global scale, a vast amount of carbon is stored in them. According to estimates, northern peatlands contain as much as one-third, up to 450 Gt, of terrestrial carbon stored globally, while only covering approximately 2-3% of the Earth's surface (Gorham, 1991; Limpens *et al.*, 2008). As a result of this large store, it will be very important in the future to understand the controls of carbon flow in peatland systems, as they are very common in Canada, especially at colder latitudes. Under warming conditions, these northern peatlands could become unstable as temperature warms in the coming years (McGuire *et al.*, 2009; Turunen *et al.,* 2002). The movement of carbon in peatlands depends heavily on the hydrologic parameters that define water movement in and out of the system, via pathways such as surface runoff and groundwater movement. Since the peatland areas represent both a store of water (groundwater and soil water) and carbon (peat and vegetation) any changes to the equilibrium of these systems can have significant effects on the global carbon balance (Fraser *et al.*, 2001a). One of the most important controls on the overall carbon balance of peatland ecosystems is the depth of the water table, or the depth at which soil is completely saturated and anoxic conditions are often found (Frolking *et al.*, 2002). The surface micro-topographic variation of peatland ecosystems is one of their most important distinguishing characteristics, and the distinct hummock-hollow surface pattern can have far-reaching biogeochemical implications. Elevated hummocks and trough-like hollows often differ in the depth of the unsaturated peat layer beneath them, and the various carbon pathways of peatlands all depend in some way on the depth of the saturated zone below the surface. The general aim of this study is to define the relationship among the surface topography of a raised ombrotrophic bog, its water table depth and its water table elevation above an arbitrary datum. If the moisture regime of peatland ecosystems can be defined based on the roughness of the surface, then modelling exercises designed to estimate carbon fluxes can better incorporate peatlands, and the general study and prediction of carbon flux will be advanced.

Chapter 2 of this thesis will summarize findings from the scientific literature so as to provide sufficient background information for the study. A general introduction to the carbon pathways and hydrologic characteristics of peatland ecosystems will be followed by a thorough description of the role that surface patterning plays in peatlands. Furthermore, the specific research objectives associated with this study will be outlined, and the hypotheses will be clearly stated in the context of the pre-existing literature. Chapter 3 will provide background information about the history of the study site and a thorough description of the methodologies employed in the field will be included. Site selection criteria, measurement techniques and plans for future research at the site will be outlined in this section. In chapter 4, the results of the study will be presented, and these results will be explained in the context of the three principal research objectives summarized in chapter 2. Finally, the thesis will conclude with a discussion of major findings in chapter 5, and the material from chapters 3 and 4 will be considered so as to advance discussion for future research. Research reported on in this thesis seeks to build on the pre-existing literature by quantifying the temporal and spatial extent of water table level fluctuations in an ombrotrophic bog and defining the link between these fluctuations, the micro-topography and surface elevation of the peatland, and the biogeochemical cycling of the ecosystem.

CHAPTER 2: LITERATURE REVIEW & RESEARCH OBJECTIVES

2.1 – Peatland Types and General Ecology:

Peat is decaying or decayed organic material that has formed in place. Differences in the quantity and quality of vegetation, the moisture regime and depth of the peat itself help to identify the various types of peatlands found around the world (Charman, 2002). A relatively thin un-saturated zone is one of the most important distinguishing characteristics of peatlands, and anoxic conditions often occur close to the surface. Marshes have very thin peat layers, and contain submergent vegetation in stagnant or slow-moving water (Rydin and Jeglum, 2006). Swamps typically have thicker oxic layers of peat, and can support more robust, woody vegetation such as trees and shrub thickets. Swamps and marshes often have patches of open water within them.

Traditional definitions of peatlands denote that a minimum peat layer of 30-40 cm is needed for an ecosystem to be considered as a peatland. Fens and bogs usually satisfy this criterion, and contain similar vegetation cover, with a mixture of low shrubs, herbs and a dense cover of *Sphagnum* mosses. Fens and bogs differ in the way that they receive water and therefore receive nutrients differently. Fens are minero-trophic, meaning that they receive groundwater from the surrounding area (Charman, 2002; Rydin and Jeglum, 2005). A bog is a peat forming ecosystem that lacks any significant groundwater inflows, and is therefore ombrotrophic. Raised ombrotrophic bogs are so named because their surfaces are raised, often by several metres, above the surrounding mineral soils. The convex, dome-like shape of ombrotrophic bogs are brought about by the annual accumulation of peat material over a course of thousands of years (Ingram, 1982; Nungesser, 2003).

2.2 – Carbon in Peatland Ecosystems:

2.2.1 - Peatland Carbon Balance:

Three basic processes control how much carbon is sequestered annually in a peatland ecosystem: accumulation, production and decomposition. The interaction of these three factors determines the general rate of accumulation. Since most peatland ecosystems are carbon sinks, the rate of accumulation is an important determinant for the global carbon balance (Clymo, 1984). Peatland carbon balances are based on four general pathways; gross primary productivity, ecosystem respiration, methane exchange and dissolved organic carbon. All four of these pathways depend heavily on the hydrologic regime of the ecosystem (Blodau and Moore, 2003). The relative depths of the acrotelm (unsaturated, periodically aerated peat) and the catotelm (inundated, stagnant peat) alter the rates of production and decomposition in a peatland, and water moves much more freely above the boundary between these two layers (Evans *et al.*, 1999). The role of short-term changes in hydrologic storage is much more pronounced in the acrotelm, as greater values of hydraulic conductivity allow for lateral groundwater flow and vertical changes in the depth of the water table, where saturated conditions occur.

2.2.2 - Peatland Carbon Pathways:

The main pathway through which carbon enters a peatland system is via gross primary production through photosynthesis. The amount of carbon sequestered from the atmosphere for plant growth depends on the abundance of vegetation available to take in carbon dioxide, as well as the length of the growing season in the peatland in question (Frolking *et al.*, 2002). The two most prominent groups of vegetation on the surface of peatlands, mosses and shrubs, react to variations in the water table in different ways.

Ecosystem respiration, which is the sum of autotrophic and heterotrophic respiration, represents the first and most significant outflow pathway of carbon in a peatland. Heterotrophic respiration takes place within the soil under the surface of a peatland, and is therefore very dependent on the depth of the water table. Under anoxic conditions below the water table, heterotrophic respiration is limited, and a smaller carbon dioxide flux is associated with these conditions (Dise, 2009). For autotrophic respiration, a peatland with a shallow-intermediate water table will have more vegetation growth on the surface, leading to greater autotrophic respiration (St. Hilaire *et al.*, 2008).

Wetlands are one of the most important natural global sources of methane, and decomposition in peatlands results in production of this greenhouse gas

(Clymo and Bryant, 2008). In peatland systems, there are multiple pathways by which methane is emitted, including bubbling to the surface, and venting facilitated by plant structures. An important control of methane release from peatlands is the prominence of plants which facilitate methane exchange, because of the above-mentioned aid that plant structures provide for methane release. The presence of clear pathways for methane vastly increases flux to the surface, as bubbling towards the peat surface is a much slower process than plant-facilitated venting. Also, water table depth plays a key role in the release of methane from peatland surfaces, as the general rate of methane consumption is much higher in the unsaturated zone, as a longer 'path length' for this methane flux can result in consumption (Rydin and Jeglum, 2006).

A third pathway by which carbon leaves a peatland ecosystem is in the form of dissolved organic carbon (DOC). The major controls of DOC outflow are the amount of runoff leaving the peatland, and the concentration of DOC in these outflow waters (Fraser *et al.*, 2001a). When the depth of the water table fluctuates, this concentration of DOC in laterally-flowing waters can fluctuate also, as increased soil moisture in previously unsaturated soils will lead to higher flux of organic carbon. In peatlands with high levels of annual runoff, this outflow of carbon can represent a significant portion of the carbon balance. Peatland runoff is directly related to the depth of the water table, as lateral flow towards the fringes is affected by various hydraulic conductivity values at different depths. In the acrotelm, hydraulic conductivity generally decreases as depth increases, due to the changes in porosity and pore size distribution, and the increased decomposition of organic matter (Frolking *et al.*, 2002).

The four primary carbon pathways that make up the carbon balance in peatlands are all influenced in some way by the depth of the water table, and the extent to which carbon is exchanged with the atmosphere via these pathways is affected by the depth of the water table. Modelling of peatland carbon balances is important to management of these ecosystems, and the depth of the water table is one of the key variables defined in many of these models. In many cases, the depth of the water table is a critical parameter describing the water storage in modelled peatlands, and the thickness of the active layer and the thickness of the boundary between it and the saturated zone is often one of the key inputs to the model (Frolking *et al*, 2002).

2.3 – Peatland Hydrology:

The water balance of a peatland ecosystem can be simplified to:

$$\Delta S = P - ET - R \pm G_o \qquad \textbf{(1)}$$

Where ΔS denotes a change in storage, P denotes precipitation input, ET denotes evapo-transpiration losses, R denotes catchment runoff and G_o denotes the net groundwater seepage at the peatland margins or across the mineral – peat interface. For ombrotrophic bogs, it is assumed that there are no significant inflows of either groundwater or surface water, and the only input is precipitation.

Groundwater flow patterns are controlled by rates of *P* and *ET*, and the rate of losses through evapo-transpiration, runoff and groundwater seepage depends on the depth of the water table (Evans *et al.*, 1999; Fraser *et al.*, 2001b).

2.3.1 – Water Table Importance and Controls:

The physical characteristics and feedbacks that control biogeochemical processes in peatlands are numerous and complex. However, one of the most important hydrologic parameters influencing these processes is the storage of water and this is usually indicated by the depth of the water table below the surface. The depth of the water table is one of the most ecologically significant hydrologic properties in peatlands (Lafleur *et al.*, 2005). Water availability for evapo-transpiration is determined by the depth of the water table, and the extent to which changes in evapo-transpiration rates can alter both the soil moisture regime and the make-up of the plant communities is considerable. Furthermore, smaller-scale groundwater and soil-water movements are affected by the depth of the water table, as movement of water between micro-topographic forms occurs if there is variability in the water table depth below these respective landforms (Blodau and Moore, 2003). The transition between the dynamic, aerated acrotelm and the stable, stagnant catotelm is significant in terms of hydraulic conductivity and decomposition rates, and the long-term depth of the water table in a peatland is what determines the depth at which this transition occurs.

2.3.2 - Peat Structure:

The defining characteristic of peatlands is that dead plant material only partially decays below the surface and this lead to an accumulation of peat over time. The thickness of the annual cohort of decaying organic matter represents how much plant biomass is added to the peat each year. Two distinct layers are present, based on the saturation and presence of oxygen (Charman, 2002). The acrotelm and catotelm more or less correspond to zones of aerobic and anaerobic activity, respectively (Ivanov, 1981). These two layers differ in that the upper layer (acrotelm) contains some living organic material, and is aerated on a periodic basis. The acrotelm interacts with the atmosphere and surrounding area frequently, exchanging moisture, and this is a process which is often facilitated by the living plant cover of mosses and shrubs present on the surface of the peat (Holden and Burt, 2003b). This periodic aeration allows aerobic bacteria to thrive in the acrotelm, leading to a higher rate of decomposition of peatland vegetation. Therefore, the acrotelm can be thought of as the peat-forming layer (Ingram, 1981). The amount of moisture in the peat near the surface affects how much of this near-surface layer is aerated, leading to frequent fluctuations in the level of the water table within the acrotelm. The water level can fluctuate quite quickly, since the porosity of the soils in the acrotelm, especially near the surface, can be relatively high (Ivanov, 1981). As a result of the high porosity and relatively high density of the peat, especially deeper in the peat column, influxes of water in this layer can affect the depth of the water table. Towards the base of the acrotelm, the soil becomes saturated, and the hydraulic conductivity is lower. The base of the acrotelm corresponds to the deepest drop of the water table level within the peat column (Ingram, 1982; Holden and Burt, 2003a). Water moves most freely near the surface of the peat soils due to the very high hydraulic conductivity. This is also because of the relatively large pore spaces where soil moisture levels are relatively lower. Vegetation often captures moisture infiltrating the soil column, especially under dry conditions when precipitation is rarer, and plants are in need of water. The rate at which water moves vertically into the soil is a function of the vertical hydraulic gradient, which is in turn affected by the differences in soil moisture within the acrotelm (Reeve *et al.*, 2000). The water table level and overall moisture content in the acrotelm are affected by varying precipitation and evapo-transpiration rates, which fluctuate due to periodic aeration. In the catotelm, where the soils and atmosphere do not generally interact, moisture conditions are much more stable (Charman, 2002).

In the catotelm, exchange with subjacent and adjacent areas is considerably less compared to the acrotelm above (Holden and Burt, 2003b; Siegel *et al.*, 1995; Siegel and Glaser, 1987). Furthermore, because of the saturation conditions and the density of the organic matter in the catotelm, the hydraulic conductivity in this layer is up to five orders of magnitude less than in the acrotelm (Ivanov, 1981). Finally, because of the inability of oxygen to diffuse into the saturated catotelm layer, aerobic decomposition of the peat material is greatly reduced. Therefore, anaerobic decomposition, a slower process, dominates in the catotelm, and carbon fluxes from decomposition are affected by this change in micro-organism composition (Charman, 2002). The physical characteristics of these two peat layers differ significantly, and the relative thickness of each has important implications for water movement, decomposition, plant growth and carbon exchange. The differences in physical characteristics between these two layers indicates that there definitely are two layers present within the peat column, although recent work suggests that the hard division between the two layers should be considered as more of a transition zone, and not an interface (Morris *et al.*, 2011).

2.3.3 - Groundwater Flow in Peatlands:

The subtle dome-like shape of the peat in bog areas is due to the annual accumulation of peat layers as decaying organic matter becomes saturated and denser. This dome-like shape can affect the lateral flow of groundwater and soil water, as a gradient can develop between the elevated centre of the dome and the fringes (Rydin and Jeglum, 2006). If the gradient between the centre of the peat dome and the water level at the fringes is steep the rate of the water flowing laterally in the soil towards the fringes of the peatland will increase (Ingram, 1982). The hydraulic conductivity of the soil in the peat dome also affects how water moves within the peatland, and vertical flow from the upper, active acrotelm layer to the more stagnant catotelm layer beneath is affected by the depth of the water table and the soil moisture content in the unsaturated acrotelm soils (Lafleur *et al.*, 2005). Furthermore, vertical hydraulic gradients within the soil layers are affected by the evapo-transpiration that occurs at the surface of the peatland. In the catotelm, vertical movement of water can even be reversed when evapo-transpiration fluxes lead to changes in the vertical hydraulic gradient (Fraser *et al.,* 2001b). Lagg streams are sometimes situated on the fringe of peatland areas, and these ponds are good indicators of the hydrologic gradient that may exist between the dome-shaped peatland centre, and the lower margins (Ingram, 1982). The relationship between the height of a peat dome, its width and the balance of inflow and outflow of water in the ground can be described by the quotient U/K, which denotes the balance between net water recharge (U) and the permeability of the peat deposit (K). The dimensions of the peat mound are related to this quotient by the expression:

$$\mathbf{U/K = (H^2)/2Lx - x^2} \qquad \mathbf{(2)}$$

Groundwater flows from areas of high hydraulic head to areas of low hydraulic head. This is dependent on the height above an arbitrary datum (elevation head) and the pressure that the water is under from surrounding forces (pressure head). As hydraulic conductivity is relatively high near the surface of the peatland, most of the movement of groundwater occurs in the acrotlem. Small-scale recharge movements of water can occur due to the micro-topographic variation on the surface of the peatland, and gradients between adjacent microforms can be much steeper than the overall elevation gradients seen across the 'dome' cross section of a bog (Fraser *et al.,* 2001b).

Increased evapo-transpiration affects the vertical hydraulic gradients, altering how water infiltrates from the upper acrotelm where plant life thrives down to the saturated, oxygen-deprived catotelm layer. More saturated conditions closer to the surface alters the amount of runoff originating from percolation and infiltration-excess conditions during heavy rainfall events (Evans *et al.*, 1999). The exchange of moisture between the peatland and the atmosphere is reduced in winter months, especially in areas where snow cover is present. Evapo-transpiration fluxes and infiltration from incoming liquid precipitation and melting snow cover are associated with the spring months, when thawing soils become accessible to the atmosphere again. As a result of this, increased runoff is associated with the spring months, and runoff continues to taper off throughout the growing season (Rydin and Jeglum, 2006). Gradients of hydraulic conductivity control how water moves within peat below the surface, and the resulting yield of water moving through the ground depends on the level of the water table, the general wetness of the peat, and the compaction of the peat caused by an external load (Ivanov, 1981; Holden and Burt, 2003a). Therefore, runoff from a peatland system depends largely on the depth of the water table, and changes to the outside controls of the peatland's water table can lead to changes in runoff.

2.4 – Peatland Surface Patterning:

2.4.1 – Peat Accumulation and Pattern-Forming Mechanisms:

Plant matter is added to the surface of actively growing peatlands every year, and as dead plants decay their defining structural elements are lost and compaction occurs. In bogs with a relatively thin peat layer, the addition of plant matter on the surface may exceed the total losses from decomposition occurring beneath the surface, leading to accumulation (Clymo, 1984). Many peat accumulation hypotheses exist, and most determine the boundary between the oxic acrotelm and the anoxic catotelm to be based on the depth of the water table (Belyea and Baird, 2006). The peat 'dome' geophysical model described in section 2.3.3 comes about due to annual accumulation of this sort, where water-logged conditions are present (Ingram, 1982). The development of a raised bog ecosystem requires peat accumulation for several thousand years, and equilibrium is eventually reached in a bog's vertical expansion, where accumulation and decay are balanced (Belyea and Baird, 2006). On a smaller scale, surface patterns can emerge due to local differences in species composition, nutrient availability and variations in water balance.

Peatland surface patterns often follow a distinct pattern of highs and lows, called a hummock-hollow sequence. In ombrotrophic bogs, hummocks and hollows, which are local highs and lows, respectively, can alternate on a scale of 1-3 metres (Nungesser, 2003). In peatland ecosystems, the degree and type of surface patterning can significantly alter the different carbon fluxes of the system, modifying the overall carbon balance. While these patterns can be discerned visually, the mechanisms that cause their initial emergence are poorly understood, partly because of the variability between study sites and the uncertainty associated with functions such as nutrient accumulation and pattern formation. Eppinga *et al.* (2009a) identified several environmental mechanisms that they believe to be responsible for the formation of hummock-hollow or ridge-like patterns on the surface of peatlands. The four key variables used in their model to simulate the formation of patterns due to different mechanisms include vascular plant biomass, acrotelm thickness, groundwater table dynamics and available nutrient pool (Eppinga *et al.,* 2009a).

If variations in the thickness of the acrotelm affect the productivity of plants on the surface of the peat, then there must be an optimum range of active layer thickness for water-related stress on surface vegetation (Belyea and Clymo, 2001). This relationship is described by a negative feedback between acrotelm thickness and evaporation rate: a thicker acrotelm will result in lower evaporation rates because of a greater distance between the saturated zone and the surface (Charman, 2002). Variations in plant communities inevitably indicate differences in transpiration and growth rates, as accumulation occurs un-evenly when vegetation heterogeneity is present (Nungesser, 2003).

The role of hydrology in peatland pattern formation cannot be understated. Studies show that transmissivity of the peat does indeed decrease with increased acrotelm thickness (Fraser *et al.*, 2001a; Ingram, 1982), as a result of increased decomposition and depth, and the added weight of overlying peat in areas with thicker active layers. Certain moisture conditions are needed for specific communities of vegetation on the surface of the peatland, and this heterogeneity is reinforced by the ponding of water beneath elevated micro-topographical features with a thicker active layer (Eppinga *et al*, 2009a).

Small-scale variations in the availability of plant biomass and the rate at which they transpire can indeed lead to surface heterogeneity, and variations in local accumulation and environmental gradients can lead to the formation of a hummock/hollow-like pattern (Nungesser, 2003). Empirical results suggest that denser vascular plant biomass is an indicator of hummock-like microforms, while bryophytes are often more prominent in hollow-like areas (Bubier *et al.*, 2006). The interaction between water table depths, peat accumulation and vegetation composition is complicated, and many feedback mechanisms exist within these complex systems. The formation of surface patterns such as the hummock/hollow sequence is brought about by these feedback mechanisms, where small initial variations in nutrient availability, moisture conditions or vegetation composition are amplified over the thousands of years necessary for these patterns to form (Belyea and Clymo 2001; Frolking *et al.*, 2010).

2.4.2 – Physical Characteristics of Hummocks and Hollows:

The spatial organization of the hummock and hollow patterning that constitutes many bog systems at northern latitudes affects the depth of the water table and how the water table varies due to storage changes. Hummocks are elevated above hollows, and therefore have a thicker acrotelm. In the hollows, saturated conditions are often very close to or at the surface, indicating that these trough-like areas between the elevated hummocks have very thin or no acrotelm at all (Eppinga *et al.*, 2008). In drier areas, peatlands with deeper water tables allow for increased accumulation with increased water input. Furthermore, in wetter sites, peat accumulation is limited by low rates of production (Hilbert *et al.*, 2000). The distribution of vegetation is different between hummock and hollow microforms. The drier hummocks with a deeper active layer tend to support more shrubs and woody biomass, whereas the often-inundated hollows are usually dominated by mosses which can thrive under saturated (oxygen-deprived) conditions, such as *Sphagnum* mosses (Bubier *et al.*, 2006). Micro-topographic variations on the surface of a peatland ecosystem indicate possible variability of the water table depth below the surface – this differential water table depth and the redistribution of water between hummocks and hollows implies it is a critical element to the feedback that Belyea and Clymo (2001) infer. They present an analog of hummocks and hollows being like a ‘dog on a leash’, and the critical controller of the ‘leash’ is the depth to water table. However, aside from some single point measurements in hummocks and hollows, the spatial and temporal relationships between the surface micro-topography, the depth of the water table beneath microforms and the response of the water table to storage changes beneath these microforms have not been examined. One would expect that differences in decomposition due to variable thickness of the active layer would lead to higher hydraulic transmissivity beneath hollows (Nungesser, 2003).

While the relationship between surface roughness and the spatial variability of the water table depth is interesting for testing theories of peatland develop, if there are relationships they could be used to assist in larger-scale predictions regarding carbon exchange in peatlands. Peatland models (St-Hilaire *et al*., 2010) are fixed point or only semi-distributed (Sonnentag *et al*., 2008) but it is believed that microtopography can have an effect on the biogeochemistry and therefore gas exchanges (Baird *et al*., 2009). Ways of parameterizing the influence of this heterogeneity (e.g. Wu *et al*., 2010) are needed. Statistical relationships based on field studies and/or emerging remote sensing techniques that can estimate either surface topography, or moisture directly (once calibrated) (e.g. Touzi *et al.*, 2007; Touzi and Gosselin, 2009) may offer some possibilities.

2.5 – Research Questions:

The surface patterning of a peatland such as the Mer Bleue bog can affect how water table depth reacts to changes in wetness both at the micro-scale and macro-scale (Eppinga *et al.*, 2009a). The distribution of vegetation varies according to the range of the micro-scale topographical changes, and hummock and hollow vegetation patterns are quite different (Bubier *et al.*, 2006). In the research presented in this thesis I explore the effect that peatland patterning has on water table variations in the Mer Bleue bog, and determine the role variations in elevation of the peatland surface has on these relationships. My overall objective is to determine the relationship among the surface topography, the water table depth, and the water level elevation above an arbitrary datum in a cool temperate ombrotrophic raised bog. This research has three broad goals.

The response of the water table beneath different micro-topographical forms to changes in storage will be compared to determine whether these micro-forms react differently. The storage changes to be analyzed will range from short-duration intense precipitation events to seasonal patterns. To answer this question, three time scales will be analyzed: heavy rainfall events lasting up to several hours, sustained rainfall events or sustained dry periods enduring up to 10 days, and seasonal variations due to climate occurring over several months. Rates of short-term water table recession will be calculated using the following equation:

$$Q_t = Q_o K^t \therefore \mathbf{K = \sqrt[t]{[WT_t/WT_o]}}$$

where K is the slope of the water table’s drop, Q is the storage, and WT indicates water table. It is expected that the rate of water table response will be similar regardless of surface microform at all three time scales. However, when initial water table depth is at or below the acrotelm/catotelm boundary, the recession will be different among hummocks and hollows. For water table rise due to precipitation inputs, comparisons among rates of rise and response ratios will help to determine how similarly the water table at different microforms reacts to inputs.

Secondly, I will investigate whether there is a relationship among the spatial variability in the surface elevation of a peatland created by micro-

topography and the spatial variability of the water table and whether this relationship changes with time. Data for two spatial extents will be analyzed to answer this question at two scales - the 'plot scale' and among adjacent microforms. If it can be determined from the results of question 1 that the response of the water table to storage changes is similar regardless of micro-form, then this relationship can be investigated at the 'plot scale' and at the microform scale within these plots. The spatial variability of the role of micro-topography in water table response will be analyzed here. **Furthermore, I will compare the magnitude of variability of the water table in hummocks and hollows.** It is expected that the spatial variability of the peatland surface (surface roughness) is significantly greater than the spatial variability of the water table.

Thirdly, I will determine how much of the variability in water table depth is explained by variations in the water table and surface elevations. To answer this question, the water table will be considered in absolute elevation above an arbitrary datum (mean sea level), not as depth below the surface since the latter has variations in surface elevation embedded. It is expected that the degree of variability in water table depth and water table elevation is related to the degree of spatial variability in surface micro-topography. In this way, a rougher peatland surface would indicate a more variable water table 'surface', regardless of whether the water table is considered as a depth below the surface or an elevation above an arbitrary datum.

2.6 – Research Objectives and Hypotheses:

The research goals will be obtained by attempting to attain three specific objectives and their related hypotheses:

1) **The depth of the water table at two representative 20 x 20 m plots at the Mer Bleue bog will be analyzed over a long time period**. Recording wells will be established at numerous points within these two plots to enable a comparison between water table records in different micro-forms. These will be analyzed to determine whether micro-topography plays a role in the response to storage change events. *I hypothesize that fluctuations in water table depths are the same across the peatland regardless of micro-topography.* Therefore:

a) The magnitude of rise in water table in response to rainfall inputs is independent of micro-topographical location.

b) The water table recession after events is independent of location; micro-topography does not produce variable recession activity, except when:

c) Initial water table depth is at or below the acrotelm/catotelm transition (in the layer where hydraulic properties of the peat change rapidly). In this case, the recession and rise will be different among hummocks and hollows. The conditions for this exception are after an extended period of time with little to no rainfall, when $\mathbf{\Sigma Et >>> \Sigma P}$.

2) **Within the two instrumented plots, the spatial variability of the water table depth will be recorded with manual groundwater wells, and comparisons will be made between water table depth and surface topography between the two plots and within each plot over time.** The spatial variability of the depth of the water table will be computed by establishing enough point measurements, and carrying out these point measurements several times throughout the season. *I hypothesize that there is a relationship between surface elevation, water table and water elevation over the range of micro-topography found at Mer Bleue.* Further I hypothesize that:

a) The spatial variability of the peatland surface is significantly greater than the spatial variability of the water table;

b) As a consequence of (a) the variability in water elevation is less than the variability in water table.

3) The surface elevation of points within both instrumentation plots will be recorded at a sufficient resolution as to classify the various micro-topographical landforms within both plots. Furthermore, the water table will be classified by its elevation above sea level, so as to define the role that surface elevation plays in the spatial variability of the water table.

This study will seek to define how much of the variability in water table depth is explained by variations in the water table elevation and variations in surface topography. *I hypothesize that the range (degree) of variability in water* *table and water elevation is related to the range (degree) of variability in surface roughness*. Therefore, if surface roughness is large then range of water table depth and elevation will be larger than when the surface roughness range is smaller, and vice-versa. It is expected that the variability of the water table elevation will be significantly less than the spatial variability of the surface of the peatland.

CHAPTER 3: SITE DESCRIPTION, MATERIALS & METHODS

3.1 – Site Description:

3.1.1 – Field Site – Bog Complex, Climate and Ecology:

At the Mer Bleue peatland, in the northwest sector of the conservation area, modelling and measurement activities have taken place for the past fifteen years, to determine the water, energy, and carbon gas fluxes and the general ecology and biogeochemistry (Lafleur *et al.*, 2003). The peatland area is located at 45° 23’ 00” to 45° 25’ 15” N and 75° 26’ 00” to 75° 33’ 30” W, with a total area of about 28 km^2 and is designated as part of the NCC’s Greenbelt (see Figure 3.1). The three distinct fingers of the Mer Bleue peatland drain towards the west into the Ottawa River valley. The research reported on in this study took place in the northeast ‘finger’. The general hydraulic gradient of the northeast finger of the bog is ~ 0.0008 (Fraser *et al.*, 2001b). It is ~ 4 km on the long axis and 3 km in width. It is slightly domed with the peak height located near the centre of the width. In the ombrotrophic bog sector of the research area, two sites, referred to as plots A and B, were selected in May 2010 for the installation of a series of manual dipwells and automatic capacitance water level recorders. Each plot contains 100 manual water table measurement pipes in a 20 x 20 m grid, and a series of automatic water table level recorders in transects across a sequence of micro-topographic relief. The observations reported in this thesis took place between June 9th 2010 and December 20th, 2010.

The ombrotrophic bog sector of Mer Bleue has a hummock-hollow micro-topographic pattern, with vegetation cover consisting of deciduous shrubs such as blueberry (*Vaccinium myrtilloides*) and ericaceous shrubs such as leatherleaf (*Chamaedaphne calyculata),* Labrador tea *(Rhododendron groenlandicum)* and sheep-laurel *(Kalmia augustifolia*). Sedges (*Carex* spp.) and cottongrass (*Eriophorum* spp.*)* are also present, with an underlying blanket of *Sphagnum* mosses. Trees occur in patches across the peatland. They are tamarack (*Larix laricina),* gray birch *(Betula populifolia)* and black spruce *(Picea mariana).* The climate is cool mid-continental with a growing season from May to September. The mean annual temperature is 5.8° Celsius and the mean annual precipitation is 910 mm (Roulet *et al.*, 2007). This study ran well beyond the end of the growing season and the mean temperature for the study period was 13.5° Celsius. The total precipitation during the study period was 539 mm.

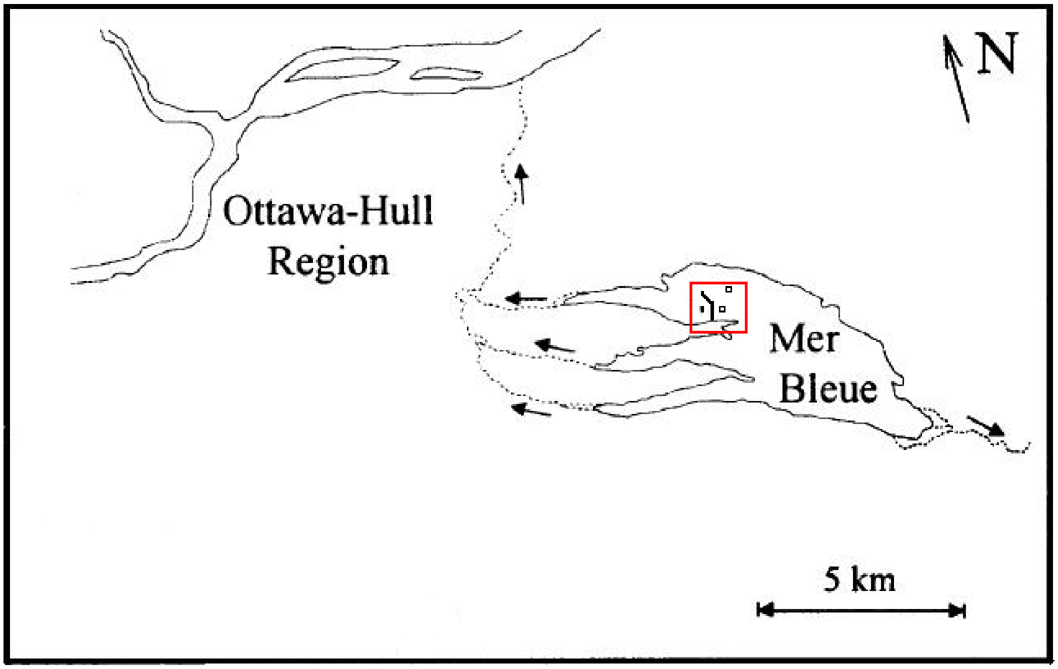


Figure 3.1: Mer Bleue bog and the Ottawa Region (adapted from Fraser *et al.*, 2001a). Study site outlined in red.

3.1.2 – Hydrology:

The three 'fingers' of Mer Bleue bog were once melt water channels that eroded into the marine clay, and are currently separated by ridges of sandy deposits. Discharge from the bog occurs at a number of points at the western edge of the drainage basin (Figure 3.1). Because of the dome morphology, Mer Bleue bog is ombrotrophic, meaning that all water, mineral and nutrient inputs come from precipitation and that groundwater seepage into the bog does not occur (Fraser *et al*, 2001a). Peat in the research area ranges from a depth of 1-2 metres at the fringes to greater than 5 metres near the centre. Water table levels have been measured at various locations around the bog since the establishment of the research site in 1998 (e.g. Fraser *et al.*, 2001b; Roulet *et al*., 2007). Beaver ponds can be found along the fringe on the southern edge of the bog. Over the past five years, water levels of the beaver ponds have been 0.50-0.75 m higher than in the conditions studied by Fraser *et al.* (2001) (Roulet, personal communication). This change may influence the water table on the bog but this has yet to be confirmed.

Sites for this study were selected in two different locations of at the Mer Bleue research area. Plot A is located near the tower access boardwalk and Plot B is located about 200 m to the northeast in the ‘Blue Dome’ sector of the bog (Figure 3.2). While plot A is located only about 200 metres away from the beaver ponds at the edge of the bog, plot B is located towards the peak of the peat ‘dome’. These sites were chosen to see if there was any influence on the water table and surface elevations due to distance from the margin of the bog. The specific location of the plots was decided to minimize the influence of previous research on the surface.

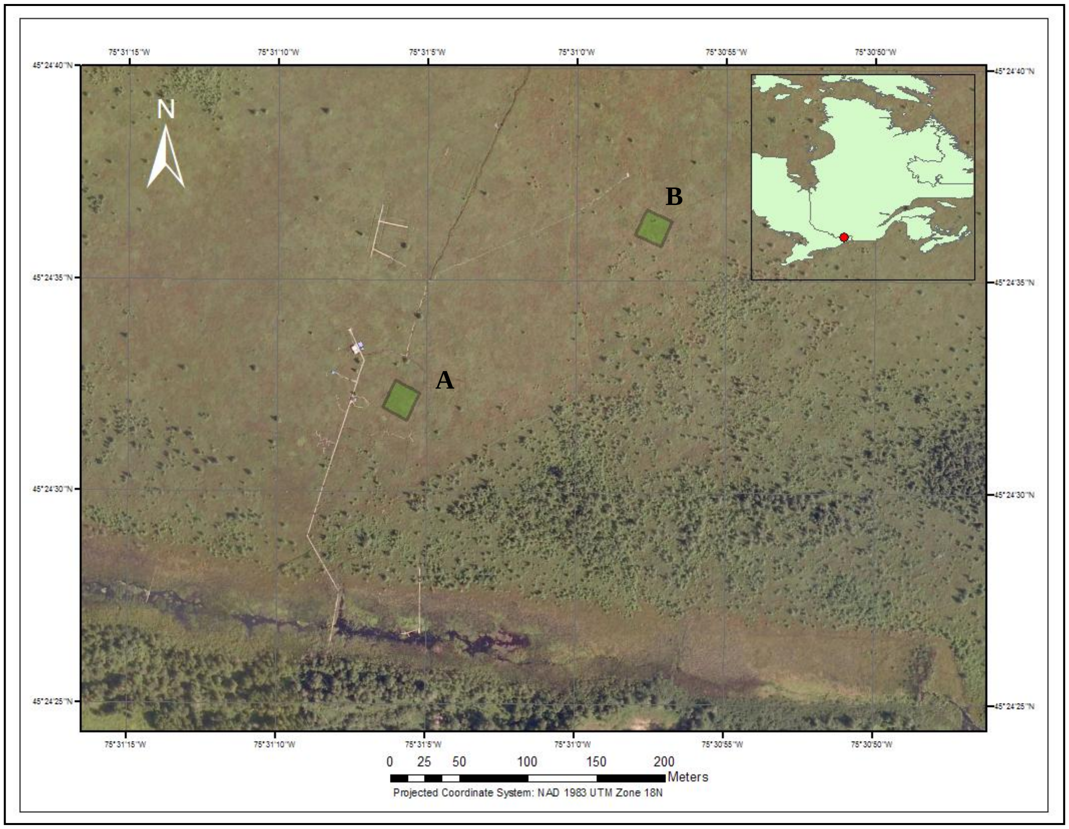


Figure 3.2: Satellite image of study site. Instrumentation plots in green. Image accessed through Bing maps layer via ESRI ArcGIS Software.

Mean water table depths in the A and B plots for the study season were -37 cm and -25 cm, respectively; with an annual range of approximately 30 cm (see Chapter 4 for complete results). The micro-topographic variation on the surface of the peatland allows for a representative amount of variation in water table depth within the relatively small plots (400 m^2). This study entailed a detailed survey of the surface elevation of each plot, periodic measurements of water table depths across each plot, and continuous measurements of water table depth in specific micro-topographic features in each plot. The description of the methods used to obtain these measurements and how the observations were analyzed is presented below.

3.2 – GPS Elevation Surveys:

3.2.1 – Data Collection and Rationale:

A Sokkia GRX-1 differential GPS Total Station was used to collect point elevations and locations (X-Y-Z coordinates) in each of the sampling plots and the surrounding area in early September 2010. The surface elevations of each groundwater well (manual and automatic) as well as their location were also measured. Elevations were referenced to a standard mean sea level and the X-Y-Z coordinates were recorded as Northing, Easting, and Elevations (Table 3.1).

Table 3.1: Coordinates of corners at instrumentation plots. Check N-E

Plot A	**UTM Coordinates**
NE	459439.3789 W; 5028523.5722 N
NW	459455.4123 W: 5028515.7175 N
SE	459431.2869 W; 5028506.9673 N
SW	459446.8579 W; 5028498.6722 N
Plot B	
NE	459620.8671 W; 5028647.4804 N
NW	459639.2801 W; 5028643.3226 N
SE	459615.4783 W; 5028630.5843 N
SW	459633.0875 W; 5028625.6048 N

For individual elevation measurements a 5 x 5 x 1.25 cm block of wood was placed on the surface of the moss and the tip of the surface rod that supported the mobile GPS unit was then placed in the centre of the block. This was done to minimize depressing the surface during a measurements and to ensure a constant method of obtaining the surface across all measurements. Once the rod was in place, it was levelled using a bubble level attached to the survey rod and then a surface elevation and location was obtained. The GPS unit automatically recorded the elevations and position coordinates and these were downloaded as a text file. The mobile unit was referenced to a total station which was positioned on fixed platforms near the plots. The fixed platforms were used to ensure the base station did not move during the survey. To ensure that the location of the base station was consistent throughout the several days of surveying, station locations were saved at the end of each day and the setup was either returned to the same location the following day or a new stable location was tied into the previous day's location and elevation. In this way, the same coordinates were used for the base station for all surveying days. The uncertainty in the surface elevations was estimated to range from a minimum of ± .003 m to a maximum of ± .01 m horizontally and ± .005 m to ± .015 m vertically, depending of the number of satellites that were visible to the unit at the time for each measurement. In total, more than 1400 points were recorded in each plot. Local benchmarks were established and metal rods were driven into the underlying marine clay so that data may be verified at a later date if the need arises. One of the difficulties of working on peatlands is the surface is easily compressed. This would cause errors in the surface elevation and repeated sampling over the study could also permanently alter the peat surface, so snow shoes were used in the plots at all times. The snow shoes had a surface area of ~ 1 m^2, over which the weight of the observer was distributed. This produced minimal if any instantaneous or permanent influence of the surface of the peatland.

3.3 – Manual Water Table Observations:

Each plot had 100 manual wells evenly spaced on a 2 x 2 m grid pattern. The manual wells were made of 1 m long, 1.25-inch inner diameter PVC tubing, and were inserted to a depth of 0.8 m at the beginning of May 2010. Holes were drilled the length of the wells to ensure no pressure effects. The wells were installed in a guide hole made in the peat surface with a length of re-bar. Duct tape sealed the bottom of the wells to prevent peat entering the tube as the wells were installed. 10-20cm of un-drilled PVC length extruded from the peat for each well.

On June 9th, all 200 water table depths were recorded for the first time using the blow-tube method. For each well the depth to water table from the top of the well was measured and then the height of the well above the peat surface was measured. The water table depth was surveyed 11 times over the 2010 field season. The final survey took place on November 15th, 2010. These water table surveys took place every 2-3 weeks throughout the season, with a total sampling period of 159 days. Although the de-commissioning of the automatic capacitance loggers occurred in late December, the manual wells were inaccessible due to snow and ice at that point in the winter.

3.4 – Continuous Water Table Observations:

The wells for the automatic water level recorders were installed in the same two plots as the manual wells. The water level sensors were capacitance

Odyssey sensors with a nominal precision of ± 0.8 mm. These water level sensors contain a wire of various lengths and a data-logger. Calibration was completed in the lab prior to installation, using two pre-determined points along each capacitance cord and a submergence bucket. Wires were held immobile using a clamp during calibration to ensure that voltage values were accurately recorded. Capacitance cords of various lengths had various degrees of change along the wire in terms of mV per mm, with values between 16 and 24 mV/mm. The water level can be recorded at a variable frequency programmed by the user, and about 32000 data points can be stored between downloads, though data was downloaded much more frequently than was required for data security reasons. The data was downloaded as a text file from each logger every 7 to 21 days.

Twenty one and sixteen wells were installed in plots A and B, respectively. 5 cm ID ABS pipe was used for these wells because the data logger fit nicely in the top. As with the PVC wells, the ABS wells were drilled with holes for 80 cm and sealed at one end with duct tape. The length of pipe extruding from the surface of the peatland varied according to the length of the capacitance cable of the logger in use for a particular well. Loggers were held in place suspended above the peat surface in the pipes using bolts. The capacitance cables for these recorders were 100 cm, 150 cm or 200 cm long, and the ABS wells were installed so that the loggers could record to a maximum depth of between 80 and 90 cm.

Wells were located in groups of 5-7 along hummock-hollow transects, with sites chosen as representative of the plot. Transects typically covered a distance of about 10-12 m for 5 to 7 wells. However, local maximums and minimums were selected along these transects, with the longest hummock-hollow sequence available used. Raw data was downloaded using Odyssey Data Logging Software 1.0.0.2 and converted to water table depths with Microsoft Excel, using calibration values. The ABS pipes were installed in June 2010 and the loggers began recording at a 60-minute interval on June 15th, while recording occurred every 15 minutes from June 22nd to the end of the season. The 2010 field season ran from mid-June to late December, and all automatic loggers were removed on December 20th, 2010.

Figures 3.3 and 3.4 show the location of manual (white triangles) and continuous (black circles) water table wells within Plot A and Plot B, respectively. Elevation contours are also visible in these diagrams. A common set of contour intervals was used for both of these plots, with a colour spectrum ranging from light green (69.3 m asl) to red (70.0 m asl). Contour intervals correspond to 0.05 m, with a total of 14 categories among the 70 cm range of elevations seen in the two plots. In both diagrams, North is located towards the top of the Figure. See Figure 3.2 for the location of these two plots within the research area at Mer Bleue. More detailed descriptions of the elevation distributions of the two instrumentation plots can be found in chapter 4 (section 4.3).

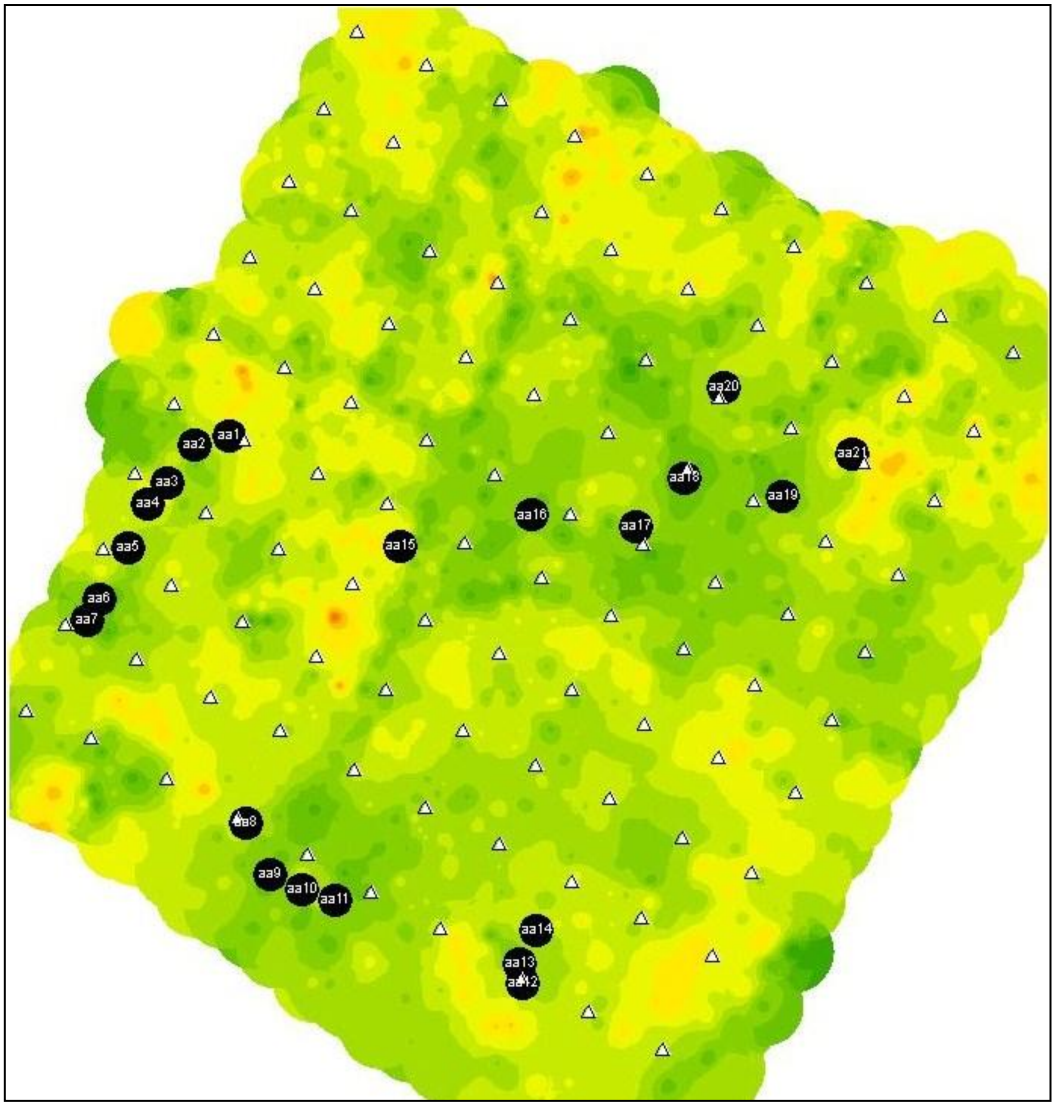


Figure 3.3: Plot A water table well configuration. Contour intervals are 0.05 m, total area of the plot is 20 m x 20 m.

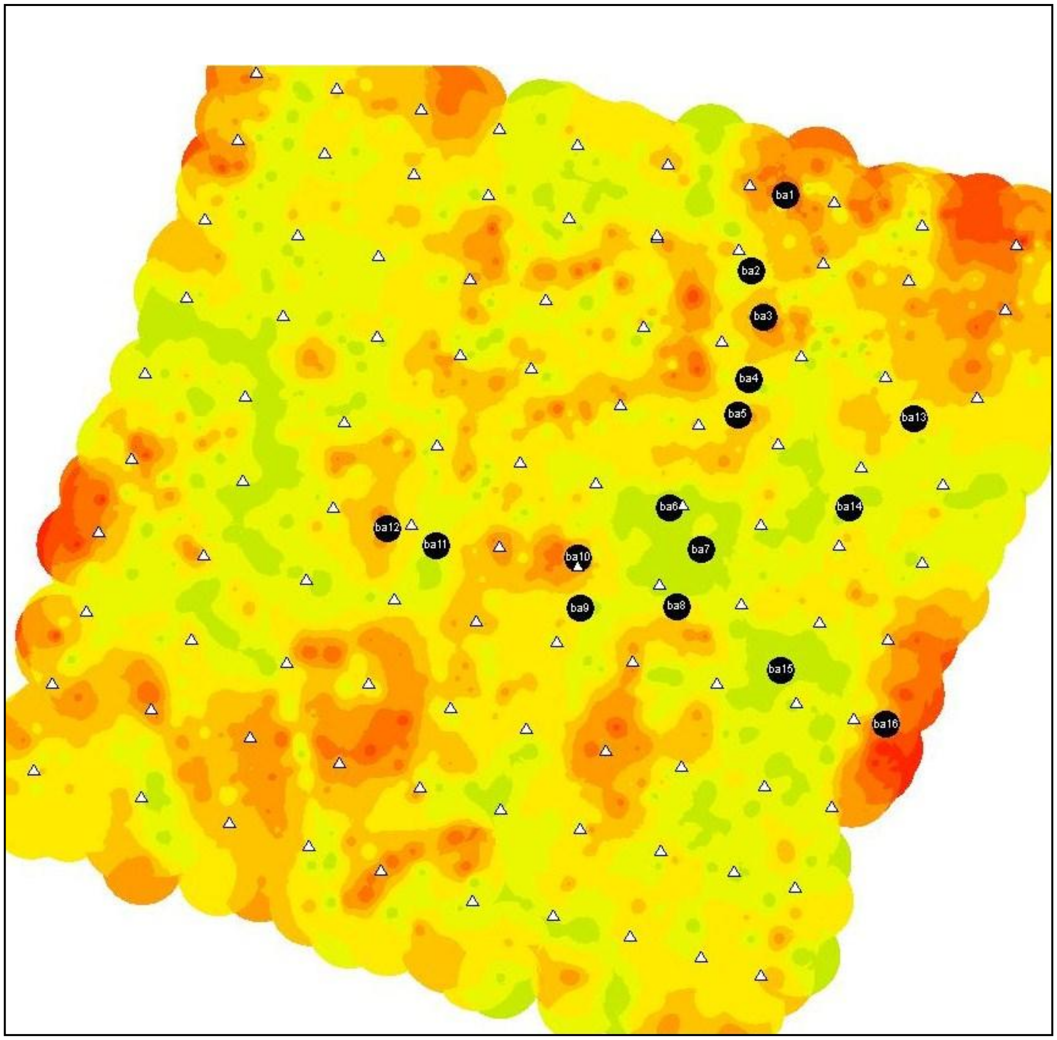


Figure 3.4: Plot B water table well configuration. Contour intervals are 0.05 m, total area of the plot is 20 m x 20 m.

3.5 - Data Processing and Analysis:

Many of the data sets associated with this study are made up of thousands of point measurements. Elevation data was recorded as X-Y-Z coordinates in a .txt format. During the recording of coordinate data in the field, names were given to each point to facilitate sorting and organization upon returning from the field. Survey points taken at well locations were given names corresponding to their type and name. For example, manual well #31 in plot A was named 'am31'. Survey points not corresponding to any groundwater well or other point of interest were simply named 'a' or 'b' to denote which plot in which they were measured. Using these names as categories, the raw .txt data was opened and saved as a comma-delimited Microsoft Excel file, with a separate sheet created for each group of data points. After this initial organization, each category of coordinates was opened in Sigmaplot 11.0 to display the statistical distributions. Box and whisker plots and histograms were created to look for obvious outliers caused by errors in recording. Histograms presented in Chapter 4 were created using approximately 50 groups for each plot, giving a total elevation range of approximately 50 cm for each plot.

Coordinates recorded during the GPS surveying were used to create spatial plots using a number of software applications, including Sigmaplot 11.0, ESRI ArcGIS 9.3.1 and ESRI ArcScene 9.3.1. The high spatial resolution of surveyed points allowed for the production of a very precise 3-D representation of the peat surface. Section 4.3 contains the outputs of this activity. In ArcScene and ArcGIS, extrapolation methods were used to create a smoothed surface from the ~1500 points recorded in each 20x20 m plot. A simple spline algorithm was used with vertical exaggerations of between 5:1 and 10:1 to produce plots that adequately display the heterogeneity of surface topography in the instrumentation plots. Finally, to denote elevation variations, contour intervals were added to the displays.

In addition to these Figures, cross-section diagrams were created in Sigmaplot 11.0, for each individual row of 10 wells in both plots. The distances between adjacent wells along rows of 10 were calculated for all 10 in each plot, both in the East-West Direction and the North-South direction. Although wells were meant to be spaced exactly 2 m apart, the Pythagorean Theorem was used to calculate the exact distance between wells, using GPS coordinate data. With recorded peat elevations and water elevations and the utilization of a spline gap-filling technique, these ‘row distances’ were used to create diagrams that roughly represent the cross-section of the peat surface and water table surface along each row of wells. Examples of these results can be seen in Figures 4.14 and 4.15. Peat surface and hydraulic ‘surface’ gradients were also calculated for all adjacent wells, to determine whether the water table ‘surface’ is as locally variable as the peat surface. These calculations were performed in Microsoft Excel using coordinate data and mean annual water table data. Gradients were calculated as m/m ratios of steepness. These results are presented in Tables 4.3 and 4.4.

Manual water table measurements were taken a total of 11 times in 2010, between June 9th and November 15th. Water table depths were calculated by subtracting the height of the well above the peat surface from the depth of the water table measured with the blow-tube. Point measurements were entered into a Microsoft Excel spreadsheet and organized according to the day of the year on which they were taken. Distributions were then opened using Sigmaplot 11.0 and box & whisker plots were visually scanned to ensure that all values entered into the spreadsheet fell within the acceptable range of water table depths historically seen at the Mer Bleue bog. Spreadsheet values were also double-checked against data written on the sheets in the field. No obvious mistakes in data entry were encountered during these processes.

Since accurate elevations were recorded for each water table well, water elevations were calculated by adding each well location's height above mean sea level. The process of organizing and processing these water elevation values was the same as with the manual water table depths. The precision of water elevations was restricted by the precision of the manually measured water table depths, which were measured to the nearest 1 mm. Although elevation data was measured by the total station to the nearest 0.1 mm, water elevation data could only have a precision of 1 mm. However, with an average annual range of about 30 cm, this precision value represents just .033% of this range. Each water elevation data point was calculated using a water table depth measured in the field, meaning that the two datasets were identical in terms of the size of each sample and the timing of each sample day. As a result of this, distributions of water elevations were also opened in Sigmaplot 11.0 and box & whisker plots were created. Side-by-side comparisons of distributions of water table depth values and water elevation values were done using box & whisker plots, and the results of these comparisons can be found in the following chapter.

For the automatic recording groundwater wells, a field laptop running Odyssey Data Logging Software 1.0.0.2 was used to communicate with the loggers in the field and download raw data values. The raw data was downloaded as a .PRN file, which was subsequently opened in Microsoft Excel as a comma-delimited spreadsheet. Equations calculated using the bucket calibration were used to convert raw mV data points into their corresponding water table depths, and these data points were then organized by date. Raw data included a time stamp for each individual point recorded by the loggers, and these points were used to create a consistent time decimal value for each data point. Julian day numbers were used, with each data point corresponding to 1/96 of a day (15 minutes). In this way, a time reference accurate to the nearest 15-minute interval was given to each water table depth so direct comparisons between well records at specific points could be made. Spreadsheets of water table values were then visually skimmed to look for error points and severe outliers. False points were often recorded by the loggers immediately after re-starting, so that each point in the time record at which the loggers were stopped for downloading could contain up to 3 invalid points. However, these false points were often clustered together immediately after the re-starting point, and within 15 minutes of the re-starting point the loggers had returned to normal. Therefore, very few points that were actually needed for the water table records had to be discarded.

After records were visually skimmed for false points in Microsoft Excel, data points for each well record were plotted in Sigmaplot 11.0 as a time series record. To ensure that no false points had been missed in the visual skimming, these time series graphs were visually scanned, with clear error points often becoming apparent during this phase. Each complete well record consisted of water table depths recorded every 15 minutes for a period of 188 days, with a total of over 17400 points. The size of these datasets meant that scanning for outliers often had to be performed several times before all false points had been removed from the record. The best method for spotting false points was the visual analysis of Sigmaplot time series graphs, as error points would often appear as vertical spikes deviating from the otherwise moderate record. Continuous water table depths were converted into water elevations in the same way that manual water table depths were converted into water elevations; simply by adding the surface elevation of each well to the data points taken at that location.

3.6 – Short-term Water Table Responses:

Continuous water table measurements were recorded frequently enough to allow for analysis of short-term responses (± 15 minutes) to precipitation inputs and extended warm, dry periods. For the responses to precipitation events, the overall rate of rise of the water table of each well was calculated by dividing the change in water table by the time period of interest. As can be seen in Figure 3.5, the time period of interest for each well began with the start of the rainfall event and ended when the local peak water table was reached for the majority of the wells in the plot. To allow for direct comparisons between well responses, a common time interval was used for all wells for each period of calculation.

Water table recession coefficients (see Section 2.5) were calculated for different time intervals throughout the 188-day period during which the automatic loggers were recording. Initial water tables corresponded to the point at which the water table began to drop, and the final water table points corresponded to the point at which the recession stopped. Although some wells experienced slightly different periods of rise and recession, the same time intervals were used for all wells. See Table 4.3 for precise time intervals and water tables used for the coefficient calculations.

For each period of water table rise, 5 points of interest were chosen for each well record. The specific time points at which each record reached 10% and 90% of its total rise were found for each well, to represent the moment at which water table rise began and was almost complete, respectively. Also, the points at which each well record reached 25%, 50% and 75% of its rise were found in the complete records. These three additional points of interest, corresponding to the quartile marks of each well record, allow for a consistent comparison of the speed of each individual well's water table rise. The results of this investigation are presented in Section 4.6.

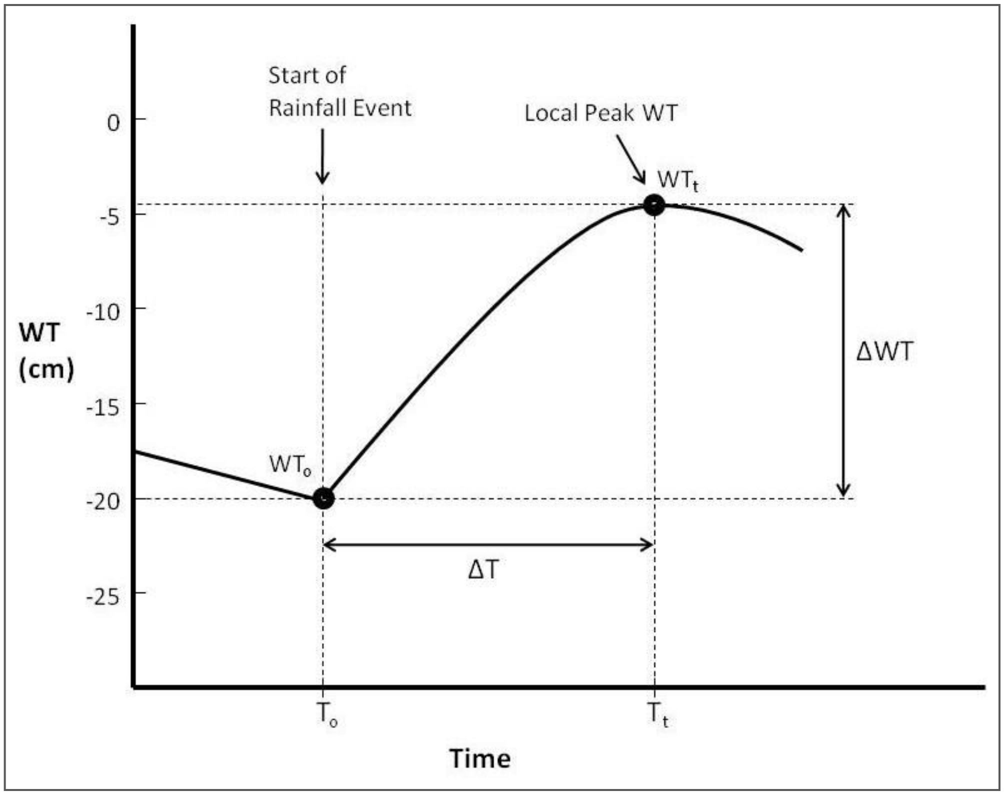


Figure 3.5: Points of interest used for calculation of water table rise.

CHAPTER 4: RESULTS

4.1 - Climate at Mer Bleue:

Multiple meteorological and climatic instruments were installed at the Mer Bleue site in 1998 and data collection has been continuous since then. These long term records can be compared to the environmental conditions of 2010 to establish where the study year fits in. Furthermore, climate normal data from 1971 to 2000 is available from Environment Canada and this data provides a useful baseline for comparison for 2010. In this section the precipitation, temperature and water table conditions recorded in 2010 will be compared to the long term record from Mer Bleue and the climate norms calculated for nearby MacDonald Cartier Airport.

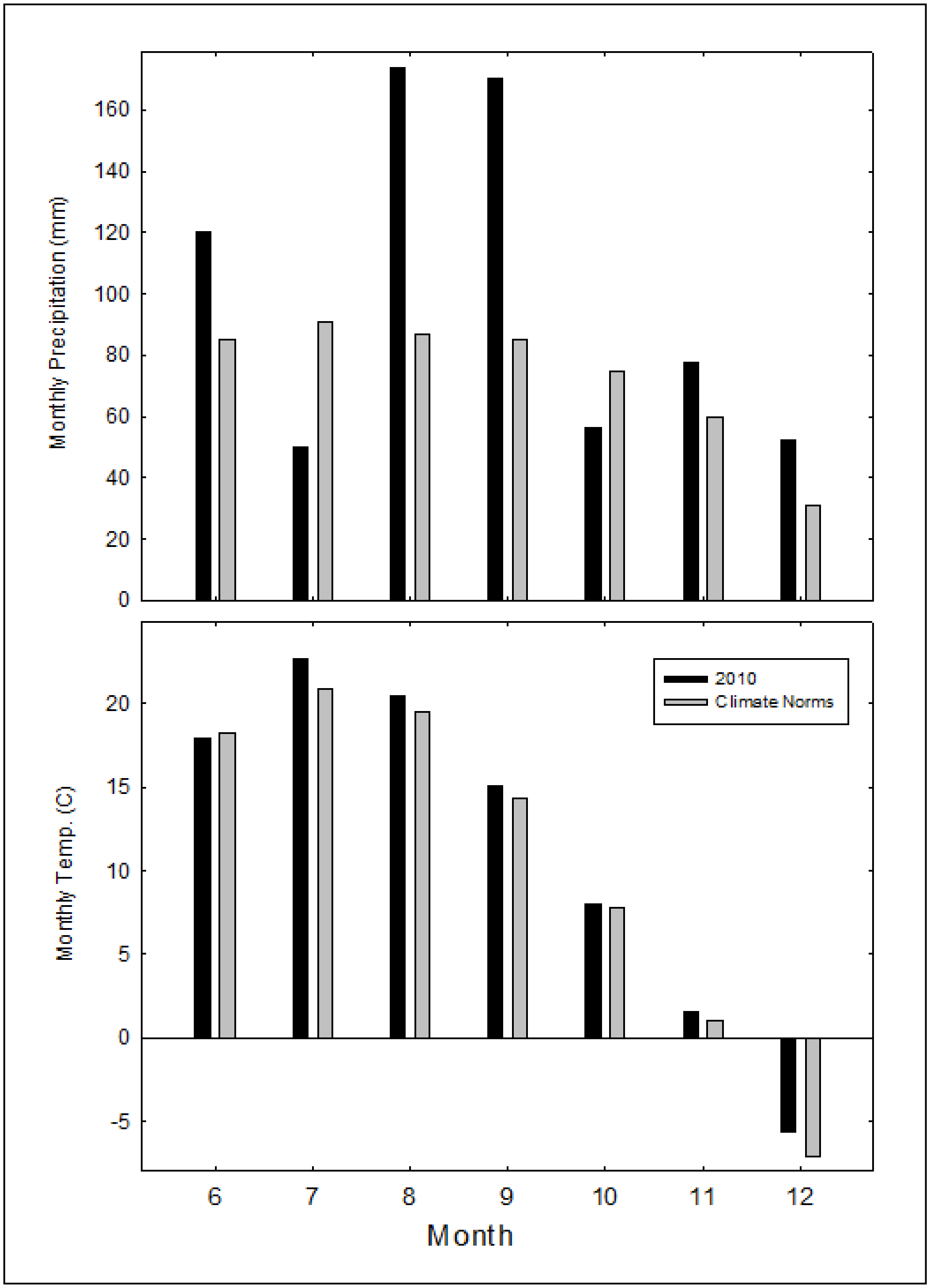


Figure 4.1: The 2010 monthly rainfall and mean monthly temperature (June – December) for 2010 and the respective 30 year monthly norms for the MacDonald Cartier Airport, Ottawa.

The six months of study for 2010 were in general much wetter and slightly warmer than normal. June, August and September of 2010 were especially wet months, and September 2010 was one of the wettest months on record for Ottawa, with 173 mm of rainfall - only 3 mm short of the record set in 1945. Figure 4.2 shows the daily rainfall measured at Mer Bleue for the study period. There were three periods, indicated in red, when there was little rainfall. There were also several heavy rainfall events, indicated in blue. These periods of no rain and rain events were selected for analyses of water table rise and drawdown (see Section 4.6). Mean daily temperature, and hummock and hollow water table from the continuous water level sensors from the two study plots is also displayed.

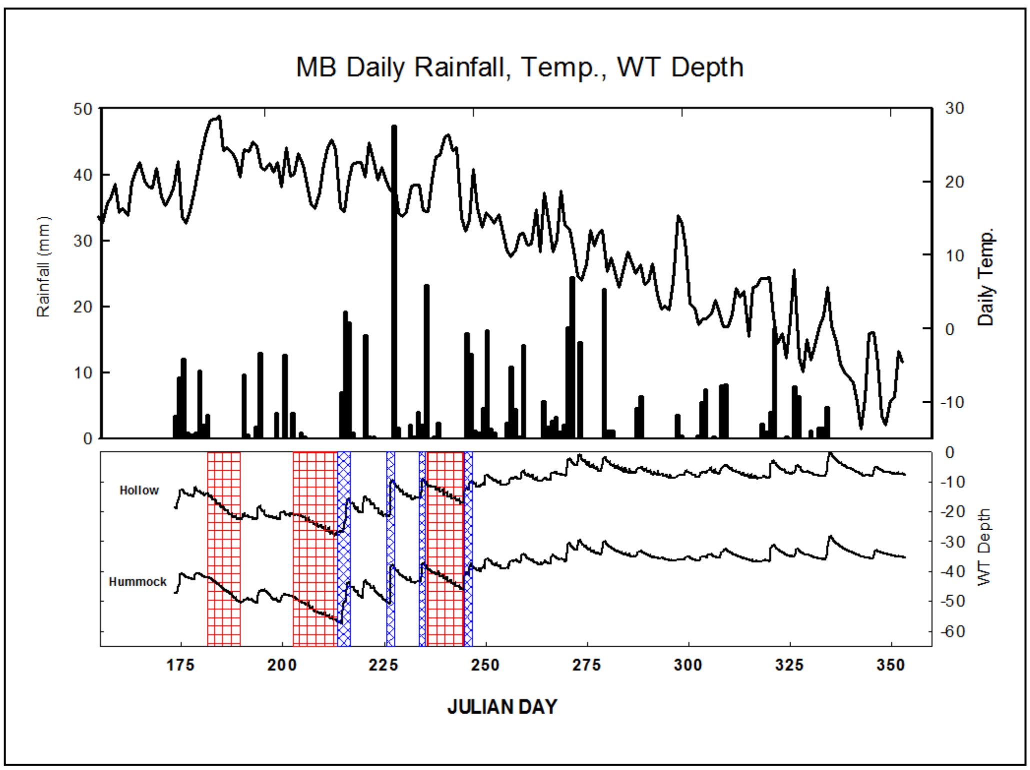


Figure 4.2: Daily Rainfall recorded at Mer Bleue, Hummock and Hollow WT, Daily Temperature.

4.2 – Water Table Depth at the Mer Bleue Tower:

The principal hydrological variable measured during this study was water table depth. Water table has been measured at a single point (hummock microform) near the micro-meteorological tower at Mer Bleue since 1998 and this record can be compared to that of the same site for the 2010 study year (Figure 4.3). Also shown in Figure 4.3 is the mean daily water table depth of all 13 yearly records. The period shown with these lines coincides with the duration of data collection for this study, from mid June (day 160) to late December (day 360).

Figure 4.3: The water table for the years 1998 to 2009 measured at the main site of Mer Bleue (in grey). The water table record at the same site in 2010 (solid black line) and the mean water table for 1998-2010 (dashed black line) for the same location are also shown.

Although the 2010 well record does not follow any particular year's pattern, for the most part it lies within the range of water table depths seen at different points of the year throughout the 13 year recording period, despite the precipitation being not typical. The water table values observed in late July 2010 were the deepest for that period of the 13 year span, while the water tables from mid-September on were some of the shallowest. Cumulative water table frequencies for each year from 1999 to 2010 can be seen in Figure 4.4.

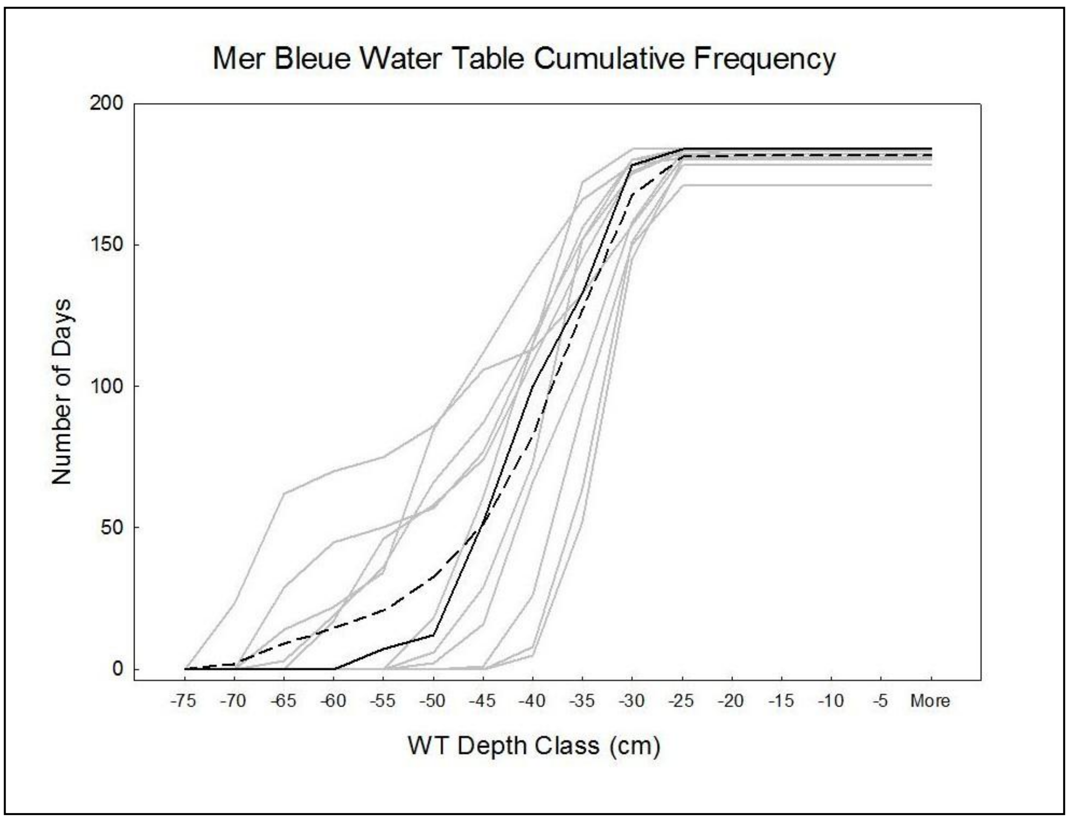


Figure 4.4: Annual cumulative frequency of water table depths, 1999-2010. (Unpublished data provided by N. Roulet, 2011). As in Figure 4.3, all water level records are in gray, the 2010 record is in black, and the mean of all years is indicated by a dashed black line.

The presence of the 2010 line (black) in the middle of the distribution further indicates that 2010 water table depths lied within the range seen during the course of recording at the Mer Bleue tower. The 2010 record differs from the mean cumulative frequency record in that there is a relatively low frequency of the deepest water table depths seen during the period from 1999-2010 (below -50cm).

4.3 - Elevation Survey Data:

To establish the range in elevations and spatial variability of the hummock-hollow micro-topography observed at Mer Bleue, elevation surveys were undertaken on the two plots in early September 2010. A critical assumption in using a single survey to estimate surface topography is that the surface of the Mer Bleue peatland does not vary significantly with time. Because of the reports in the literature (Roulet *et al.*, 1991; Kellner and Halldin, 2002; Waddington *et al.*, 2010) of variations in peat surfaces due to changes in water and gas storage, continuous measurements of surface elevation relative to an arbitrary datum were initiated in 2007 and have continued since. These measurements show that the maximum change over the snow-free period (~240 days/yr) for the four years is < 4.4 cm in a hollow (3.2 cm in a hummock) and that the largest standard deviation around the mean seasonal elevation for four years was < ± 1.5 cm, again in a hollow (0.73 cm in a hummock) (Roulet, unpublished data, 2011). The statistics on continuous measurements of surface elevation change for the 2010 season are presented in Table 4.1. The maximum potential error in calculation of surface water elevations in the 2010 year is ~ 3.1 cm but based on the very low standard error, > 66% of the water elevation data would have an error due to the assumption of a fixed surface elevation, of < ±0.04 cm (i.e. ±0.4 mm).

Table 4.1: Statistical analysis of peat surface elevation from the continuous measurements in 2010. All values are daily surface elevations in cm. The mean surface elevation is relative to the initial surface elevation on the first date of measurements (unpublished data kindly provided by N. Roulet and M. Dalva, McGill University, 2011).

Statistic	***Hummock***	***Hollow***
Mean	-0.27	-0.63
Standard Error	0.02	0.04
Median	-0.25	-0.65
Standard Deviation	0.35	0.57
Range	3.14	2.10
Minimum	-1.63	-1.61
Maximum	1.51	0.49
Days of observation	240	240

Over 1500 measurements of elevation were collected in both plots in the September 2010 surveys. This data was used to determine the spatial variability of the surface of the peat, and to create plots and images to illustrate the variability (Figures 4.5 and 4.6).

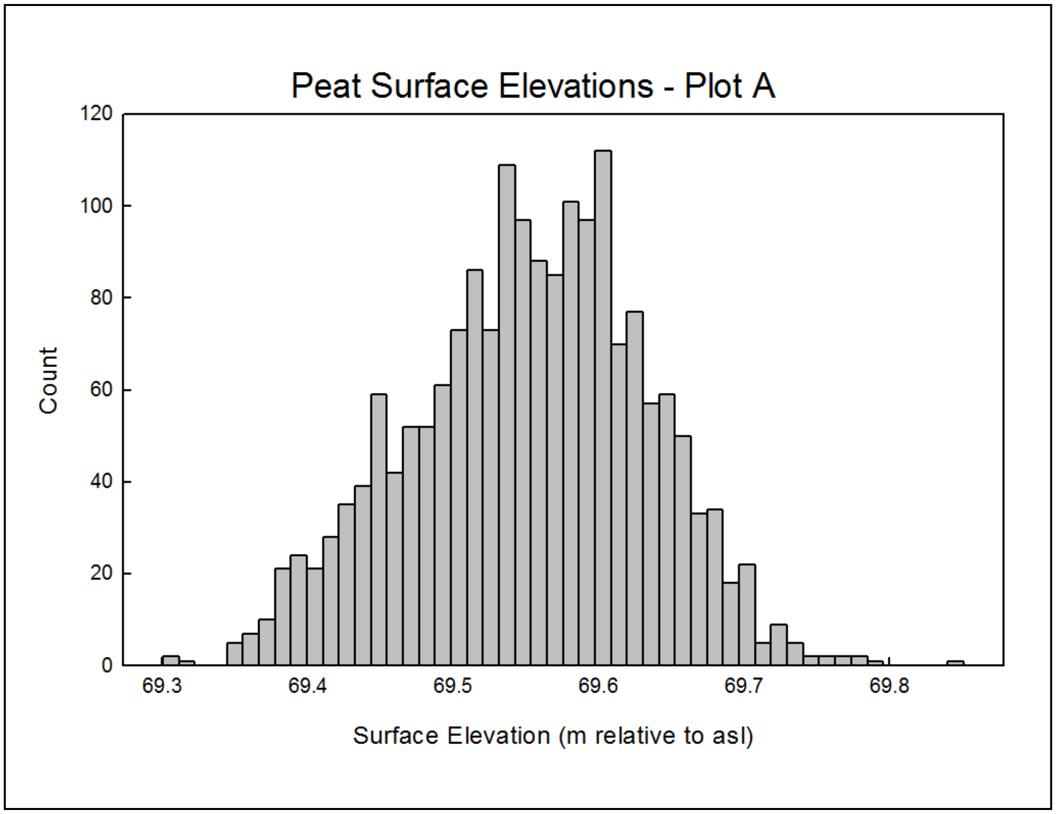


Figure 4.5: Distribution of Elevation points taken in Plot A, September 2010. The mean elevation is 69.552 ± 0.002 m and the sample size was 1806. A class size of 0.01 was used resulting in 55 classes and a total range of 0.5 m.

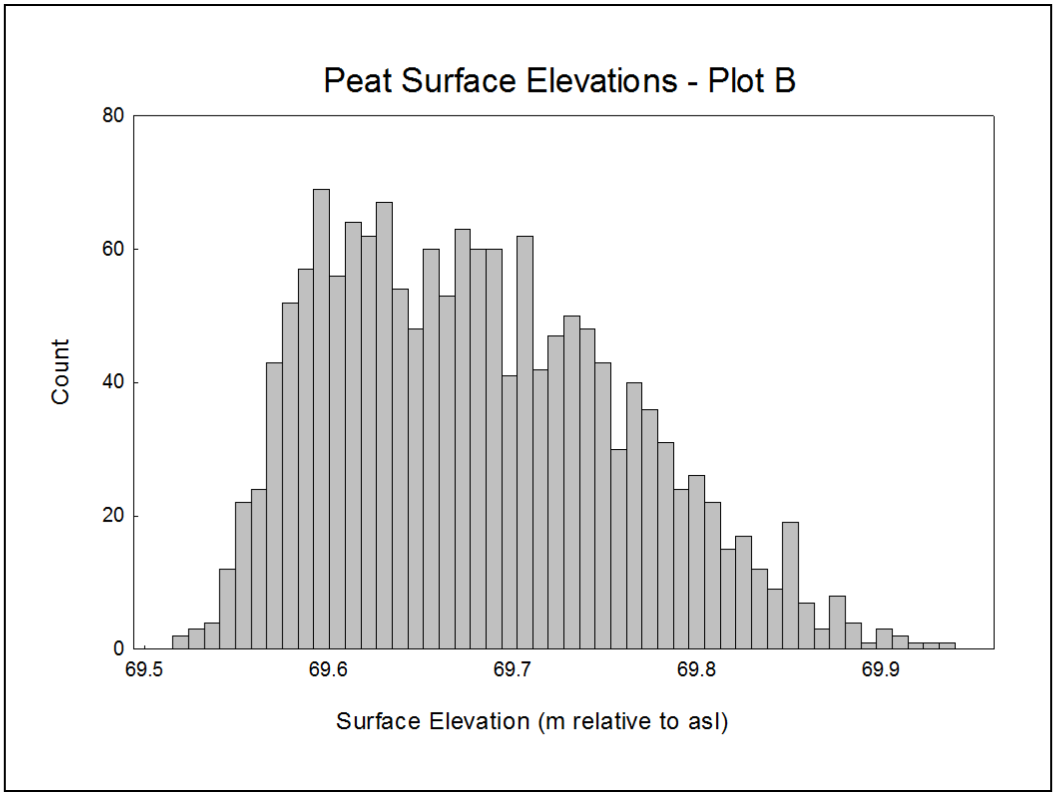


Figure 4.6: Distribution of Elevation points taken in Plot B, September 2010. The mean elevation is 69.681 ± 0.002 m and the sample size is 1568. A class size of 0.01 was used resulting in 55 classes and a total range of 0.5 m.

The mean elevation of plot B is higher than that of Plot A, because it is higher up on the gradient of the peat dome (see Table 4.2). The elevations in plot B are not as normally distributed (Figure 4.6), and lower elevations seem to dominate the distribution, compared to that of plot A (Figure 4.5). There are many low-lying, flat sections that could be designated as peat lawns present in plot B and this gives the left shift to the distribution. The data in Table 4.2 show the distribution of the surface elevations in the two plots.

Table 4.2: Statistical Parameters of Plots A & B, Sept. 2010. Metres relative to sea level.

Statistic	***Plot A***	***Plot B***
Mean	69.552	69.681
Standard Error	0.002	0.002
Median	69.556	69.673
Standard Deviation	0.088	0.080
Range	0.551	0.425
Minimum	69.300	69.515
Maximum	69.851	69.940

A second elevation survey was conducted in July 2011, to establish whether there is a significant difference in the statistical character of surface elevations in the peatland from one year to the next. As can be seen when data from Tables 4.2 and 4.3 are compared, there is a strong similarity in the statistical characteristics of the two sets of elevation survey data. A similar number of data points were collected in both plots in both years.

Table 4.3: Statistical Parameters of Plots A & B, July 2011. Metres relative to sea level.

Statistic	**Plot A**	**Plot B**
Mean	69.536	69.669
Standard Error	0.002	0.002
Median	69.538	69.65
Standard Deviation	0.0825	0.0722
Range	0.651	0.384
Minimum	69.186	69.522
Maximum	69.837	69.906

Geographic information software (GIS – see Section 3.5) allows the elevation data to be displayed in a 3-D envrironment (Figures 4.7 and 4.8). Since there are many ways this data can be represented and the visual effect is a function of the vertical exaggeration, two different representations are shown for the diffferent plots. For both of the figures below, the total plot area (20 x 20 m) is shown, and North is towards the top of both diagrams. These two diagrams show an oblique view of the data first shown in Figures 3.3 and 3.4.

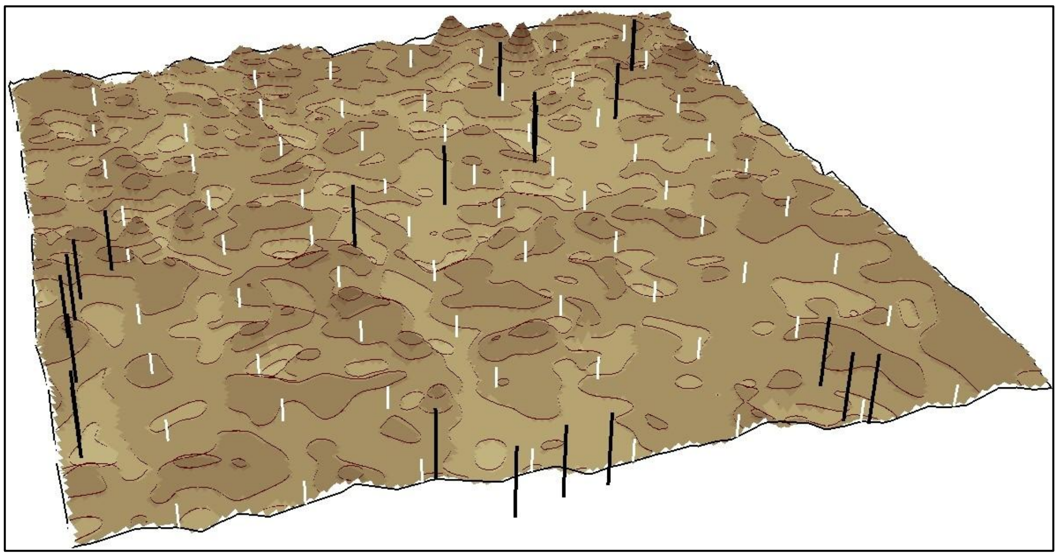


Figure 4.7: GIS contour map of surface elevations in plot A. The contour interval is 0.1m, plot area is 20m x 20m and the vertical exaggeration is ~5:1. The locations of water table wells are shown in this image, with automatic recording wells in black and manual dipwells in white.

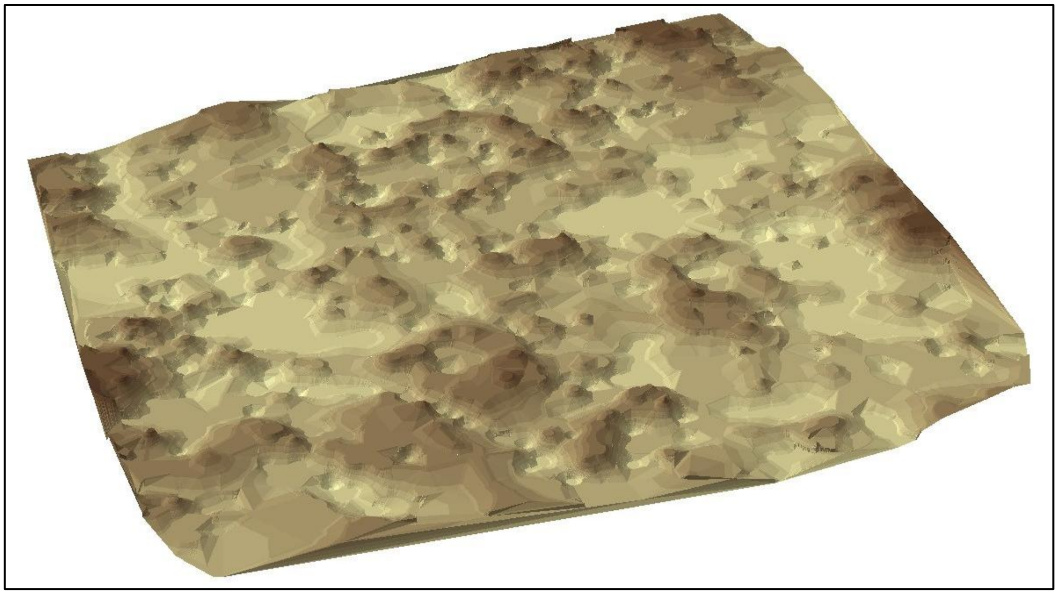


Figure 4.8: GIS contour map of surface elevations in plot B. Contour interval is 0.1m, plot area is 20m x 20m and the vertical exaggeration is ~3:1.

4.4 – Manual Well Records – Water Table Depths and Elevations:

Over the course of the 2010 field season, the 100 manual water table wells in each plot were sampled every 2-3 weeks. The water table depth is measured as a depth below the peat surface and the water elevation was computed from the water table depth and the measured surface elevation relative to mean sea level. While the mean water table varies by ~ 0.15 m over the measurement period in plots A and B the variation in water table within each plot at a given date (~ 0.35 to 0.40 m) is much greater (Figures 4.9 and 4.10). The statistical character of the distribution of water tables is quite consistent from date-to-date. The seasonal pattern of water table fluctuations is driven by the balance of precipitation and evaporation. The deepest water tables occurred during the hot dry period in late July, and shallower water tables occurred during the wetter months of September and October. Further analysis of the seasonal patterns of water table depths is presented in Sections 4.5 and 4.6.

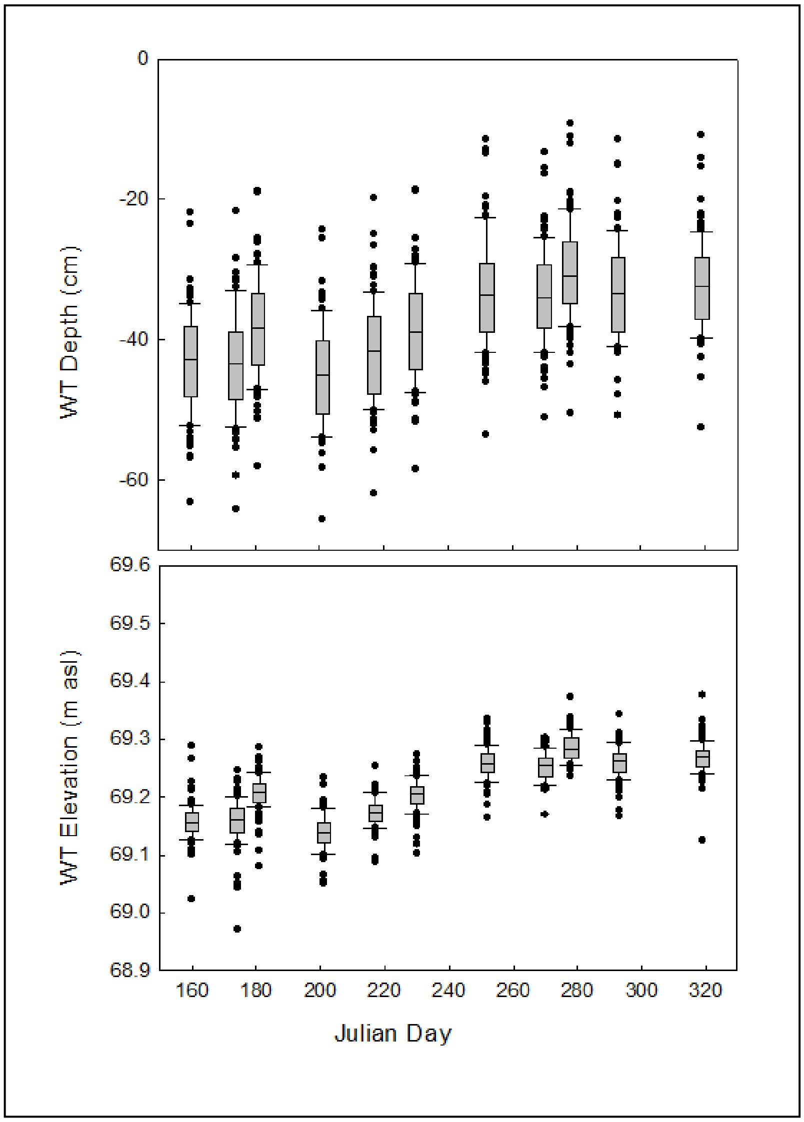


Figure 4.9: Boxes of 100 water table depths and water elevations in Plot A for the measurement period. For Figures 4.8 and 4.9 the upper and lower quartiles are top and bottom of the boxes, respectively; the line in the box is the 50th percentile or median; the upper and lower 'whiskers' of the boxes represent the location of the 90th and 10th percentiles; and the data beyond the 90th and 10th percentiles is represented by the dots above and below each box.

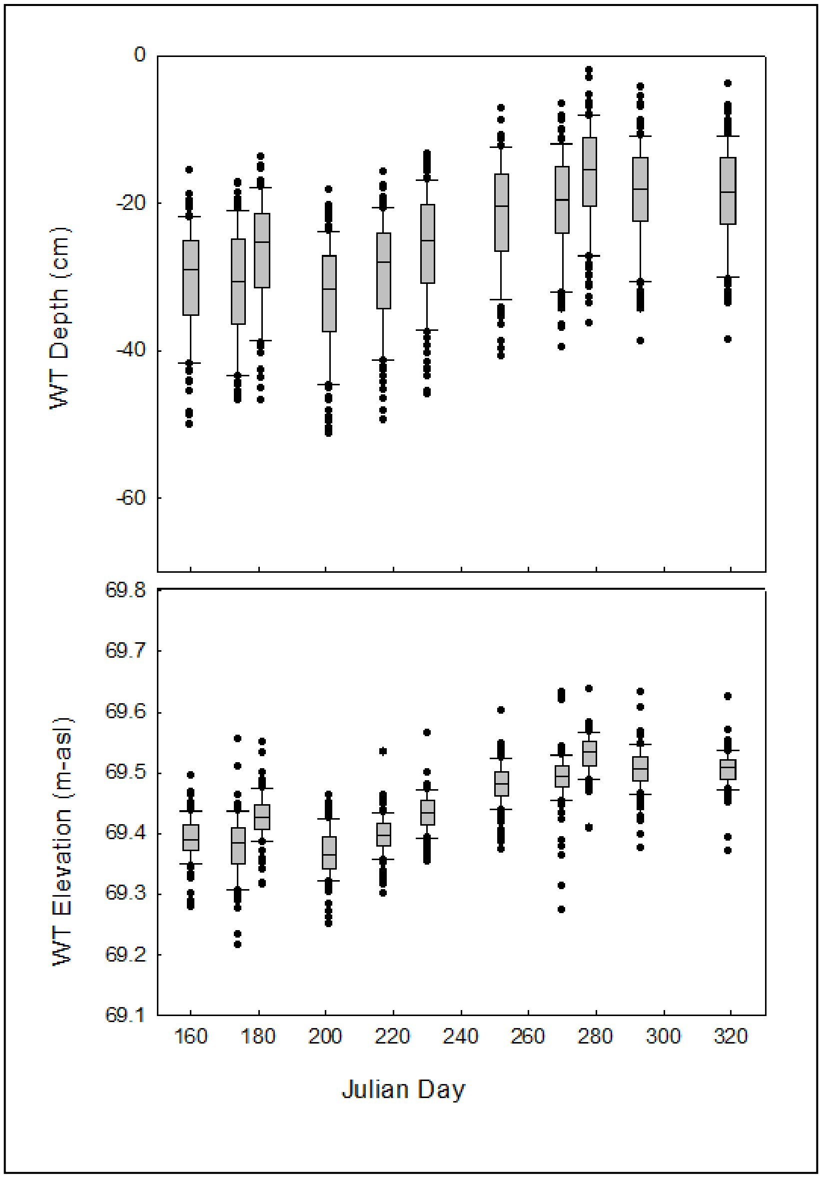


Figure 4.10: Box & Whisker of 100 water table depths and water elevations in Plot B for the measurement period.

There is considerably less range in the water elevation compared to the variations in water table depth. Over the study period the mean water elevation varied ~ 0.14 m in plot A and ~ 0.10 m in plot B. Like the pattern for variation in the water table, the variance in water elevations across a given plot is greater at any one time than the seasonal variation in the mean. The range in water elevation across the plots varies between ~ 0.17 and ~ 0.26 m in plot A and ~0.21 and ~ 0.34 m in plot B. On average, range of water elevations is ~ 63% of the range in water table depths for a given set of 100 point measurements taken on a given day. A greater range in water elevations occurs on dates when the mean water elevation is less –i.e. when the corresponding mean water table is lower or deeper in the peat. Also, the range in water elevations is greater in plot B than plot A on a given date, which is opposite to that of the water table.

The relationship between micro-topography and water elevation can be visualized in a 3-D representation in a manner similar to that of the surface evalations (Figures 4.11 through 4.13). In these diagrams the water elevations are laid under on the scale vertical scale as the surface topography and the 3-D representation of the surface topography is made semi-transparent to allow the reader to 'see' the corresponding pattern of water elevation. The shape of the surface of the water elevations does vary over the season but the pattern is a subdued version of the highly variable peat surface above.

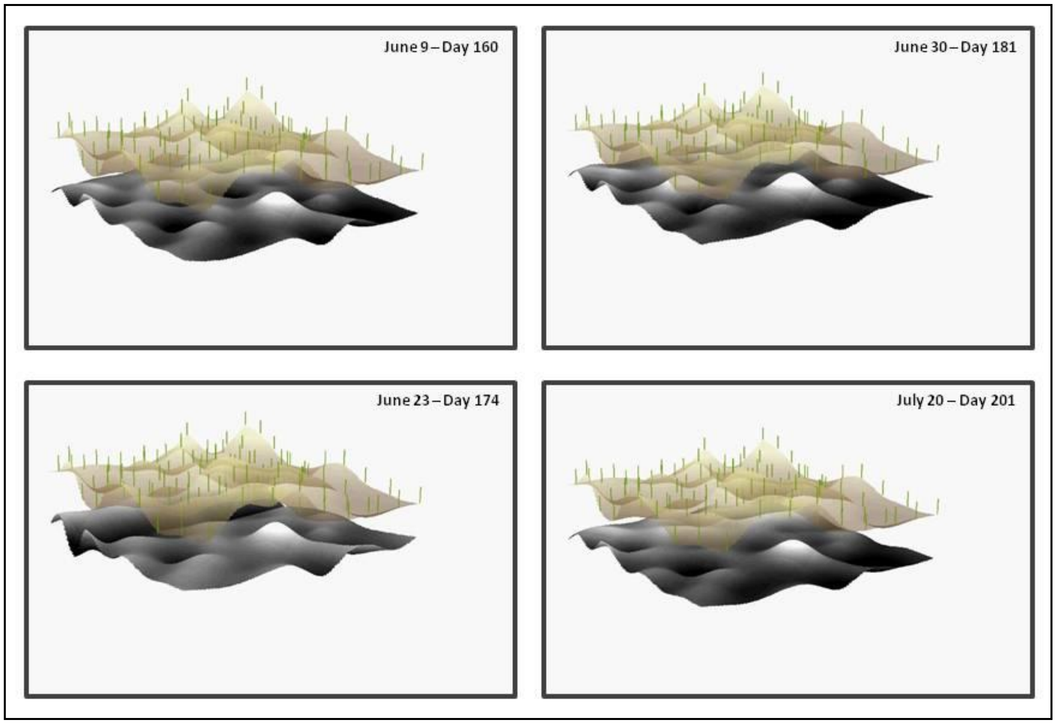


Figure 4.11: Shape of WT 'surface' and peat surface, first 4 Surveys, Plot A. The vertical exaggeration is ~ 10:1.

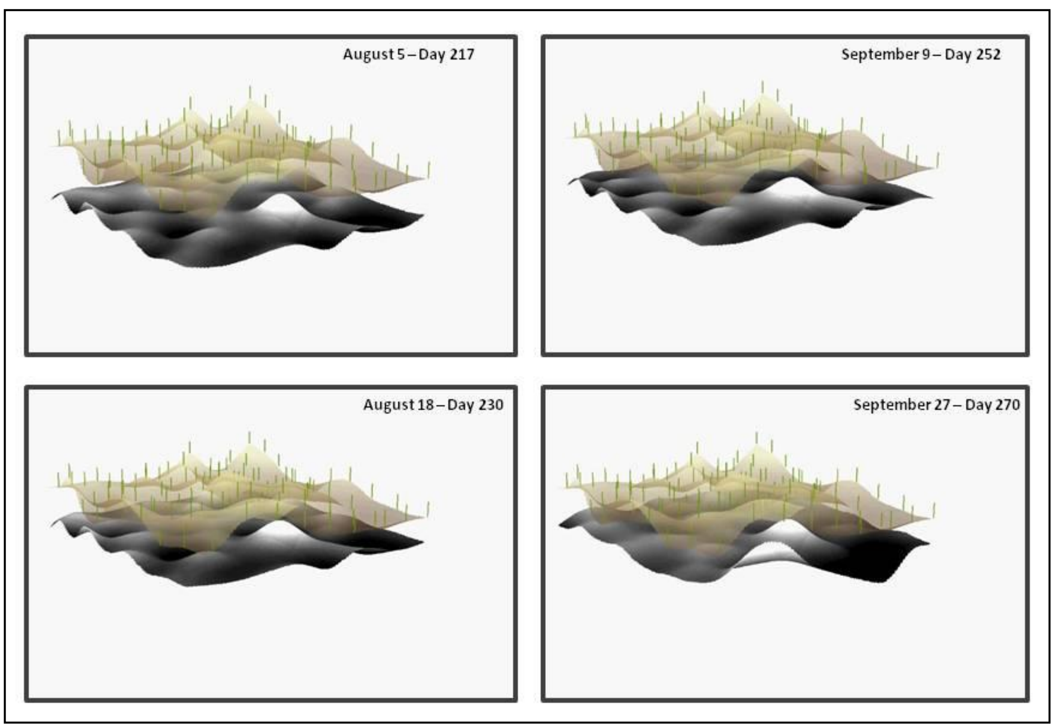


Figure 4.12: Shape of WT 'surface' and peat surface, Plot A. The vertical exaggeration is ~10:1.

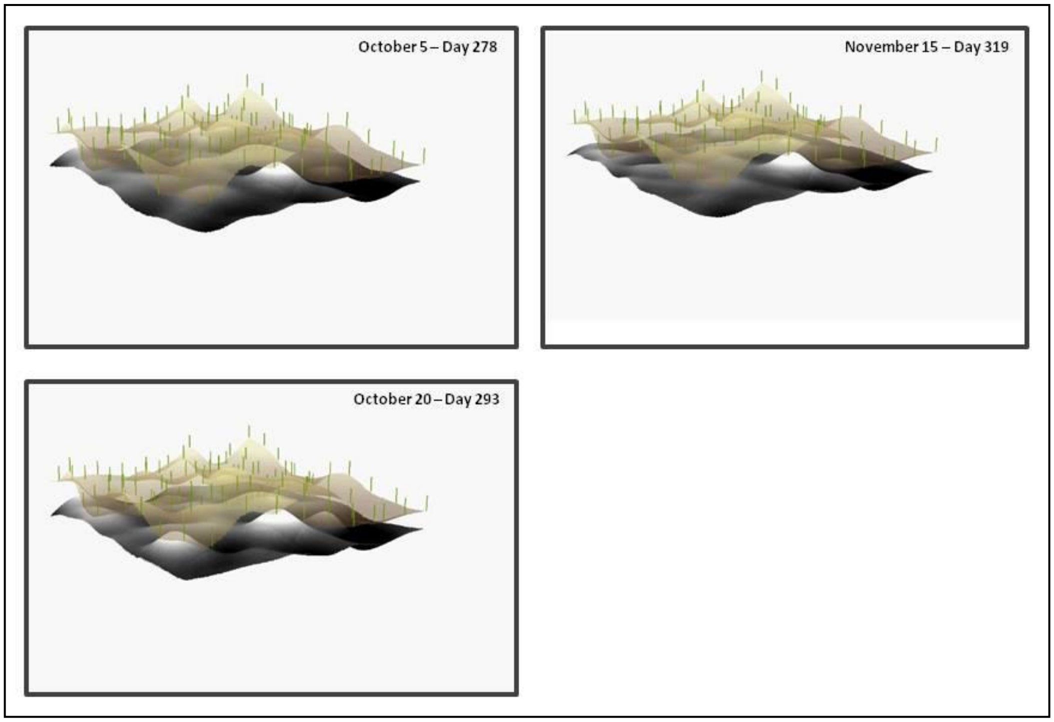


Figure 4.13: Shape of WT 'surface' and peat surface, Plot A. The vertical exaggeration is ~10:1.

To further illustrate the relationship between variation in topography and water elevation a cross-section through plot A and B was generated using a smoothing function in Sigmaplot 11.0 (Figures 4.14 and 4.15). The smoothing was done to "fill" the surface and water elevations across the 3-D plots. Horizontal distances between wells (x-axis) were calculated using the GPS coordinates recorded during surveying. For each plot, one row of 10 wells is shown in each dimension; running roughly East-West and North-South, due to the orientation of the plots (see Figure 3.2). The Pythagorean Theorem was used to calculate the exact distance between surveyed wells based on GPS coordinate location. Elevations were then plotted using a simple spline extrapolation that simulates a gradual variation of surface elevation between wells located on various micro-topographic forms. The upper line on each figure corresponds to the elevation of the peat surface at the 10 wells within each row. The lower lines represent the average elevation of the water table over the course of the sampling period. The water table elevation and surface elevations across the rows of wells follow a similar pattern.

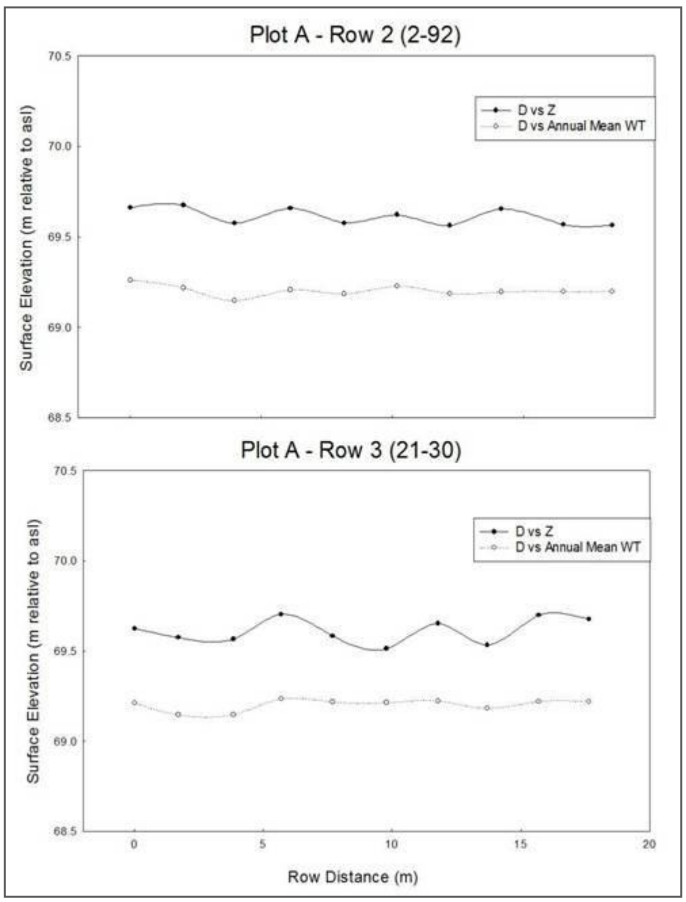


Figure 4.14: Cross Sections of Plot A, constructed using elevation data. Extrapolated data from East-West Row (a) and North-South Row (b) shown.

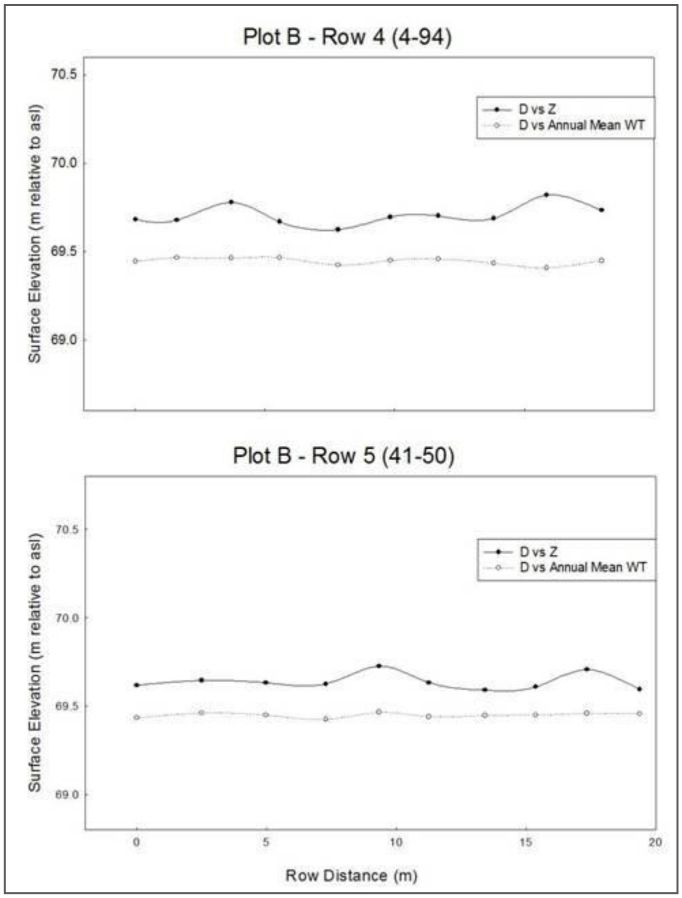


Figure 4.15: Cross Sections of Plot B, constructed using elevation data. Extrapolated data from East-West Row (a) and North-South Row (b) shown.

The water elevations vary less than the surface elevations across each row. The difference in height between two respective water elevations corresponds to the difference in hydraulic head or potential, and this divided by the distance between two respective points gives a rough estimate of the lateral hydraulic gradient. Differences in surface and water elevations between adjacent wells were used along with distances calculated for adjacent wells to determine peatland surface and hydraulic gradients. For both plots, local hydraulic gradients are consistently lower than local surface gradients (see Tables 4.4 and 4.5). For all wells, the mean local slope between adjacent wells (0.0345) is almost three times as large as the mean hydraulic gradient (0.0124) of the plot. The hydraulic gradients are a proportion of 34%, 38% and 36% of the slope of the corresponding surface caused by the microtopography, respectively for Plot A, B and A & B combined. The local lateral re-distribution of water in the soil is controlled in part by the local hydraulic gradients, so the amount of water flowing laterally from one well's location to the next may not be as high as might be suggested by the steeper local gradients on the peatland surface.

Table 4.4: Peatland surface gradients between adjacent wells.

Statistic	Surface - A	Surface - B	Surface - All
Mean	0.0340	0.0350	0.0345
Standard Error	0.0020	0.0019	0.0014
Median	0.0285	0.0317	0.0296
Standard Deviation	0.0268	0.0256	0.0261
Sample Variance	0.0007	0.0007	0.0007
Range	0.1525	0.1345	0.1531
Minimum	0.0009	0.0003	0.0003
Maximum	0.1534	0.1348	0.1534

Table 4.5: Hydraulic Gradients between adjacent wells.

Statistic	Hydraulic - A	Hydraulic - B	Hydraulic - All
Mean	0.0116	0.0132	0.0124
Standard Error	0.0007	0.0010	0.0006
Median	0.0097	0.0093	0.0094
Standard Deviation	0.0090	0.0131	0.0113
Sample Variance	0.0001	0.0002	0.0001
Range	0.0468	0.0770	0.0770
Minimum	0.0002	0.0001	0.0001
Maximum	0.0470	0.0771	0.0771

4.5 – Auto Well Records of Water Table Depths:

In the previous section the spatial variance in water table was examined for 11 different dates, but water table is a continuous variable. It is cost prohibitive to examine water table continuously on such a fine grid but to obtain a higher temporal resolution, recording water level sensors were installed across several transects of contiguous micro-topographic forms – i.e. hummock/hollows in plots A and B. The continuous observations will be used to further investigate the coherence among water tables and elevations between hummocks and hollows and to examine response of the water elevations to inputs of water (rainfall) or persistent losses of water (drainage and evapo-transpiration). Figure 4.16 shows complete automatic well records from all three transects in plot A; these water table values are shown as their depth below the surface (left) and their elevation above sea level (right).

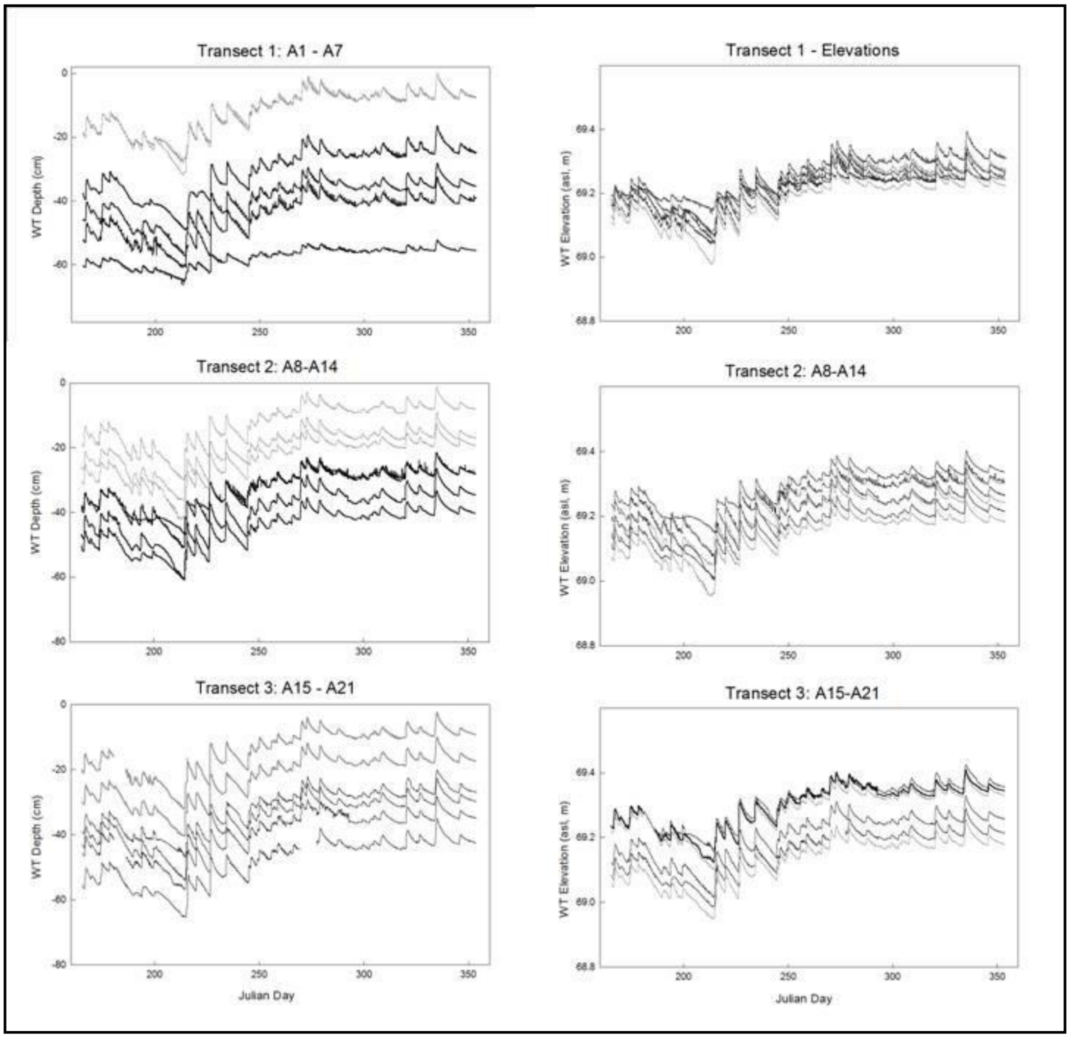


Figure 4.16: Recording well records of water table depths and water elevations, A Plot. For this Figure and all remaining the grey lines denote the water table or elevation in hollows while the black lines indicate water table or elevation beneath hummocks.

Water tables from the three transects in Plot A show a great deal of coherence throughout the sampling period, in that records follow each other with respect to the timing and magnitude of fluctuations. Plot B values show a similar coherence (Figure 4.17).

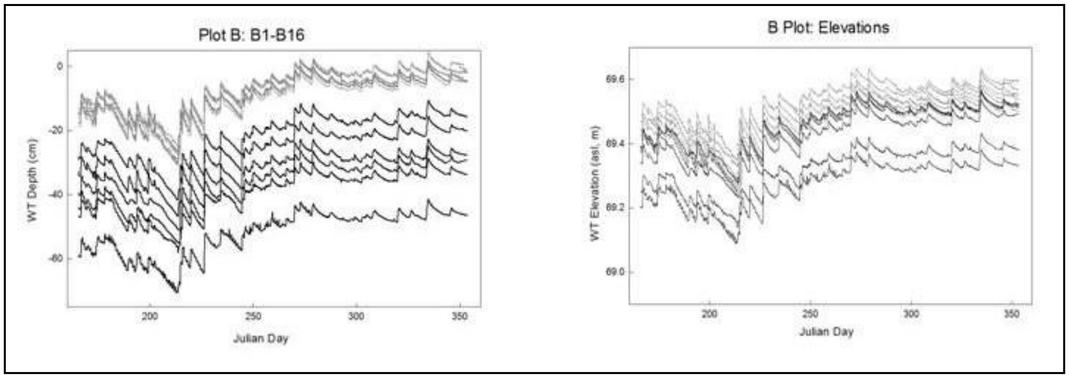


Figure 4.17: Recording well records of water table depths and water elevations, B Plot.

As would be expected from the spatial surveys the variation in water elevation over time is much less than that of water tables over time. Although automatic recording wells were installed on the highest hummocks and lowest hollows within both plots, the same effect occurs when water tables are shown as water elevations. For each plot, the range of water table depths and water elevations was calculated for each measurement point in the time series records. Range among water table depths was 0.47 m and 0.45 m for plot A and B, respectively. Range among water elevations was 0.20 m and 0.26 m for plot A and B. The range of water elevation values is about half of that when the water tables were shown in relation to the peat surface, as the complete records are much more condensed vertically. For water elevation plots, hummock and hollow well records are no longer visible as two distinct groups as they were when expressed as water table depths.

Seasonal averages were calculated for each water table record using all water table data from June 22nd to December 20th. Each 15 minute water table value was expressed as a deviation from the seasonal mean. Hence, each data point could be considered as an anomaly from the seasonal average of a given well record. This normalizes all the water table records to a common reference. The complete seasonal record for all three transects in plot A and all wells in plot B can be found in Figure 4.18, where water table depths are plotted as a deviation from each record's individual seasonal average.

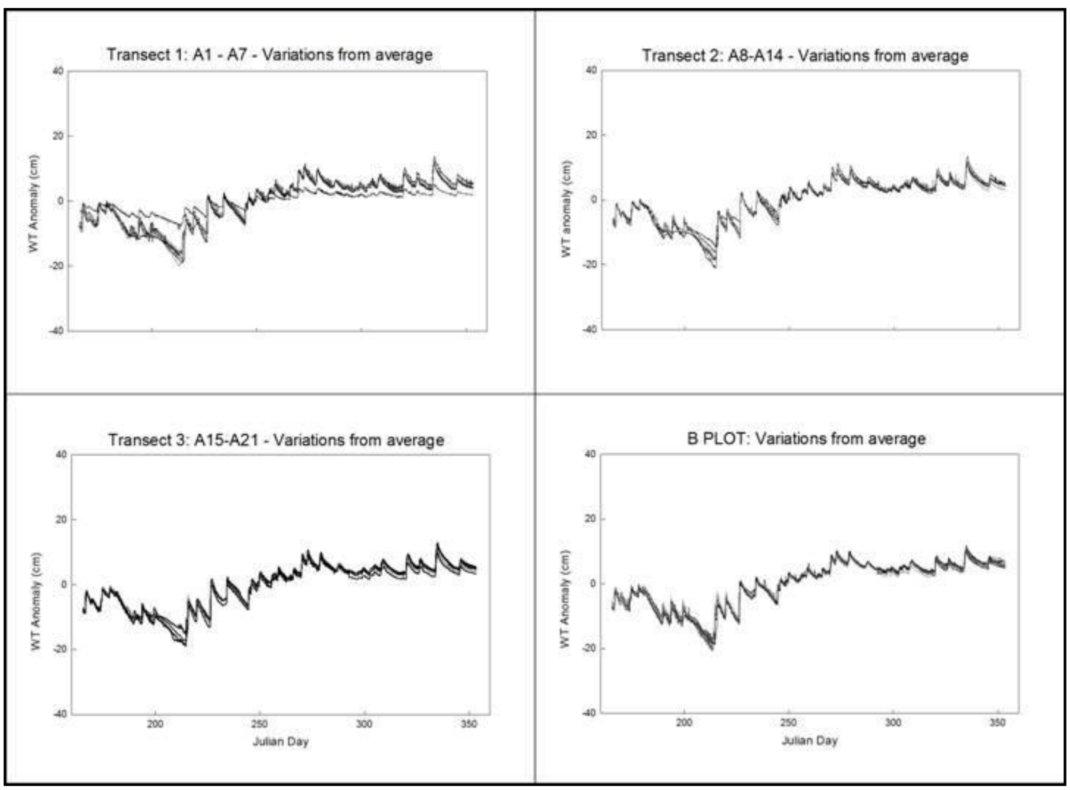


Figure 4.18: Water Table Variations from season average, all wells.

The changes occurring in water table depth are synchronized and are of a similar magnitude for all wells in the plots. The fact that the lines are so close together for most of the season indicates that the wells react very similarly to changes in storage, and that most values are almost identical when normalized to a seasonal average. Figure 4.18 shows that in relation to its year-long average water table depth, instantaneous water table depths vary to the same degree, with a few minor exceptions. In plot A, one well record in the first transect (A3) is located on a particularly high hummock. The location of this well is one of the highest points in the entire plot, and the steep edges and extremely thick aerated layer of this site mean that the water table is very deep below the surface. As can be seen in Figure 4.16, this well record is consistently the deepest water table and it can be seen in Figure 4.18 that this record deviates the most from the other records. This well site represents an exception to the otherwise prominent pattern of consistency seen among the rest of the well records shown in the figures above.

Some deviation among records can be seen during the long water table drawdown from day 180 to 220. During this period, water table depths were low, and in some cases were up to 20 cm deeper than the mean value calculated for the 13 years during which Mer Bleue has been instrumented (see Figure 4.3). In some cases, these extremely dry conditions meant that depths of the peat were unsaturated for perhaps the first time in many years. Well records deviate during this particularly dry period to a greater degree, but there is still a significant level of coherence among most of the well records. This coherence among well records that vary in terms of spatial location and microform means that the long-term patterns of water table fluctuations may be predictable even when a limited number of well records are available. Closer analysis of interesting time periods such as this may provide insight into how well records from different microform locations deviate in response to inputs or over periods of prolonged water loss.

Figures 4.16, 4.17 and 4.18 demonstrate the coherence among water table depths, water elevations and water table anomalies among wells at different locations. Box plots of the individual season-long well records can be seen in Figures 4.19 and 4.20. Boxes for water table depth, water elevation and water table anomalies are stacked to show that the range of these box and whisker plots shrinks as water table depth is computed as water elevation. For both plots A and B, boxes are even more tightly clustered vertically when water table anomalies are shown.

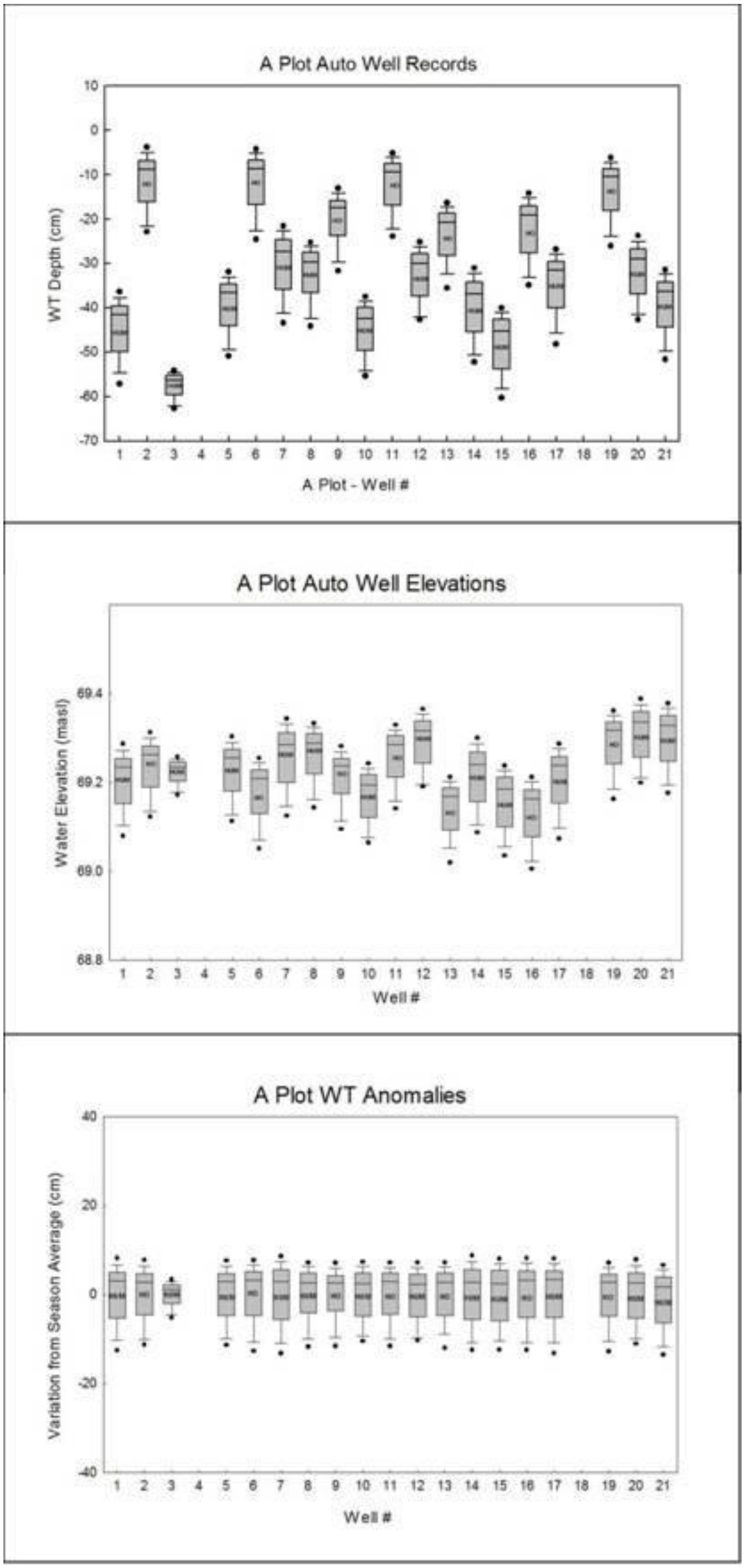


Figure 4.19: Boxes of Full-Season Auto-well water table levels, water elevations and variations from average, Plot A.

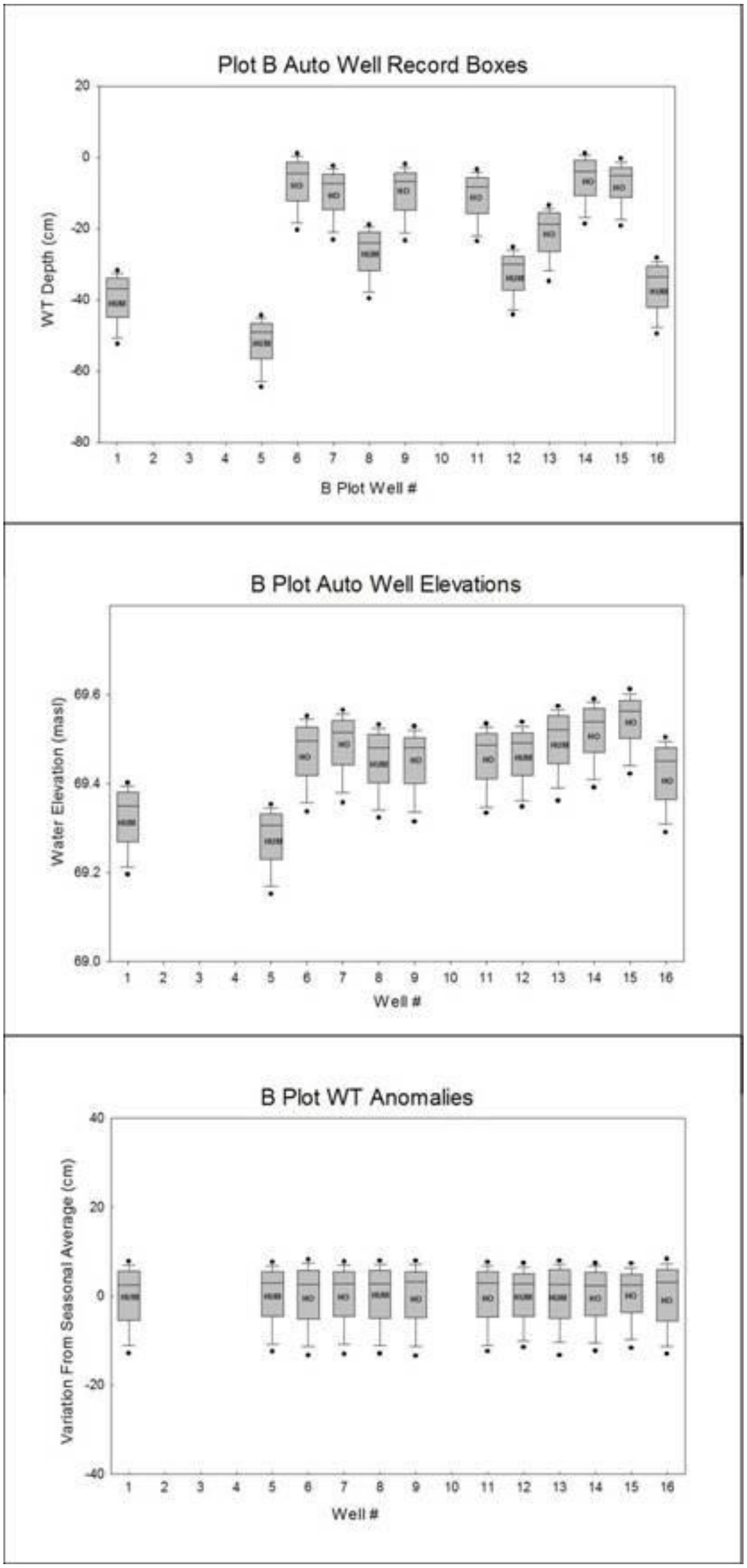
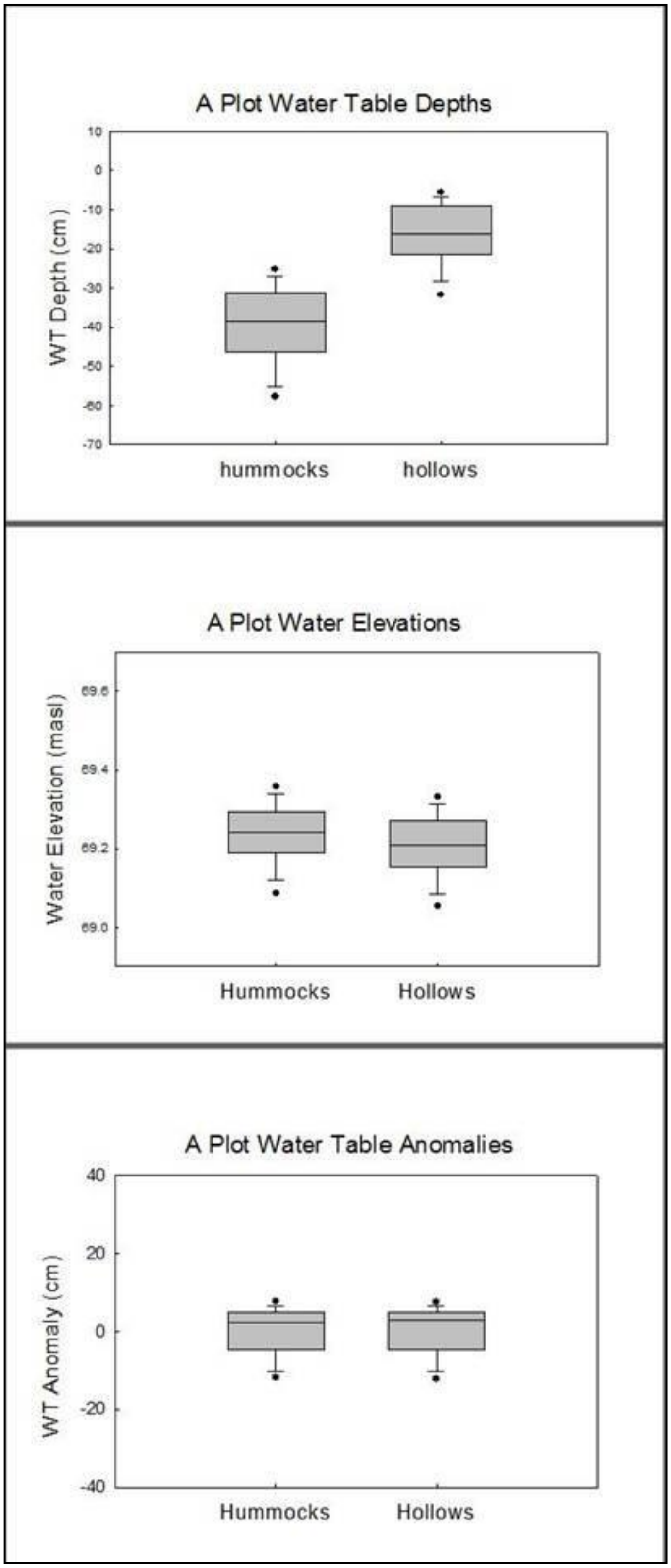
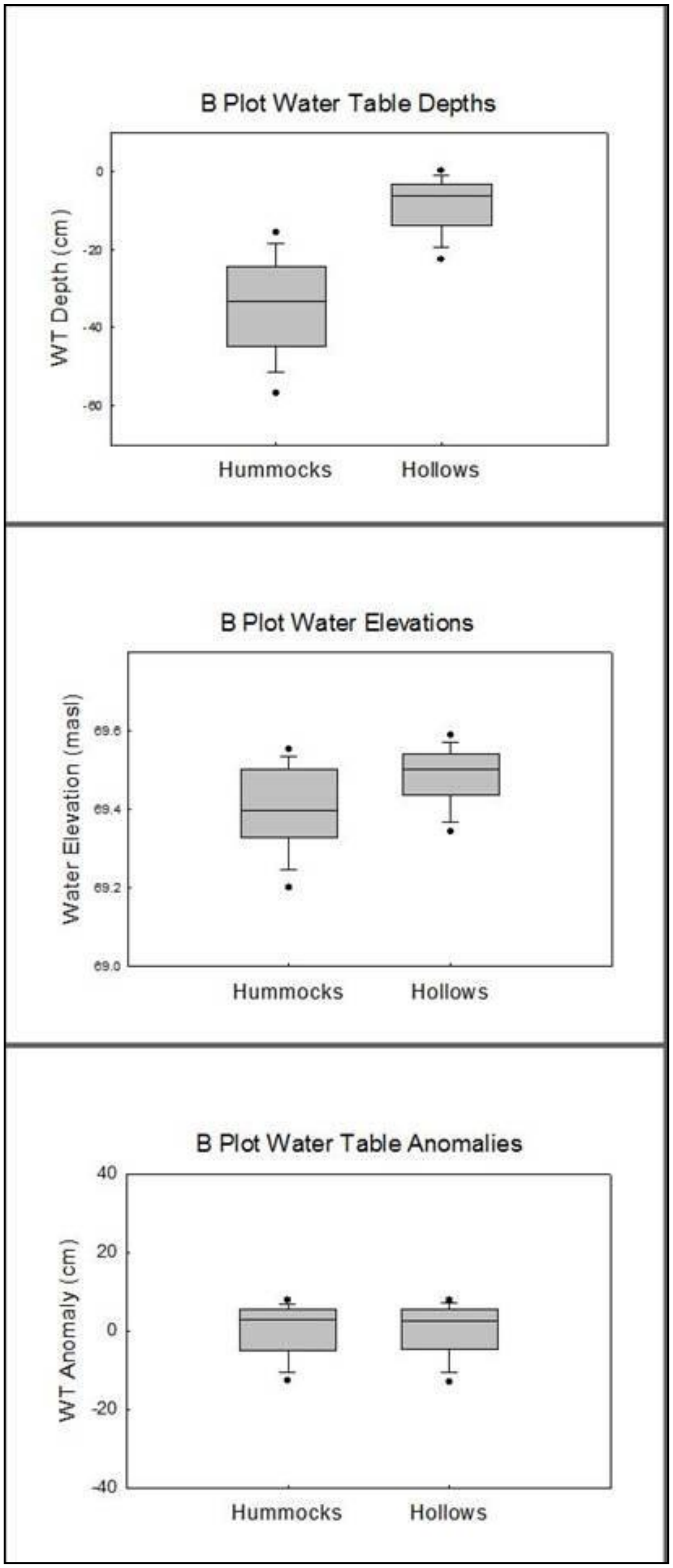


Figure 4.20: Boxes of Full-Season Auto-well water table levels, water elevations and variations from average, Plot B.

Complete wells records were then aggregated into two groups for each plot, with all water table depths, water elevations and water table anomalies assigned to either the ‘hummock’ column or the ‘hollow’ column for each plot. Figures 4.21 and 4.22 demonstrate the results of this grouping, with separate boxes for hummocks and hollows for water table depths, water elevations and water table anomalies. As was the case with the manual water table depths (see Figures 4.9 and 4.10), water elevations show a much smaller range than water table depths. Furthermore, there is an even less prominent difference between distributions of water table anomalies of hummocks and hollows. Descriptive statistics for water table depths for both microform types at both plots are shown in Table 4.6.



4.21: Boxes of all water table records in Plot A, comparison between hummocks and hollows. See Tables 4.6-4.8 for details.



4.22: Boxes of all water table records in Plot B, comparison between hummocks and hollows. See Tables 4.6-4.8 for details.

Table 4.6: Descriptive statistics of Hummock/Hollow Water Table Depths.

	Water Table Depth (cm)			
	Plot A		Plot B	
	Hummocks	Hollows	Hummocks	Hollows
Mean	-39.57	-16.50	-34.50	-8.78
Standard Deviation	10.12	8.22	12.70	7.18
Standard Error	0.022	0.024	0.043	0.022
Range	50.09	42.27	60.18	35.24
Maximum	-16.41	0.03	-10.58	4.50
Minimum	-66.42	-42.23	-70.75	-30.75
Count	209702	122328	87390	104868
Skewness	-0.399	-0.495	-0.390	-0.785
Kurtosis	-0.674	-0.346	-0.543	-0.231

There is a significant amount of variability between microform types at both plots when water table depths are aggregated. However, markers of variability are diminished when water tables are computed as elevations above sea level and aggregated in groups based on microform location in both plots. Table 4.6 demonstrates that distributions in both plots are much more similar when water elevations are computed.

Table 4.7: Descriptive statistics of Hummock/Hollow Water Elevations.

	Water Elevation (m-asl)			
	Plot A		Plot B	
	Hummocks	Hollows	Hummocks	Hollows
Mean	69.235	69.205	69.402	69.486
Standard Deviation	0.080	0.086	0.110	0.077
Standard Error	0.000176	0.000245	0.000373	0.000236
Range	0.440	0.451	0.514	0.395
Maximum	69.425	69.400	69.604	69.635
Minimum	68.986	68.950	69.089	69.241
Count	209710	174758	87388	104866
Skewness	-0.391	-0.426	-0.388	-0.646
Kurtosis	-0.243	-0.236	-0.675	-0.166

Table 4.8: Descriptive statistics of Hummock/Hollow WT Anomalies.

	Water Table Anomaly (cm)			
	Plot A		Plot B	
	Hummocks	Hollows	Hummocks	Hollows
Mean	-0.105	-0.451	-0.00185	0.000543
Standard Deviation	6.494	6.596	6.964	6.959
Standard Error	0.0142	0.0189	0.0236	0.0215
Range	34.847	32.419	31.493	32.249
Maximum	13.783	12.477	11.155	11.42
Minimum	-21.063	-19.942	-20.338	-20.829
Count	209708	174756	87388	104865
Skewness	-0.743	-0.828	-0.797	-0.841
Kurtosis	-0.348	-0.294	-0.437	-0.288

Distributions of hummocks and hollows become more similar through the above succession of tables, with the difference between hummocks and hollows in both plots much less significant in water elevations when compared to water table depths. This can be seen in Table 4.8. Furthermore, water table anomalies show even more similarity among distributions of hummocks and hollows at both plots when compared to water elevation.

4.6 - Short-term Water Table Responses:

The full record of water tables revealed a pattern of rapid response to water inputs and slow, persistent decline over periods of little or no input. In order to further investigate the temporal variability of the water table I examined the response of the water table to five rainfalls and three periods with no rain. The five specific precipitation events were selected based on duration and intensity of rainfall – they were the longest-lasting and/or most intense precipitation events during the study period (see Figure 4.2).

It is important to note that although there is some variation in short-term (minutes to a few days) response to the precipitation input shown in the Figure 4.19, the overall rise in water table depth over the course of three days is similar among all wells. Table 4.9 summarizes the various responses calculated for each period of interest. Response ratios show the water table rise resulting from the specific precipitation input. These ratios were of a similar magnitude for all five periods of interest that were investigated, despite variable precipitation magnitudes and intensities. Rates of response were calculated for each well, based on the total rise of water table over the course of the precipitation event.

Table 4.9 - Summary of Storm Responses:

Start Date	Start T	End T	ΔT	P (mm)	P(mm/day)	ΔWT (cm)	Response Rate (cm/day)	Response Ratio (WT/P)
Aug-01	213.6562	216.4375	2.7813	43.8	15.75	12.61	4.53	2.88
Aug-15	226.2187	226.8125	0.5938	47.4	79.82	12.26	20.65	2.59
Aug-21	233.8333	234.5937	0.7604	25.4	33.40	5.77	7.59	2.27
Sep-01	244.6771	244.9062	0.2291	16.0	69.84	5.04	21.99	3.15
Sep-02	245.8125	246.3333	0.5208	13.8	26.50	3.14	6.04	2.27

Details on the statistical character of response rates for the periods of interest can be found in Table 4.10. All values in the table were calculated using precipitation response data from all wells in both instrumentation plots.

Table 4.10 - Summary Statistics of Response Rates (all wells):

	WT Response Rate (cm/day)				
Start Date	**Mean**	**Stdev**	**Max**	**Min**	**Range**
Aug-01	4.53	0.80	6.05	2.07	3.98
Aug-15	20.65	1.76	23.68	14.36	9.32
Aug-21	7.59	1.36	9.84	3.71	6.13
Sep-01	21.99	2.16	25.97	16.89	9.07
Sep-02	6.04	1.08	7.99	2.23	5.76

The temperature and rainfall at Mer Bleue during these periods of interest is summarized in Figure 4.2. For the most part, short-term responses were very similar among different wells. Precipitation events of shorter duration (Aug. 15 and Sept. 1) resulted in higher but more variable response rates. Figure 4.23 shows the time series water table records used for the calculation of the water table response.

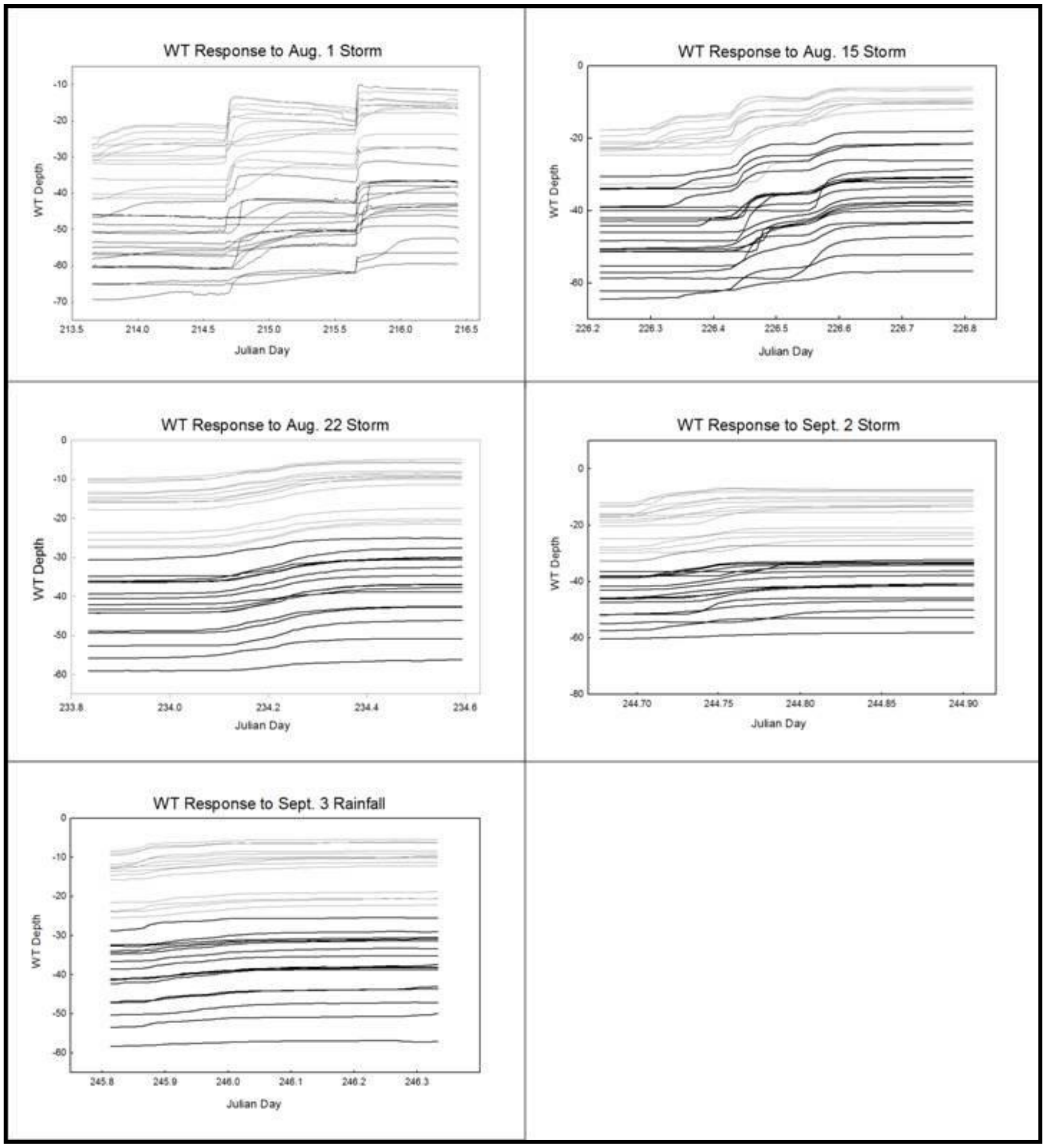


Figure 4.23: Water table response to 5 different precipitation events.

Although the overall rise of water table was very similar among all wells during precipitation events, some well records responded more quickly than others. To investigate for any differences in the speed and steepness of water table responses, 5 points of interest were found for each record during its individual rise. By examining the complete water level records, the points at which each well reached 10%, 25%, 50%, 75% and 90% of its overall rise were found and noted to the nearest 15-minute measurement point (Figure 4.24). Some of these sets of points of interest show a great deal of coherence throughout the period of water table rise (August 21, September 2) while some distributions are more scattered (August 1, September 1).

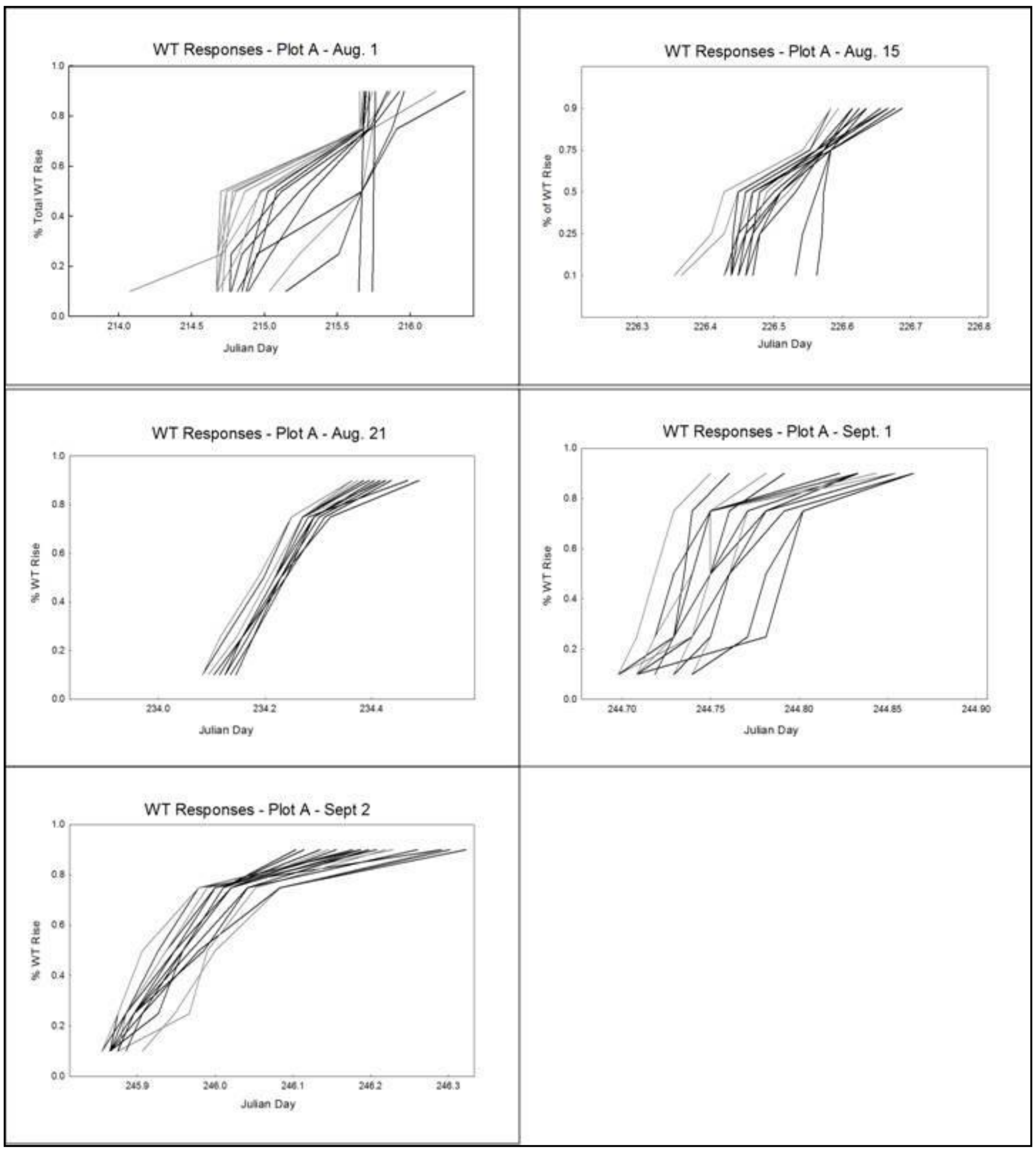


Figure 4.24: Water table responses to precipitation. 5 Points shown for each WT record during precipitation events; 10%, 25%, 50%, 75% and 90% of individual well's WT rise.

Three periods where significant water table drawdown occurred were selected based on visual analysis of the complete water table records. During these periods, little to no rainfall was recorded, and sustained evapo-transpiration caused a continuous drop of the water table at each well location. Table 4.6 shows the results of calculations done using Equation 1, and the general statistical character of the group of results from all wells are shown in this table. In Figure 4.25, the water table responses for all three extended dry periods are shown. As was the case with water table rise calculations, patterns of water table drawdown are similar across both plots and across the various microform locations that these well records represent.

Table 4.11: Statistical Parameters of the recession coefficients for periods of prolonged water table lowering.

Start Date	Start T	End T	ΔT	Mean Temp.	ΔWT (cm)	K_{mean}	K_{median}	K_{max}	K_{min}	SD_K
Jun-29	180.8125	189.4583	8.6458	23.57 °C	8.64	1.0016	1.0011	1.0035	1.0003	0.00096
Jul-22	202.3750	213.6354	11.2604	19.53 °C	8.39	1.0009	1.0007	1.0019	1.0002	0.00052
Aug-22	234.5937	244.6771	10.0834	20.72 °C	7.83	1.0016	1.0011	1.0038	1.0002	0.00099

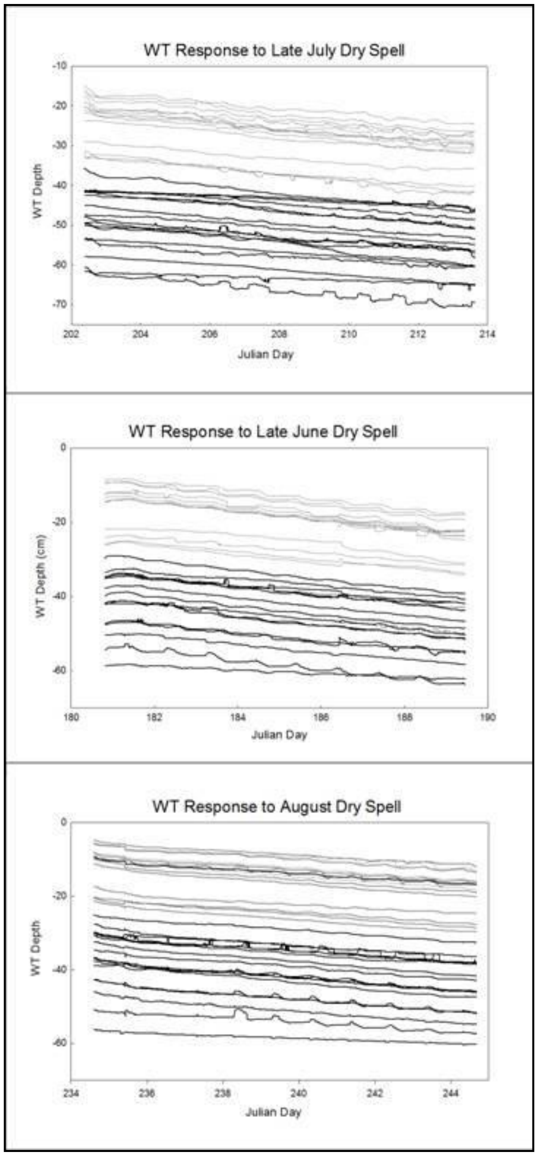


Figure 4.25: Water table responses to extended dry periods.

CHAPTER 5: DISCUSSION & CONCLUSIONS

The objective of my research was to examine the relationships between a peatland's microtopographic heterogeneity and the spatial and temporal variability of water table depth. Data collected over six months in 2010 indicate that although the water table is spatially variable, its variability is only about a third of that of the surface. The short-term and year-long fluctuations of the water table were similar across different microforms. These similarities were found in two plots separated by more than 200 m. In this chapter I will discuss whether the research questions and hypotheses in Sections 2.5 and 2.6 were answered and will determine if the evidence presented is sufficient to falsify the hypotheses. I will then compare my results to those of previous studies where comparable measurements have been made. The implications of my results as they relate to hypotheses of peatland development and water table importance will be explored. I will conclude this chapter with some suggestions on what future research at the Mer Bleue bog and in other peatlands is needed to further explore the topic of my thesis and will make several recommendations on the possible uses of this data from my research.

Most of the results presented in the previous chapter relate in some way to the variability of the surface of a peatland. One of the critical assumptions of my work is that the surface elevation of the Mer Bleue bog does not move significantly over the year or between years. Based on the observations using the

Roulet 'bog shoe', the maximum temporal variability in surface elevation during the snow free period of 2010 was < 2 cm (N. Roulet and M. Dalva, pers. comm.). Furthermore, a second exhaustive elevation survey conducted in July 2011 concluded that the mean elevation in the two plots changed by < 1.6 cm from that of September 2011 (see Tables 4.2 and 4.3). This difference is not significant even at the p=0.001 level. With ranges of water table depths at individual sites as high as 35 cm in some cases, this annual maximum fluctuation represents a small change throughout the season. The upper layer of the peat surface at Mer Bleue is evidently stable enough to not compress or expand due to the frequent changes in moisture conditions, and no significant compression occurred due to the pressure of the snowshoes on the surface during sampling.

Some previous studies have found that 'mire breathing' can be responsible for a significant portion of variations in the depth of peat and water budget of peatlands. A 2002 study conducted at a *Sphagnum* bog in central Sweden found that up to 40% of annual water budget variability at an undisturbed bog was caused by swelling and shrinking in the underlying peat layers (Kellner and Halldin, 2002). Other studies have found similar results, with some variation in the degree to which the peat surface may shift over time. For example, a study conducted in 1991 at a subarctic fen in northern Quebec concluded that the surface of the peatland there is quite variable, with a vertical range of 20-30 cm (Roulet, 1991).

It is important to note that many studies of this nature are conducted at higher latitudes, where freeze-thaw processes may have a more significant effect on annual variations of water table depth. However, it is clear from over 4 years of data collected at Mer Bleue that the surface of the peatland does not shift substantially throughout the year. In some cases, high levels of methane production can lead to larger variations in peat surface position (Glaser *et al.*, 2004). Results from a study of a peatland in Northern Minnesota indicate that small oscillations (±3 cm) in peat surface can occur due to precipitation cycles, and that longer-term oscillations of up to 20 cm can occur during dry periods. Glaser *et al.* (2004) hypothesize that these peat deformations are largely controlled by the ebullition of methane. At Mer Bleue, methane production is relatively low throughout the year so the changes in peat surface position due to gas exchange do not occur to a significant degree (Blodau and Moore, 2003).

If it is assumed that the surface of the peatland does not move over the season or between years, then it is possible to compare water elevations measured over time at the same locations. Water table depths were recorded in 2010 with a frequency of once every 2-3 weeks, and it was possible to show these depths as 'water elevations' relative to an arbitrary datum, in this case mean sea level elevation, measured at one point in time. It was essential to establish that the surface of the Mer Bleue peatland was stable, or the computations of water elevation would be meaningless.

5.1 – Answering the Research Questions:

5.1.1 - Temporal Water Table Fluctuations:

Section 4.6 presents results of short-term responses of the water table depth to precipitation inputs and periods with little or no precipitation – i.e. evapo-transpiration and runoff losses. For the most part there was very close agreement among the recession coefficients for each water table record. Minor variability occurred on a daily time scale, with some water tables exhibiting a daily rise and drop within the general recession that was being analyzed. Similar daily modulations have been observed in other studies (Evans *et al.*, 1999; Eppinga *et al.*, 2008; Holden *et al.*, 2011). Daily fluctuations such as these can be attributed to the water demand by plants and the subsequent hydraulic lift. More pronounced daily variations occur under drier conditions. It is interesting that the daily lift/fall of water table occurs only at some well sites, and further investigation will be needed to determine what exactly causes the daily fluctuations. Comparing the vegetation density at different well sites could help determine if rooting depth and/or biomass, as a surrogate for the withdrawal of water by the vascular plants, are the cause of the daily fluctuations. I hypothesize that areas that show the daily water table fluctuations have active roots present near the water table depth, and that these roots enhance the water loss and promote hydraulic lift in response to transpiration.

A similar level of coherence among short-term variations can be seen when one compares the responses to different precipitation events seen in Figure

4.24. A stronger response can be seen in the first precipitation event, which occurred immediately following an extended dry period. In fact, the 44 mm precipitation event in early August began when the water table was generally at its deepest point of the season, with a mean depth of -44.57 cm. The second storm event, whose responses are also seen in Figure 4.24, are more subdued because moisture storage in the peat was greater as indicated by the nearly 7 cm higher initial mean water table: -37.59 cm. A similar precipitation input occurred for both these events (see Table 4.8). The greatest divergence of water table responses occurred towards the end of the longest dry spell that was analyzed, when water table depths were much deeper. We have not yet analyzed the hydraulic properties of the peat in the micro-topography plots, but we know from the work of Fraser *et al.* (2001b) that hydraulic conductivity is about one order of magnitude lower at -45 cm compared to -35 cm. However, at the time of work by Fraser *et al.* the intensive micro-topographic surveys had not yet taken place at Mer Bleue, and studies of the spatial variability of hydraulic conductivity due to micro-topography (Andrew Baird, University of Leeds, pers. Com., February 2012) were not considered. Assuming the other hydraulic properties such as specific yield and retention follow the general pattern of hydraulic conductivity (e.g. Letts *et al.*, 2000; Chason and Siegel, 1986) then we would expect a greater response per unit addition of water when the water table is deeper. We now have a clear picture of the spatial variability of micro-topography and water table in the plots, so a spatial study of hydraulic properties will help to solidify an estimation of hydraulic conductivity in the plots.

There is little variability among the rates of rise and recession coefficients calculated for the periods of interest shown in Figure 4.2. Fluctuations in the water table depths are the same across the two instrumented plots, regardless of surface micro-topography. Similar responses across various microform types indicate that infiltration and subsequent percolation rates are likely very high and relatively uniform in the upper 50 cm of the Mer Bleue peatland. Percolation rates are similar on a time scale of 3 days or less, and water table lowering in response to evapo-transpiration is similar across a time scale of ~ 11 days or less.

Adjacent hummock and hollow water table wells exhibited similar water table responses to short-term storage changes and to more gradual changes over the course of the field season. Regardless of their microform location, plot or mean water table, the water level records move within the peat column in unison throughout the year. This is most evident in Figure 4.19 where the strong coherence among well records can clearly be seen. Despite the coherence throughout the course of the 2010 field season, there is some slight deviation among the water table anomalies during the extremely dry period in late July (day 200-210). As can be seen in Figure 4.19 the water table anomalies separate to a small degree during this period, indicating that as the water table drops into the deeper sections of the peat column, there is less coherence among the wells at different microforms. Water table depths in 2010 were relatively 'wet' in comparison to previous years (see Figure 4.3) and for the later 2/3^{rds} of the study season, the value of water table depth for 2010 is well above most of the records from the previous 12 years. This leads us to believe that in 2010, extremely low water table depths were not reached in many of the sites of the automatic recording wells. This is further demonstrated by the cumulative water table frequencies in Figure 4.4, where the data from 2010 is near the middle of the distribution of full-year records, but the deepest water table depths (deeper than -60cm) are not represented in comparison to other years. The results from 2010 are representative in that the conditions experienced at the bog in that year were quite close to average, but it begs the question what relevance is the average water table depth over a multiyear record. However, it is possible that the coherence among auto well records could break down if drier conditions were present for a longer time period. I hypothesize that the well records will show greater divergence in years with the extended period where there is little precipitation, similar to what occurred in 1999, 2001-2003, and 2005. To test this hypothesis several of the automated water level records along contiguous hummock-hollow sequences could be monitored in a summer that replicates the mid to late summer lower water tables.

5.1.2 - Spatial Variability of Water Table Depth:

Data from automatic recording wells provided a high temporal resolution of water table depth, but each transect of consecutive microforms only covers 10-13 metres of the plot in a single dimension. In general, the water table is deeper below hummocks than below hollows, indicating that the acrotelm thickness varies according to micro-topography. The coherence among short-term water table responses and seasonal patterns of water table fluctuations for all wells indicates that although the surface heterogeneity of each plot is considerable, these differences in elevation do not affect how the water table reacts to inputs and outputs. Adjacent microforms had similar water table reactions to precipitation events and evapo-transpiration surpluses, and the same can be said about plot-wide time series records.

Despite the water table coherence among different microforms, further investigation into the peat properties at hummocks and hollows is needed in order understand how properties such as bulk density and hydraulic conductivity vary (or not) between hummocks and hollows. The similarity of water table fluctuations at hummocks and hollows indicates that the physical properties of the peat may be similar in different microforms around the range of water tables observed in this study.

The water table position does not necessarily indicate the position of the acrotelm/catotelm boundary. The idea of there being two distinct layers comes from the model of Ingram (1982) but recent models such as *Digibog* (Baird *et al.*, 2011; Morris *et al.*, 2011b) and HPM (Frolking *et al.*, 2010) do not have as much of a hard boundary but more a zone of transition between the surface and depth. Morris *et al.* (2011a) recently argued the two layer model of peatlands was an inappropriate characterization. This boundary forms over a long time period and it is therefore possible that the spatial variability of such a transition zone varies in a subdued pattern similar to the microtopographic variation of the surface, as water table does. A spatial study of peat properties could lead to further conclusions about the relationship between micro-topography, water table, water elevation and the acrotelm/catotelm boundary. If there is little or no coherence between the spatial variability of water elevation and the peat layer boundary, then it is possible that differences in acrotelm thickness are controlled more by accumulation/decomposition rates at depth than by hydrologic conditions such as water table. I hypothesize that in the two instrumentation plots, hydraulic properties are a subtle reflection of the general shape of micro-topography and water table spatial distribution, and that further investigation of the physical properties of the peat such as those being done in Cors Fochno, western Wales by Andrew Baird (University of Leeds) would be a test of this hypothesis.

The 100 manual wells covered 400 m^2 of each plot. The box and whisker plots (Figures 4.19 and 4.10) show that the elevation of the water is much less spatially variable than the depth of the water table below the surface. Elevation survey data established that the surface of both instrumented plots is highly variable and adjacent hummocks and hollows can differ in absolute elevation by as much as 30 cm over a horizontal distance of 1 to 2 m. Although the range of water table depths below the surface in any of the 11 'snapshot' distributions taken was as high as 40 cm, the distributions are much more tightly clustered when water elevation is expressed relative to the same constant datum – i.e. sea level. The range in water elevations is ~ 20 cm, about half that of the water tables. Since the water elevation gives the hydraulic head at the water table, an analysis of the hydraulic gradients across the plots can be done. The water elevations in Figures 4.14 and 4.15 show the hydraulic gradients beneath adjacent microforms over a distance of ~ 20 m. The variations in water elevation are much more subdued than the surface of the peatland. Surface and hydraulic gradients calculated for adjacent manual wells in both plots indicate that in general, hydraulic gradients are a factor of 3 smaller than the slopes of the surface topography. Still, the hydraulic gradients between adjacent micro-topographic features (0.0124) are two orders of magnitude greater than that the macro-form gradient across the peatland from the peak to the margins (0.0008) (Fraser *et al.*, 2001b). The difference in mean water elevation between plots A and B was between 0.129 and 0.133 m (Table 4.2 and 4.3) and these plots are ~ 150 m apart relative to the beaver ponds at the margin of the peatland, therefore the macro-form hydraulic gradient during the year of the study was ~ 0.0009 which is similar to that of Fraser *et al.*, (2001b). Therefore, the potential for local lateral re-distribution of water at the micro-scale is greater than the potential for macro-scale flow of water along the dome to the bog margins.

Rates of local re-distribution of water from hummocks to hollows and lawns are hypothesized to affect the way in which microforms interact, and differential accumulation rates among microforms can be affected by this type of lateral flow (Belyea and Clymo, 2001). A rough estimate of the amount of lateral flow between adjacent microforms can be calculated roughly as K × h × G, where K is the hydraulic conductivity, reported in Fraser *et al.* (2001) as between 10^{-5} and 10^{-7} m s^{-1} at 0.2 to 0.5 m below the surface, h is the thickness of water flowing laterally (assumed to be between 0.2 to 0.5 m) and G is the hydraulic gradient, taken as 0.01 as reported above. This is depth-equivalent water flow of

~ 0.1 mm d^{-1}, which is 20 times less than the vertical exchanges of water due to precipitation and percolation, or evapo-transpiration. Slight variations in the water loss through evapo-transpiration due to differences in the vascular plant biomass between hummocks and hollows could exert greater storage changes over the year than that of the potential lateral redistribution of water. The potential feedback between vegetation and water losses has been important in the simulations of the development of micro-topography (Eppinga *et al.*, 2010).

The lack of any significant redistribution of water due to lateral flow is supported by the water table anomalies in Figure 4.18. The fluctuations in water tables over the season beneath different microforms show a great deal of consistency throughout the year. Not only do these well records fluctuate in unison, but they vary in a similar way in terms of magnitude relative to their seasonal averages. Therefore, one of these records from the entire season provides sufficient information to predict the timing and magnitude of water table fluctuations in all the other locations that were instrumented in this study. Point measurements of water table depth and the elevation of the peat surface at each point would be necessary for such an extrapolation, but the potential exists to exploit the coherence among these well records in such a way.

Maximum rooting depth of vascular plants varies between hummocks and hollows, with estimated values of about 60 cm and 40 cm, respectively (Murphy *et al.*, 2009; Murphy and Moore, 2010). The water table is a significant control on evapo-transpiration (ET), and when it is near the surface, ET can proceed uninhibited by a lack of moisture supply. Moss ET will become restricted first as the water table drops down in the peat column, and when the water table reaches the maximum rooting depth of the most robust vascular plants, ET is limited by a lack of moisture. *Eriophorum* is not typically limited by water table position since its maximum rooting depth is often well below the deepest water table level. Determination of the distribution of vegetation communities in both instrumentation plots will be necessary for more specific conclusions about the relationship between 'saturated surface' spatial variability and the spatial variability of ET. Furthermore, when water tables are deeper, root production increases due to the thicker layer of aerated soil (Murphy *et al.*, 2009; Murphy and Moore, 2010). Water table is typically deeper below hummock microforms and therefore root production is often greater.

5.2 - Implications of Results:

In terms of hydrology, raised bogs are indefinitely in a state of adjustment and re-distribution due to evapo-transpiration and precipitation, and the water table surface is constantly responding to precipitation events and changes to the rate of evapo-transpiration. Lateral hydraulic conductivity is much lower than vertical hydraulic conductivity (Fraser *et al.*, 2001b) and lateral re-distribution of water near the water table is extremely slow. Therefore, moisture at the boundary between the oxic and anoxic zones does not re-distribute laterally among hummocks and hollows quickly enough to 'flatten out' before a further influx occurs. Given enough time without such a change to these factors affecting lateral flow of water in the acrotelm, and the ‘surface’ of the water table (as seen in Figures 4.11 - 4.13) could possibly become more even. In the case of Mer Bleue, the difference in surface elevation between an adjacent hummock and hollow pair on the surface is about 40 cm at most. However, the water table surface is a subdued copy of the peat surface with a much lower level of spatial variability. The difference in elevation of the water table between an adjacent hummock and hollow pair is approximately 15 cm at most. Lateral re-distribution of water occurs extremely slowly due to the low horizontal hydraulic conductivity. As a result of this slow re-distribution, the surface of the water table is unlikely to ever become completely even, and will remain a muted duplicate of the more heterogeneous surface of the peatland.

The coherence among water table fluctuations at different microform locations indicates that estimation of the spatial distribution of water table depth could be achieved at a peatland if 1 or 2 point measurements are known and the spatial variability of micro-topography is known. Water table position and range is an important factor in the formation of micro-topography, so the many biogeochemical processes that are controlled by water table are also controlled by the micro-topography (Eppinga *et al.*, 2009a). Water table position is extremely important to vegetation distribution, methane flux, evapo-transpiration and NEE, so the possibility of extrapolating a single point measurement of water table position using the spatial distribution of micro-topography would aid in the estimation of those biogeochemical processes which are spatially integrated in modelling exercises. Coupling of the long-term records of NEE and energy balance that are often recorded at Eddy-covariance towers with spatial water table position could be achieved if the micro-topography is known at a given site, allowing for larger-scale extrapolations of biogeochemical processes in models (Baird *et al.*, 2009; Wu *et al.*, 2011).

5.3 - Future Research Plans:

Re-instrumentation of the two plots for the 2011 season took place in mid April, and data collection at both the manual and automatic recording wells continued until December. Therefore, the record of water table measurements was significantly longer in 2011 than the study year of 2010, providing a more complete picture of how moisture conditions fluctuate throughout the season. To ensure that the surface of the peat in the instrumentation plots does not vary too considerably, a second elevation survey was completed at both plots in July 2011, and the data indicates that no significant elevation changes occurred at the plots between the two data collection dates. Manual water table measurements and well heights above the peat surface were taken every 10-20 days until freeze-up. Automatic recording well water table depths were once again recorded every 15 minutes, and downloading of the data took place about every 20 days. In addition, soil moisture measurements were taken starting in June 2011 at the two instrumentation plots, to establish an overall level of moisture storage. Soil moisture numbers will be added to the depth of the saturated zone to establish exactly how much water is stored in the space between the peat surface and the mineral clay in both plots. Vegetation surveys will be conducted at both plots during the summer of 2012 to determine both species composition and density. Hydrological fluxes depend on the behaviour and success of these plant communities, and transpiration and root production are limited by the availability of water in the peat column. Establishing the dependence of vegetation composition on spatial water table distribution will be important for future studies at the site which consider biogeochemical processes such as the carbon cycle.

In December 2011, a partnership began with the Canada Centre for Remote Sensing (CCRS) with the goal of further investigating the feasibility of near-surface moisture conditions at Mer Bleue through the analysis of Radarsat-2 imagery. Under the supervision of senior research scientist Dr. Ridha Touzi, I will attempt to establish the link between the spatial distribution of water table depth and the output parameters from Radarsat imagery processing. Estimation of spatial distribution of water table depth through remote sensing would be a suitable and important application of the data collected and analyzed in this study, and hopefully the results of the new collaboration with CCRS will be of interest.

5.4 – Conclusions:

No two bogs are exactly alike, and minute differences in vegetation communities, hydraulic conductivity, depth of peat and surface micro-topography can, in some cases, significantly alter the general state of ‘wetness’ on a local scale. All of these different factors depend on each other and are intrinsically linked via various biogeochemical processes, and feedback loops lead to disparities among bog sites. It is the heterogeneity at different scales that makes the study of ombrotrophic bogs so important, because understanding the linkages that exist within peatlands is a daunting task. If all bogs were exactly similar, then there would be no reason to study them, and biogeochemical models would paint a perfectly clear picture of the linkages between hydrology, vegetation, and carbon exchange. However, these landscapes are incredibly complex, and further study will hopefully allow for an increase in the understanding that we have of bogs and the cycles that occur within them. This study has established that short-term water table responses are similar regardless of surface microform location, and that long-term patterns of water table show a great deal of coherence throughout a full field season. The surface of the water table is spatially variable, and is a subdued replica of the heterogeneous peat surface. Furthermore, a significant portion of the spatial variability in water table depth can be explained by differences in elevation. If elevation distributions are known at a bog site, then a spatially coherent water table surface could be assumed if point measurements of water table depth were known. The boundary between oxic and anoxic conditions is a significant control on respiration, evapo-transpiration, gross primary productivity, methane production and expulsion, and other biogeochemical processes. Since so many biogeochemical cycles are affected by the spatial distribution and temporal fluctuation of the water table, a more accurate picture of the shape of the water table surface is an invaluable addition to peatland biogeochemical science.

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