HYDROLOGIC BEHAVIOUR AND HYDRAULIC PROPERTIES OF A PATTERNED FEN IN SASKATCHEWAN

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Abstract

A patterned, partially-treed, fen in the mid-boreal region of central Saskatchewan was the site of renewed hydrological research from 2002 to 2004. Hydraulic conductivity, transmissivity, and storativity were determined through use of a surface loading test, pumping tests, and an enclosed field drainage test. None of these field tests have been previously described in the literature as having been used in peat environments. The combined results of field and laboratory drainage tests were used to obtain a general storativity with water table depth relationship in the upper peat layer. The hydraulic conductivity, measured with slug tests, the loading test, and pumping tests, is high near the surface, declining greatly with depth. These previously untested field methods have the advantage of representing volumes of peat from tenths of a meter to cubic meters

Characterization of the hydrology of the peatland involved year round observations of water table, piezometric head, peat surface elevations, frost depth and peat temperatures. Fluctuations of the water table, and soil moisture changes produce changes in effective stress that lead to volume change in the highly compressible peat. This is particularly important for sites with thick peat deposits. Independent compressibility estimates were as high as 10^{-5} N/m^2 in the upper peat. At three fen sites, changes in peat thickness were estimated from monthly estimates of effective stress change, using year round hydrological observations, and compared to measured annual peat thickness changes. Water table changes causing soil moisture changes, and freeze-thaw processes, explained the majority of peat surface movements.

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1. Introduction

Peatlands make up significant portions of the Canadian landscape, particularly in northern regions (Tarnocai et al. 2000). These terrain types may not behave similarly to mineral soils in terms of watershed hydrology, due to important differences in how they store and transmit water. The hydraulic properties of peat, that is an important focus in this study, show significant differences from the properties of mineral soils (Letts et al., 2000). Despite the renewed interest in studies in northern peatlands, data on peat hydraulic properties is still sparse compared with mineral soils (Baird et al., 2004).

Similarities in the hydraulic properties of peat and the gradient in physical properties with depth have been discovered in different regions of the Canadian north (Quinton and Hayashi, 2004). Within the upper peat layer, there are abrupt changes in water transmission and storage properties with depth (Waddington and Roulet, 1997; Gray et al., 2001; Quinton and Hayashi, 2004). There has been a substantial amount of data collected in Canadian peatlands characterizing peat thickness, bulk density, water chemistry, pH, and vegetation types (Zoltai et al., 2000). When combined with the Canadian Wetland Classification (Warner and Rubec, 1997), knowledge of these site characteristics may allow research studies to be representative not of a single site, but also of the peatlands with similar classifications.

Studies involving hydraulic properties of peat are important not only because of the limited availability of field data, but additionally because they increase our understanding of the physical mechanisms controlling hydrological processes. The measurement, prediction, and control of physical soil processes, including the exchange of mass and energy through the system, falls squarely within the realm of soil physics (Hillel, 1982). In recognition of the unique properties of organic soils, efforts have been made to parameterize peat for use in climate/hydrology models such as CLASS (Canadian Land-Atmosphere Surface Scheme) (Letts et al., 2000). The need to explore the consequences of environmental change scenarios has been a driving factor in the development of more physically based hydrological modeling (Whitaker et al., 2003).

Characterization of the hydraulic properties of peat has, in previous studies, rarely made use of larger-scale field tests. Most of the data in the literature is the result of small-scale field tests such as slug tests, or laboratory tests using peat core removed from the field. Comparison of results from large and small-scale tests may verify the validity of the data gathered in past studies. Frequently, hydrological models utilize a fitted hydraulic conductivity parameter for calibration of hydrographs (Whitaker et al., 2003), in part, due to the lack of data from physically based field tests (Hayashi and Quinton, 2004).

Gaining an understanding of the hydrology of peatlands is best accomplished by collecting long-term data. Inter-annual observations are necessary to capture the range of variation in precipitation, microclimate, and water storage conditions. The hydrology of fens may vary from year to year due to differences in the magnitude, timing, and form of precipitation. In turn, the partitioning of runoff above or through the peatland in spring is controlled by the depth of the frost and the depth of thaw, the quantity of water stored in the peat, snow accumulation, overwinter snowmelt and infiltration events, and precipitation in spring (Nyberg et al., 2001; Gray et al., 2001; Quinton and Hayashi, 2004).

The influence of anthropogenic or natural changes on the hydrology of peatland environments has been the focus of many studies (Woo and Waddington, 1990; Rouse et al., 1997; Turetsky et al., 2004; Hayashi and Quinton, 2004). Improved understanding of the hydrological behavior of these environments will facilitate better management of these sites and prediction of potential effects from forest fires, beaver dams, road building, agricultural or forestry uses, and climate warming.

The highly compressible nature of peat is hydrologically important and creates land use problems in many parts of the world. Numerous studies have observed the natural subsidence of the peat surface that occurs when the water table drops for prolonged periods of time (Roulet et al., 1991; Price, 2003). Research has often been related to the common practice of artificially draining peat so that it may be cultivated with crops (Chow et al., 1992). In some countries, such as the Netherlands and Italy, these practices have resulted in widespread subsidence, even below sea level, that is a major land use concern (Gambolati et al., 2003; de Lange and van der Linden, 2004). Compression and expansion will likely influence runoff and water storage differently in different peatland types.

The overall aims of this thesis are twofold: 1) to compare new and contemporary methods of evaluating peat hydraulic properties, and present their results; and 2) to increase understanding of the hydrological processes operating in a patterned fen through long term observations, and to use this understanding to model the compressible behavior of the undisturbed peat on a monthly time scale.

Innovative field methods, previously untested in peat environments, were used in evaluating the hydraulic conductivity, transmissivity, and storativity of peat. The use of larger-scale methods, representing peat volumes of cubic meters, should give bulk values of hydraulic properties that are more applicable for hydrological modeling. These results will be compared with conventional methods such as slug tests.

The collection of long-term hydrological data was not possible in the time frame of this study. However, Sandhill Fen experienced a wide range of moisture conditions over the period of study, due to inter-annual differences in precipitation. In the Sandhill Fen region, the summer of 2003 experienced lower than normal rainfall, while the summer of 2004 had well above-normal precipitation. This contrast of moisture conditions allowed a relatively short period of record to be representative of a wide range of conditions. Observations made during this study include peat surface elevation, water table elevation, piezometric surface elevation, frost table elevation, peat temperature patterns with depth at several sites, monthly snow depth and snow density.

Under the highly variable moisture conditions characterizing this study, the peat surface elevation was observed to have changed significantly on a seasonal scale. In more rigid soils slight stress changes would cause inconsequential changes of thickness. However, in peat, these slight stress changes have a larger impact on thickness, and the change of thickness can represent a significant portion of total water storage within the peat. Compression and expansion of the peat may influence hydraulic properties and runoff, and therefore it should be considered an important feature of peatland hydrology.

This thesis has been divided into two main parts. The hydraulic properties of the peat and the larger-scale methods used to determine them are covered in Chapter 2. Hydrological observations and modeling of the peat surface elevation over time are presented in Chapter 3. The purpose of presenting these two areas of focus separately is to facilitate production of two papers for review in scientific journals. Therefore, the overall format of this thesis is contained within two main chapters, together with an introduction (Chapter 1) and synthesis (Chapter 4).

2. Characterization of the Hydraulic Properties of Sandhill Fen

2.1 Introduction

Peatlands cover a substantial portion (12%) of Canada's land area (Tarnocai et al., 2000) and influence the hydrological regime in boreal and subarctic regions. There are important differences in the hydraulic and thermal properties of peat compared with mineral soils (Letts et. al. 2000). There is still a scarcity of data characterizing their hydraulic properties, despite a recent heightened interest in water flow processes in northern peatlands (Baird et al., 2004). The storage and release of water in wetlands has been identified as an area requiring further study in developing hydrologic models for northern basins. Only recently have peat hydraulic parameters begun to be included in regional hydrological models such as CLASS (Letts et al., 2000).

Inclusion of changing hydraulic characteristics with depth is important in hydrological modeling of wetlands (Bradley, 1996) as it influences groundwater flow and storage. Declining hydraulic conductivity and specific yield with depth are commonly observed in peatland studies (Boelter, 1969; Quinton and Hayashi, 2004). This pattern causes strong dependence of transmissivity values on water table depth (van der Schaaf, 2004).

The challenges inherent in studying the hydraulic properties of peat are plentiful. Peat is an easily disturbed and compressible medium that is normally saturated or near saturation for the majority of the year. Expansion and compression of peat is known to influence hydraulic properties (Kennedy and Price, 2004). There is a high amount of heterogeneity of physical properties in most peat deposits. The processes of decomposition and oxidation produce gases such as methane and carbon dioxide that are often trapped and released from the peat, influencing the measurement of hydraulic properties (Price, 2003; Rosenberry et al., 2003; Kellner et al., 2004). Studies in peatlands must acknowledge and prepare for these challenges.

Most hydrological studies in peatlands have made use of small-scale methods such as slug tests and laboratory analysis on extracted core in the characterization of peat properties. One major drawback of slug tests is the dependence of the results on a relatively small area of potentially disturbed peat near the piezometer screens (Clymo, 2004). It is difficult to extract cores and analyze peat in the laboratory setting without altering the original structure of the material.

Transmissivity controls the horizontal movement of water through the total thickness of a porous medium. Therefore, transmissivity is of more importance than hydraulic conductivity to groundwater flow in hydrological models. Pumping tests were used to characterize the transmissivity of the upper layers of peat. This methodology has not yet been used in peatlands, though it is commonly used to characterize aquifers.

While pumping tests are a conventional means of evaluating hydraulic properties of mineral aquifers, the performance of pumping tests in peat presents some unique challenges. The common situation in peat deposits of significant decline of hydraulic conductivity with depth, means that the majority of flow towards a pumping well comes from a thin peat layer below the water table. With constant discharge pumping tests in homogeneous unconfined deposits the drawdown cone will normally deepen and expand over time. In peatlands however, large drawdown near the well into less permeable peat will reduce the transmission of water, and underestimate the transmissivity for a given water table depth. The high compressibility of peat will mean that subsidence will occur as water is removed. To date there is no pumping test model capable of defining these special characteristics of vertical heterogeneity, thinness of the highly permeable layer, and compressibility.

The vertical hydraulic conductivity of peat has typically been evaluated by the removal of core in sections and performing laboratory analyses. While this method has proven to be consistent (Beckwith et al., 2003a), it is labor intensive and destructive to the research site. Loading tests have been applied in other sites (van der Kamp and Maathuis, 1985) to evaluate the hydraulic diffusivity and vertical hydraulic conductivity of aquitard layers. If a load is applied to a peatland deposit, the piezometric head will rise and slowly and measurably dissipate in the layers with lower hydraulic conductivity, and compression will occur. The rate of dissipation of this excess head provides the means of estimating hydraulic conductivity.

Methods of determining the storativity of peat deposits have been limited to laboratory analysis using drainage tests (Price and FitzGibbon, 1987; Quinton and Hayashi, 2004) or moisture retention tests. The bulk storativity of the peat was measured using an experimental field test in a polyethylene enclosure, and with pumping test methods.

All methods used to determine hydraulic properties in situ have their drawbacks and advantages, and each is based on simplifying assumptions (van der Kamp, 2001). Methods that characterize larger volumes of peat on the scale of meters and that cause the least disturbance are more desirable. Objectives of this section will be 1) to characterize the physical and hydraulic properties of Sandhill Fen and compare these results to previous studies, and 2) to demonstrate the feasibility of methods not yet documented for use in peat, including pumping tests, drainage tests and loading test methods.

Laboratory methods were used to determine basic physical properties of Sandhill Fen peat on a few occasions, including bulk density, porosity, and water content. Drainage tests to measure storativity were completed on cores removed intact from the peatland. Additionally, hydraulic properties of the peat were measured through a variety of larger scale field methods, and compared to slug test results. Pumping tests characterized the transmissivity of surficial peat. A surface loading test constrained values of the hydraulic conductivity of the peat at greater depth (and lower conductivity) to within an order of magnitude. Finally, field tests of storativity were conducted in large polyethylene enclosures that were imbedded into the lower conductivity peat at depth.

2.2 Literature Review

2.2.1 Classification of fens

Peatlands occur in many landscapes from the tropics to the Sub-arctic. They are distinguishable from other wetland types in having a minimum of 0.4 m of peat accumulation (Warner and Rubec, 1997). Peatlands cover 21% of the total area of continental western Canada (Bauer et al., 2003). They are thought to initially form on substrates with little or no slope, and where drainage systems have not been well established (Halsey et al., 1998). The long-term accumulation rate of peat is the highest in wet, moderately-rich fen areas (Bauer et al., 2003). Patterned or "string" fens develop on slightly sloping terrain, with the ridges and swales oriented perpendicular to the topographic slope (Warner and Rubec, 1997). Sandhill Fen, the study site, is a patterned fen in central Saskatchewan, that represents a common terrain type in the area (Price and Fitzgibbon, 1987).

Bogs and fens are sub-classified according to relief, surface form, vegetation, water chemistry, and their proximity to water bodies. In the western boreal forest (Eco-regions Working Group of Canada, 1989) about 36% of peatlands are bogs, 35% are treed fens, and 29% are open fens (Vitt et al., 2002). Bogs differ from fens in that they are not significantly influenced by groundwater fluxes, receiving inputs of water and nutrients only from the atmosphere. Fens are subdivided from poor to rich on the basis of increasing pH, cation concentration, alkalinity, and indicator wetland species (Warner and Rubec, 1997).

In western Canada, fens are distributed over regions containing calcareous glacial drift, and are often underlain by sediments with high hydraulic conductivity (Halsey et al., 1997). These peatlands have open wet swales or "flarks" covered in sedge, with the ridges and margins dominated by shrubs and trees (Vitt et al., 2002). Peat thickness in fens is often greater than 2 m and is composed of moderately decomposed sedges, brown moss, and tree remains (Warner and Rubec, 1997).

2.2.2 Physical properties of peat

Porosity, specific yield, water retention, hydraulic conductivity, and the degree of decomposition often vary vertically in peat and may be related (Boelter, 1969). In western Canada, surveys of hundreds of peatlands have produced a large database of information on peat depth, bulk density and water chemistry (Zoltai et al., 2000; Vitt et al., 2002). Peat is often described by its degree of decomposition, ranging from fibric (slightly decomposed), hemic (moderately decomposed) to sapric (well humified).

Peatlands are generally divided into two layers; the upper fibric acrotelm layer, and the catotelm layer beneath, that is made up of hemic or sapric peat. The acrotelm is the layer in which water table fluctuations occur, and its thickness usually varies between 20 and 50 cm, but this largely depends upon the microtopography (hummock or hollows) (Quinty and Rochefort, 2003). Acrotelm peat, that experiences fluctuations in water table elevation and soil moisture, also exhibits a greater range of hydraulic properties with depth.

2.2.2.1 Bulk density

The bulk density of peat is significantly lower than for all other soil types due to its organic composition. Typical dry bulk density values for undisturbed peat are on the order of 100 kg/m^3, while mineral soils have densities in the range of 1100 to 1600 kg/m^3 (Hillel, 1982). Bulk density generally increases as the degree of decomposition increases with depth below the peat surface. Bulk density and fiber content are sometimes measured as indicators of the degree of decomposition (Boelter, 1969).

As decomposition proceeds, the size of the organic fibers decreases, creating smaller pores. Fiber content is measured as the percentage of fragments of organic material greater than 0.1 mm in size (Boelter, 1969). According to Boelter's methods, if the bulk density is less than 75 kg/m^3 and the fiber content is more than $2/3^{rd}$ of the sample, the peat is classified as fibric. If the bulk density is greater than 195 kg/m^3 and the fiber content is less than $1/3^{rd}$, the peat is classed as sapric, or well-decomposed. The intermediate category is classified as hemic peat.

2.2.2.2 Porosity

Peat is characterized by high proportions of small pores and a very heterogeneous pore structure derived from plant residues in various stages of decomposition (Weiss et al., 1998). Porosity is the ratio of the volume of voids to the total volume of soil. Peat has high porosity values ranging from 80 to 97%, compared to the porosity of mineral soils ranging from 35 to 50%. There is usually a higher proportion of large pore space in the near-surface layers, that allows for easy drainage. Porosity and pore-size distribution influence the flow and storage of water in peat (Boelter, 1969).

2.2.2.3 Volumetric water content

Fens often have fully saturated soils because the water table remains near the surface (Riley and Michaud, 1987). It is only during prolonged dry periods that the upper layers of peat become unsaturated. Losses of water from peatlands occur through evapotranspiration and through surface or groundwater pathways. The water-holding properties of peat are greater with the level of humification, and thus the volumetric water content varies with depth between peat types.

The standard method of determining water content in peat involves weighing pieces of core before and after oven drying. While this method is straight forward, it is relatively destructive. Indirect methods such as time domain reflectometry (Petrone et al., 2003) are also common, although they may require calibration for use in organic soils.

Although the measurement of water content in peat soil is relatively simple in the frost free seasons, there have been few studies documenting soil moisture after freeze-up. Movement of moisture in freezing and thawing peat soil may affect the depth and consistency of the saturated frost layer, or cause the formation of ice lenses near the surface. Over-winter processes of freeze, thaw, and moisture migration influence the distribution of water in peat, and also affect runoff during the spring snowmelt period (Nyberg et al., 2001; Quinton and Hayashi, 2004).

2.2.2.4 Water storage

The total volume of water stored in the peat profile is dependent on water table depth and the hydraulic properties of the unsaturated and saturated peat (Ingram, 1981). The storativity, also known as the storage coefficient (S) measures the amount of water released per unit change in water table. Storativity is the sum of the specific yield (S_y) and specific storage (S_s) as a function of depth (b) of the hydrologic unit.

$$S = S_y + S_s b \qquad (2.1)$$

Specific yield is the volume of water drained from a soil per unit surface area, divided by the decline of the water table. Specific storage represents the portion of total water released due to compression of the soil. As specific yield often decreases with depth, water table decline will release less and less water as the water table depth increases (Boelter, 1964). In compressible deposits such as peat, the specific storage component is sometimes higher than the specific yield (Schlotzhauer and Price, 1999).

There is a great deal of variability in specific yield values reported in the literature. Boelter (1964) measured specific yield as high as 80% in less decomposed peat, and as low as 10% in well decomposed peat. Verry and Boelter (1978) found values higher than 45% in the acrotelm, and approximately 10% in the catotelm. Price and Fitzgibbon (1987) used 24 hour drainage tests and estimated specific yield values from 13% to 31%. van der Schaaf (2004) estimated storativities of 0.2 to 0.4 in bog peat using lysimeters. Letts et al. (2000) assigned average specific yield values of 66%, 26%, and 13% to fibric, hemic, and sapric peat, respectively, for use in the Canadian Land Surface Scheme (CLASS).

The specific yield parameter may be obtained by draining cores of known volume and measuring the volume of water lost. Fetter (1994) recommended that soil columns be allowed to drain for very long time periods so that equilibrium is reached. Water retention is commonly determined on sections of core using pressure plate analysis. Boelter (1969) defined specific yield as the difference in water content from saturation to a suction of 10 kPa, that is approximately equal to one meter of negative pressure head. Peat in its natural environment rarely drains to one meter of negative pressure head. For comparative purposes, tests using this standard suction may be useful.

The organic matrix making up peat is very porous, with a high surface area, and this explains its overall high ability to retain water. The amount of water retained at low values of suction in soils is controlled by the pore size distribution, pore architecture, and the capillary effect (Ingram, 1981; Hillel, 1982). It is often observed that peat has a heterogeneous pore structure (Boelter, 1964), and for this reason it should display variability in drainage properties with depth, between sites in a peatland, and even between cores. There is a lack of information in the literature about air entry pressure heads and capillary rise values of peat soils (Bloemen, 1983). Romanov (1986) found values of capillary rise in bog peat between 0.15 and 0.2 m. At low suction values, the water retention of peat should be controlled by its pore structure, while at higher suctions, retention should be more controlled by its surface area, as suggested in Hillel (1982). With bog and fen peat soils, water retention was found to vary inversely with hydraulic conductivity, bulk density, and solid matter volume (Bloemen, 1983).

2.2.2.5 Hydraulic conductivity

Hydraulic conductivity (K) is a widely reported parameter in peatland hydrological studies. Textbook values of peat hydraulic conductivity (Dawson & Istok 1991) range from 10^{-6} to 10^{-4} m/s, and are comparable with fine to coarse sands. Values reported in the scientific literature range more widely from 10^{-8} m/s to 10^{-3} m/s (Letts et al., 2000). Hydraulic conductivity is a function of the connected void spaces in a porous medium, as well as the properties of the fluid such as viscosity. The large pore spaces found in the upper layers of the less decomposed peat usually have the highest hydraulic conductivity (Boelter, 1969). Due to differences in peat decomposition and vegetation type, the hydraulic conductivity of peat is often highly variable.

Techniques traditionally used to determine hydraulic conductivity in peat involve piezometer methods (Clymo, 2004) and constant head tests on cores (ASTM, 1996; Beckwith et al., 2003a). Slug tests can be accurate if attention is given to certain aspects of the procedure, but it is rare to see such attention given to piezometer testing in wetlands research literature (Baird et al., 2004). Heterogeneity, anisotropy, preferential flow pathways, compressibility, and methodology can all potentially affect measurements of hydraulic conductivity.

The hydraulic conductivity in peat is often anisotropic (Rycroft et al., 1975). Chason and Siegel (1986) showed the ratio of horizontal to vertical hydraulic conductivity was highly variable in their peat columns, and that horizontal conductivity (K_h) was usually an order of magnitude higher than vertical hydraulic conductivity (K_v). Schlotzhauer and Price (1999) measured that on average, vertical hydraulic conductivity was four times lower than horizontal. A modeling study by Beckwith et al. (2003b) measured increased anisotropy with depth, which had the effect of amplifying lateral flow.

The hydrogeology of peatlands underlain by sand deposits is best understood in connection with the surrounding environment. Vertical hydraulic conductivity values are important in estimating fluxes of groundwater to or from the surface due to evapotranspiration, or head differences within the peat. If the geologic layer beneath peatland is permeable, as is common when sands underlie fens, then vertical fluxes are limited by the peat layer with the lowest hydraulic conductivity. Sandy substrate below a peat deposit can favor vertical flow cells (Reeve et. al. 2000).

It is better to generate values of hydraulic conductivity at scales closer to that incorporated by most hydrological models. To determine hydraulic conductivity in the field on a large scale, Bromley et al., (2004) demonstrated the use of single and double ditch tests in cutover peat, that could be appropriately applied to physically-based regional flow models. Other methods largely untested in peat are pumping tests and loading tests, which operate on a larger scale than slug tests or tests on peat cores. These methods will be discussed in Section 2.4 and 2.5.

2.2.3 Slug tests

Slug tests are one of the few methods suitable for low hydraulic conductivity formations in which the yield of water from pumping tests is small (Papadopulos et al., 1973). Hvorslev (1951) and Bouwer and Rice (1976) methods are the most commonly applied methods of analysis in field slug tests (Domenico and Schwartz, 1998; Hyder and Butler, 1995), and the former is in widespread use in peat studies (Ingram, 1981; Bradley, 1996). Abnormal slug test recovery behavior has been observed in several peat studies and has been attributed to compressibility, particularly when a higher head difference is imposed (Dai and Sparling, 1973; Rycroft et al., 1975; Brown and Ingram, 1988; Hemond and Goldman, 1985).

The response time of piezometers is highly dependent on the condition of the peat surrounding the screen (Clymo 2004, Bromley et al., 2004, Baird et al., 2004). Pitfalls with the method include potential disturbance of the peat upon installation of the piezometer or clogging of the screen by fine organic material. Some studies found that rising head tests (bail tests) gave higher hydraulic conductivity results than slug tests (falling head tests) (Baird et al., 2004). In contrast, Clymo (2004) found no significant effect of the direction of water movement (rising or falling head) when relatively small slugs of water were used.

2.2.3.1 Hvorslev analysis

Piezometer slug test response time theory was first presented by Kirkham (1945) and Hvorslev (1951). The Hvorslev method assumes there is no anisotropy of hydraulic conductivity [m/s] and that the saturated volume of soil being evaluated is not compressible (Dawson and Istok, 1991).

$$K = \frac{\pi r^2}{F t_L} \qquad (2.2)$$

Here, t_L is the time lag when the ratio of recovered head to total head displacement is 0.37, r is the inside radius of the piezometer, and F [m] is the shape factor of the intake. This equation may be applied if the ratio of length to radius (L/r) > 8. The time lag, is obtained from a semi-logarithmic plot of the head ratio (h/h_o) versus time, where h_o is the initial difference in head imposed between the piezometer and the surrounding ground water. The shape factor concept was described by Hvorslev (1951) to represent the size and shape of the intake area. Smaller diameter piezometers with longer screens will respond more quickly to changes in pressure head, and will have higher shape factors. The shape factor for cylindrical intakes with a closed bottom may be calculated using the empirical formula of Hvorslev (1951), as modified by Brand and Premchitt (1980) and described in Hanschke and Baird (2001).

$$F = \frac{2.4\pi L}{Log_e\left(1.2L/d + \sqrt{1+\left(1.2L/d\right)^2}\right)} \qquad (2.3)$$

In Equation 2.3, L is the length of the intake and d is the outside diameter of the screen intake.

2.2.3.2 Bouwer and Rice method

Bouwer and Rice (1976) developed a solution for slug tests in partially penetrating wells for unconfined aquifers, that was a modification of the Thiem equation. Assumptions for this method identified in Hyder and Butler (1995) include: 1) specific storage is negligible 2) drawdown of the water table around the piezometer is negligible 3) flow above the water table can be ignored 4) there is no zone of disturbance created by drilling or development and 5) the formation is isotropic with respect to hydraulic conductivity.

Calculation of hydraulic conductivity using the Bouwer and Rice method is as follows.

$$K = \frac{r^2 \ln\left(R/r\right)}{2(L)t_L} \tag{2.4}$$

K is hydraulic conductivity, and L and r are the length of the screen and the radius of the piezometer. The time-lag parameter (t_L) is the inverse of the slope of the logarithm drawdown versus time plot. When a straight line is fit to the data most of the weight should be given to the earlier data points because compressible aquifers often give slightly concave plots (Dawson and Istok, 1991). The radius of influence (R) is the effective distance over which the induced head is dissipated (Fetter, 1994) and its value depends on the geometry of the flow system (Bouwer and Rice, 1976). The values of R, expressed as the natural logarithm of (R/r), were determined with an electrical resistance network analog based on measured piezometer radius, length of intake, hydraulic head difference, and thickness of the aquifer. Accuracy of the ln (R/r) parameter is 10-25%, depending on the length of the screen. If L > 0.4H than ln (R/r) should be within 10% of the actual values (Bouwer and Rice, 1976).

$$\ln R/r = \left[\left(\frac{1.1}{\ln\frac{H}{r}}\right) + \left(\frac{A + B\ln(D-H)/r}{L/r}\right)\right]^{-1} \tag{2.5}$$

Here H is the length from water table to bottom of the intake, D is the total depth of aquifer, A and B are dimensionless coefficients that are functions of L/r. The Bouwer and Rice (1976) model gives transmissivity results that appear to provide reasonable estimates in a large number of situations (Hyder and Butler, 1995). Hydraulic conductivity results are within 25% of actual field values if the storativity (particularly the specific storage) is less than 0.001 and the test isn't controlled by a hydrologic boundary (Hyder and Butler 1995).

2.2.4 Pumping tests

Pumping test methods usually measure transmissivity. This is the amount of water that can be transmitted horizontally through a unit width of saturated aquifer thickness under a hydraulic gradient of unity (Fetter, 1994). In both confined and unconfined aquifers, transmissivity (T) [m^2/s] and hydraulic conductivity (K) are related by the following equation.

$$T = Kb \tag{2.6}$$

Here, b is the thickness of the aquifer.

Pumping test solutions are limited by a number of assumptions governing the flow of water to a well; 1) The aquifer is of infinite aerial extent, 2) The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test, 3) relatively static water table, 4) constant discharge rate, and 5) a pumping well that fully penetrates the aquifer and receives water from its entire thickness by horizontal flow. The first assumption is never truly satisfied in nature, and slight deviations from these assumptions are not prohibitive to the application of these methods (Kruseman and De Ridder, 1970).

2.2.4.1 The Thiem and Distance-drawdown methods

Thiem (1906) was one of the first to describe steady state radial groundwater flow to a well in confined aquifers. Steady-state conditions are not reached until the cone of depression enlarges until it intercepts a body of water, or until there is a source of recharge into the aquifer from surrounding formations that becomes equal to the pumping rate (Johnson, 1975). In practice, quasi-steady state is reached near the pumping well when there is a constant hydraulic gradient between pairs of observation wells. The following equation describes the Thiem method.

$$T = \frac{Q \ln(r_2/r_1)}{2\pi(h_2 - h_1)} \tag{2.7}$$

In this equation, T is the aquifer transmissivity [m^2/s], r_2 and r_1 are the respective distances of the observation wells from the pumped well [L], h_2 and h_1 are the hydraulic head of the two observations wells [L] and Q is the steady discharge rate [m^3/s]. The equation is slightly altered to use two observation wells at two distances from the pumping well, that is the more accurate method because head losses through the well screen do not affect the result.

Other important assumptions of the Thiem method not already stated include 1) that the aquifer is bounded below by an aquiclude and, 2) drawdown is small compared to total saturated thickness. The latter assumption is of importance for constant-head pumping tests in peat which do not impose large drawdown in the well.

The Cooper-Jacob Distance-drawdown method (Fetter, 1994) is useful when drawdown is measured at the same time in several wells. Drawdown is found to vary linearly with distance from the pumping well when distance is plotted on a logarithmic scale. The formula used in this method is:

$$T = \frac{2.3Q}{(2\pi\Delta(h_0 - h))} \tag{2.8}$$

Here, the term $\Delta(h_0 - h)$ represents the change in drawdown per log cycle of distance (m). Distance and drawdown of the wells should be plotted for several times during the pumping test, and the slope of the lines should be close to parallel. This ensures that the results may be used with confidence.

2.2.4.2 Aron-Scott method

The phenomenon of decreasing discharge during pumping tests is fairly common (Kruseman and De Ridder, 1970). Changes in rate of discharge occur as a constant rate pump adjusts to the lowering water level in the well, in response to head-discharge characteristics of the pump and the hydraulic characteristics of the aquifer (Abu-zied and Scott, 1963; Hantush, 1964). Discharge rate depends on the rate of head decline in the pumped well with increasing pumping time (Kruseman and De Ridder, 1970). Even with constant-head pumping tests, the discharge rate may decline until constant drawdown in the pumping well is reached.

Aron-Scott (1965) proposed a method to account for a variable discharge rate from the pumping well, based on approximations of the work of Abu-zied and Scott (1963) and Hantush (1964). These methods account for transient flow to the well. Abu-zied and Scott (1963) used an exponential, continuous discharge-time relationship. Assumptions governing this method include: 1) water removed from storage is discharged instantaneously with a decline of head, 2) the diameter of the pumping well is very small, so that storage in the well can be neglected 3) flow to the well is transient, 4) the aquifer is confined or unconfined, and 5) the discharge rate declines continuously, with the steepest decrease in Q soon after pumping has started.

From a straight line plot of the ratio of drawdown (s_t) over discharge (Q_t) at time (t) on single logarithmic paper, the slope of this line is the specific drawdown difference per logarithm cycle of time $d(s_t/Q_t)$. Transmissivity (T) is calculated from this equation.

$$T = \frac{2.30}{\left(4\pi\Delta\left(s_t \div Q_t\right)\right)} \tag{2.9}$$

Then the excess drawdown (s_e) per discharge at time t (Q_t) is determined from this equation.

$$\frac{s_e}{Q_t} = \frac{\left(\overline{Q_t}\right)}{2.25\pi T} - 1 \tag{2.10}$$

Here, mean Q_t is the average discharge over time interval 0 to t [m^3/s], and Q_t is the average discharge at time t [m^3/s]. The t value (t_o) of the interception point of the straight line with the abscissa s_t/Q_t is the average of se/Q_t. This allows the calculation of storativity (S) from another equation.

$$S = \frac{2.25Tt_0}{r^2} \tag{2.11}$$

The Aron-Scott method is only valid when s_e is small compared to s_t, and if the following terms are met.

$$\frac{r^2 S}{4T\left(t_n - t\right)} \langle 0.01 \tag{2.12}$$

In this equation, t_n is the total pumping time in seconds.

2.2.5 In situ loading test

There is a need for better field methods than slug tests to estimate vertical hydraulic conductivity (Almendinger and Leete, 1998). Loading tests have been applied in the past to evaluate vertical hydraulic conductivity (Kv) and compressibility in aquitards by measuring excess head and compaction (van der Kamp and Maathuis, 1985). In most practical hydrogeological applications, the stress field is calculated in one dimension (Freeze and Cherry, 1979).

Under initial conditions before a load is applied, all the stress components are constant.

$$\sigma'_o = \sigma - u \qquad (2.13)$$

Here σ ′ is the effective stress [kPa], σ is the total stress and p is the pore pressure. When loading occurs on saturated soil there is an increase in total stress. If the rate of drainage of the soil is much slower than the rate the load is applied, there will usually be a pore pressure increase equal to the increase in total stress. This is termed undrained loading (Domenico and Schwartz, 1998) in which:

$$\Delta u = \Delta\sigma \quad \text{and} \quad u = u_o + \Delta u \qquad (2.14)$$

At this point the effective stress will remain constant and the volume of the soil unchanged. Once the loading stops, the excess pore pressure will start to dissipate as water drains away. As the pore pressure dissipates there is a corresponding increase in effective stress as the soil takes more of the load, and vertical volume change occurs. The change in effective stress at any time during the process should be equal to the initial change in total stress minus the degree of pore pressure dissipation.

$$\Delta\sigma' = \Delta\sigma - \Delta u \qquad (2.15)$$

Undrained loading is especially evident in soils with low hydraulic conductivity. The rate of consolidation (volume change with seepage) is dependent on the hydraulic conductivity of the soil, and the compressibility and the thickness of the consolidating layer.

In applying the theories of one dimensional consolidation, it is assumed that the load is applied over a large enough area that horizontal displacement can be neglected (van der Kamp and Maathuis, 1985). The following exponential equation approximately describes the decay of excess head over time.

$$\text{Ln}\ \frac{[h(z,t)]}{h(z,o)} = \frac{-4.286}{\tau} \qquad (2.16)$$

Here h(z,t) and h(z,o) are the head at a given depth at time t, and at time zero. τ (s) is the characteristic time for response of an aquitard to internal or external changes of head. Its magnitude may vary from minutes to thousands of years. This value is calculated from the slope of a plot of log head versus time using formula 2.16. The formula above is accurate to 1% if $t > 0.1\ \tau$. The decay of excess head after a load is instantaneously applied will also be exponential according to this equation after $t > 0.18\ \tau$, and probably much earlier (van der Kamp and Maathuis, 1985). The hydraulic diffusivity (K_v/S_s) may be determined from the thickness of the hydrologic layer of interest, D (m), and the characteristic response time τ [s].

$$\tau = D^2 \frac{S_s}{K_v} \qquad (2.17)$$

It is assumed that the vertical hydraulic conductivity and specific storage don't change with time, so that τ is constant, although they tend to decrease with decreasing porosity (van der Kamp and Maathuis, 1985). If the specific storage is calculated independently, the vertical hydraulic conductivity may be determined from the hydraulic diffusivity value.

2.3 Site Description

Sandhill Fen (53.8°N, 104.62°W) is located 38 km north of Smeaton, Saskatchewan, adjacent to highway 106. The fen extends approximately 6 km from north to south, is approximately 0.5 km wide at the main study site, and nearly 1 km wide in the northern part. Surface water concentrates in areas of lower elevation and drains southward to a small creek. At the fen outlet there is a 2 m drop over a series of derelict beaver dams. In 2004, the outlet creek at a streamflow gauging site was flooded by beaver dams. The primary area of research is highlighted in Figure 2.3-1.

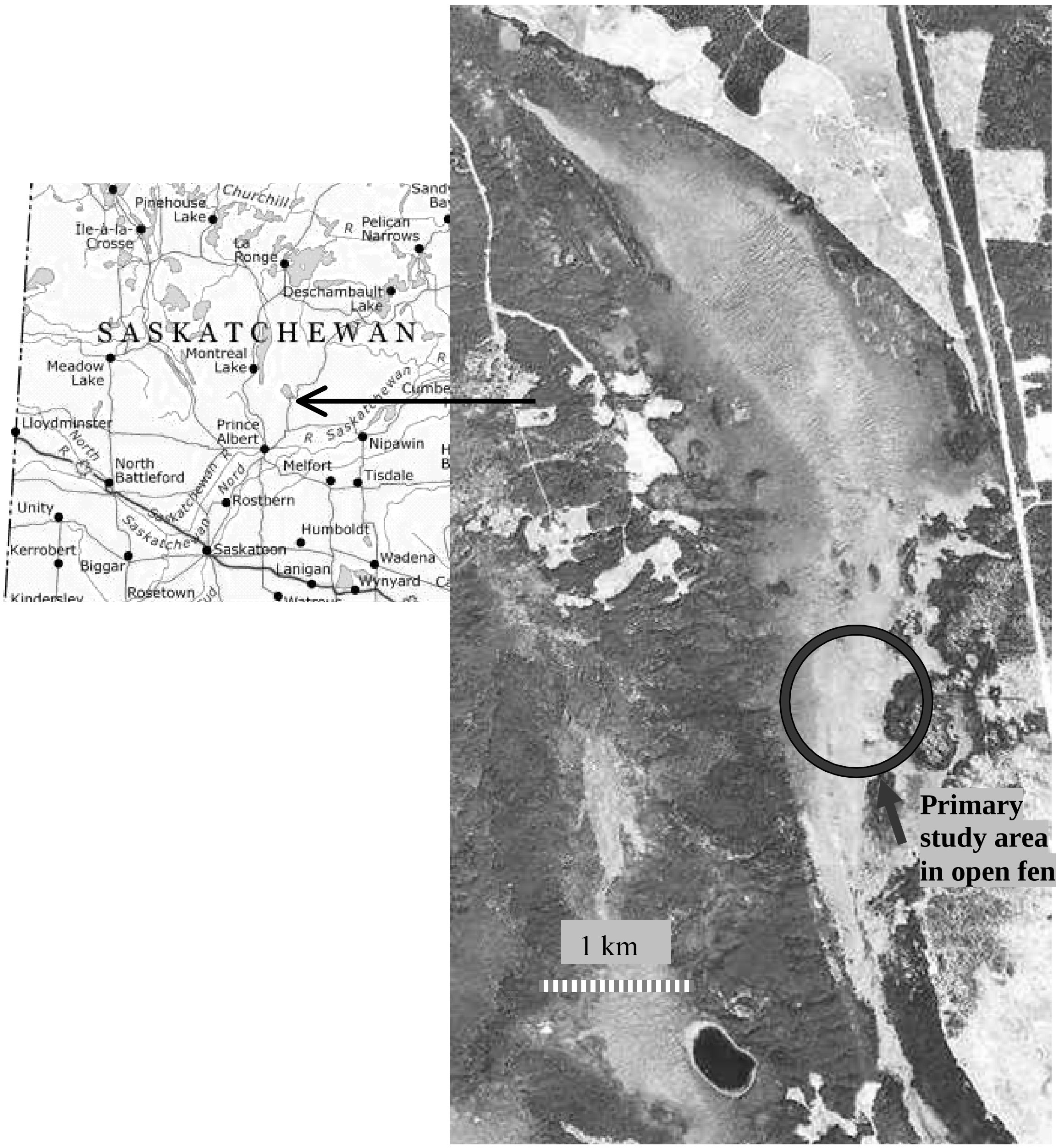

Figure 2.3-1 Location of Sandhill Fen site in Saskatchewan and the 1982 aerial photo

Sandhill Fen is located on a glacial outwash plain (Simpson, 1997) that coarsens and thickens northward to the Cub Hills (Nipawin Provincial Park). A geological test hole drilled by the Saskatchewan Research Council, 5 km south of the fen site, encountered 12 m of fine-grained sand and 160 m of glacial sediments; mainly clay-rich glacial till. Medium-fine sands underlie the fen peat to an unknown depth. Bordering its western edge is a Pleistocene end moraine, identifiable on aerial photos and topographic cross sections.

The surface topography surrounding the fen study site is shown in the digital elevation model in Figure 2.3-2. The cross sections in Figure 2.3-2 are marked by solid lines, and where these intersect is the location of the Fen Centre site, that was the primary study location for this project.

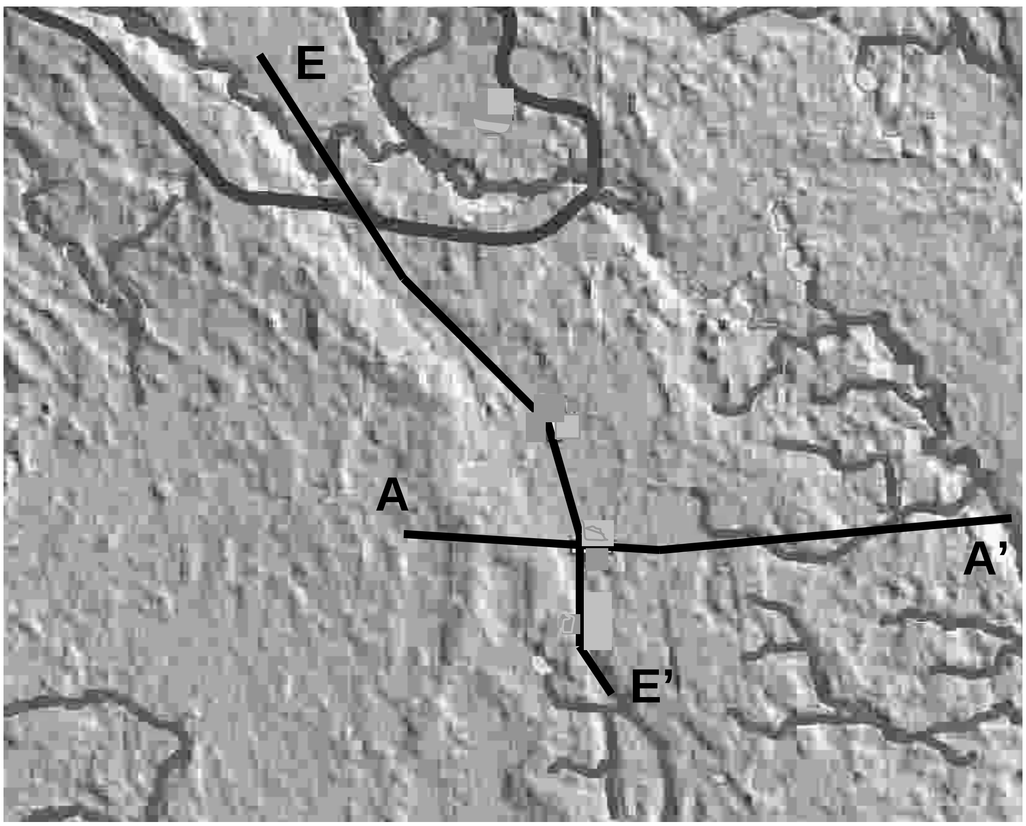

Figure 2.3-2 The location of cross sections running west-east (A-A') and north-south (E-E') across the fen region. The cross sections are bordered to the north and east by White Gull Creek

The cross section A-A' in Figure 2.3-3 runs east-west through the primary fen study site. The glacial end moraine to the west is approximately 20 m above the elevation of the fen itself. Typical moraines in this region consist of unsorted glacial till of low hydraulic conductivity. The water table elevation west of the fen has not been measured, but it is likely to follow the higher topography in that area. The water table beside the highway, one kilometer east of the fen, has been monitored since 2002 and is of similar elevation as that within the fen. Over the study period the hydraulic gradient altered in direction between the two sites. Farther east, the water table intersects a headwater creek leading to White Gull Creek, over eight kilometers to the east. Thus the regional groundwater flow likely follows the topographic gradient in a southeasterly direction.

The second cross section E-E' (Figure 2.3-4) runs north-south through the Fen Centre site. The slope of this peatland is quite low; approximately 1:1000 in the study area. There may be a topographic watershed divide between the north end of the fen and White Gull Creek. Any groundwater connection in this region has not yet been determined, and the estimated water table elevation is marked with a dotted line in Figures 2.3-3 and 2.3-4.

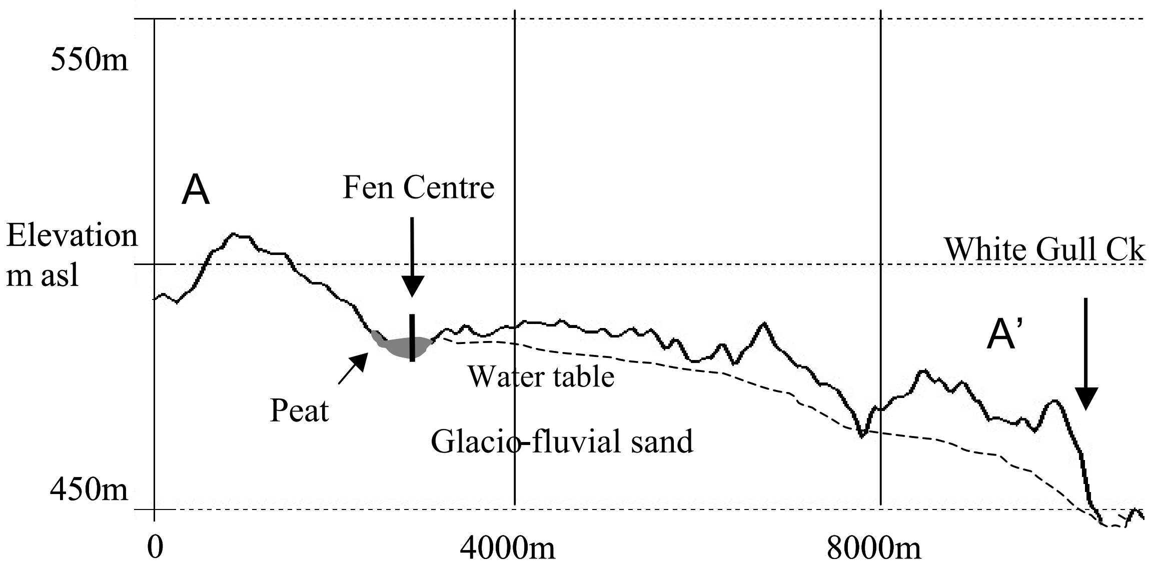

Figure 2.3-3 Cross section A-A' west-east through the Fen Centre site and White Gull Creek

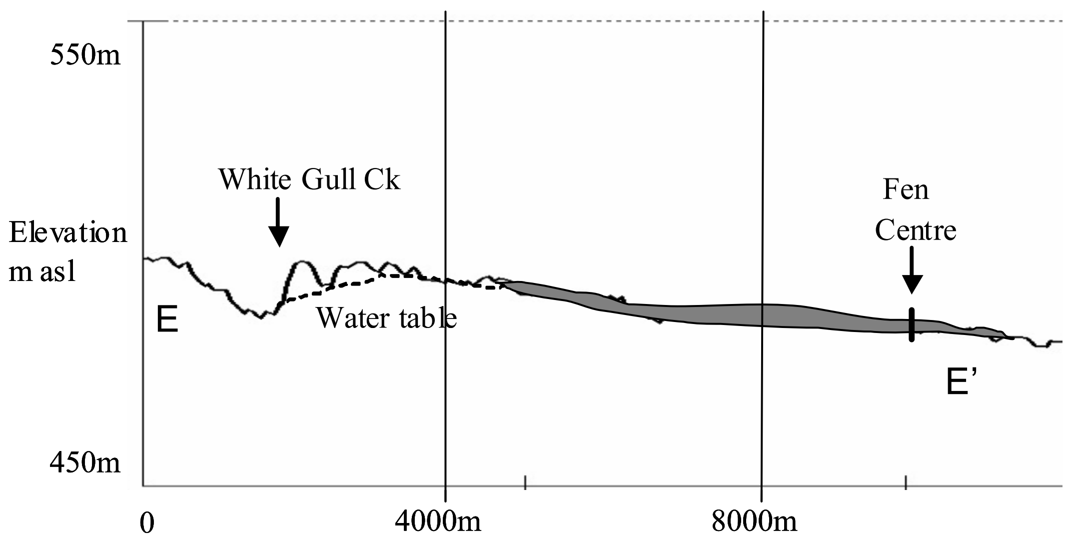

Figure 2.3-4 Cross section E-E' north-south through the Fen Centre site and White Gull Creek

The fen is located within the continental Mid-boreal Wetland region (Warner and Rubec, 1997) and the Mid-boreal Upland Eco-region of Saskatchewan. This was one of the research sites in the southern study area (SSA) of the 1994 to 1996 BOREAS (Boreal ecosystem atmosphere study) campaign. It is classified as a moderately-rich, minerotropic fen, based on its relatively high concentration of major ions such as calcium, magnesium, hydrogen-bicarbonate, and ferric iron (Zoltai et al., 2000). Sandhill Fen is a patterned fen, characterized by ridges of slightly higher elevation (0.2 to 0.4 m) crossing the peatland in the east-west direction. Hummocks and hollows are ubiquitous topographic features over the fen surface.

Black spruce (*Picea mariana*) borders the upland surrounding the peatland. Within the fen, the primary over-storey vegetation is tamarack (*Larix laricina*), that is able to survive in the wetter environment. In the portion of Sandhill Fen that is not treed, shrubs dominate the hummocks and ridges. The dominant species of shrub in the fen is bog birch, (*Betula glandulosa*), although willow (*Salix spp*.) and small tamarack also commonly exist. The most common under-storey species in the fen include; sedge (*Carex & Eriphorum spp*.), non-*Sphagnum* brown mosses, dwarf bog rosemary (*Andromeda polifolia*), bog willow (*Salix pedicellarus*.), and yellow marsh marigold (*Caltha palustris*). Buckbean (Meyanthes trifoliata) is prevalent in the swales, and pitcher plants (*Sarracenia purpurea*) are common plants on hummocks. Upland regions once covered by black spruce and jack pine (*Pinus banksiana*) have been moderately logged in the past thirty years. Regenerating, open-canopy jack pine is the primary over-storey tree canopy species in the upland areas northeast of the fen.

The primary area of research within the fen was in the southern portion, dominated by sedge and shrub vegetation. The aerial photo in Figure 2.3-5 highlights the locations of the study sites within the open fen. A meteorological tower was erected within this area in 2002, approximately 50 m west of the tower used during the BOREAS campaign from 1994 to 1996. A raised boardwalk is in place from the eastern edge of the fen to the tower. To minimize disturbance of the highly compressible peat, rail and plywood boardwalks were laid down over the surface from the tower to the various study sites. For the pumping tests, additional boardwalk-platforms were constructed to spread the weight of the observers more widely over the peat surface. The location of the pumping tests and the enclosed drainage test is also shown in Figure 2.3-5.

Three data-gathering sites were chosen to represent unique zones, as delineated by peat thickness, vegetation, and microtopography. In addition, three semi-permanent transects 100 m in length were set up in order to make observations that would represent each of the sites. Transect 1, Transect 2 and Transect 3 were located from east to west in the open fen environment. These transects are represented by lines in Figure 2.3-5, and are associated with the Edge site, the Fen Centre site, and the Partially Treed site, respectively.

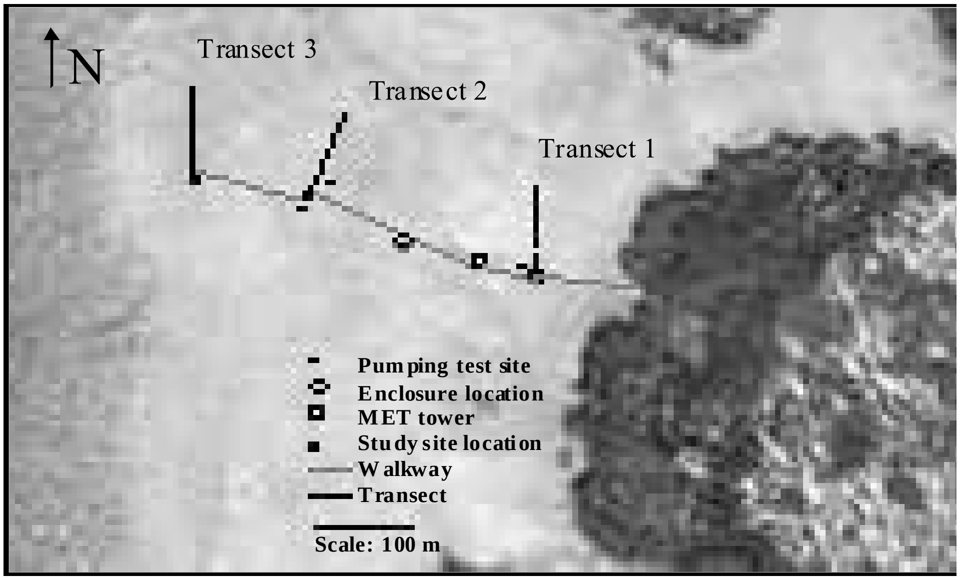

Figure 2.3-5 Aerial photo location of transects and study sites in the open fen

The easternmost Edge site and Transect 1 are located relatively close to the dense black spruce that fringes the peatland. Over the length of Transect 1, peat ranges in depth from 1.15 m to 1.5 m, and the topography is very hummocky. Transect 2 and the second study site were established farther west, near the centre of the open fen. The Fen Centre site is characterized by ridge and swale patterning perpendicular to the direction of surface flow from the north. Peat at the Fen Centre site is over 4 m thick. The Partially Treed site was named for the tamarack whose height and density increases towards the west. Larger hummocks and hollows characterize this site, and the peat is approximately 2.0 to 2.5 m thick along Transect 3.

2.4 Methods

The physical and hydraulic properties of Sandhill Fen peat were characterized with a number of in-situ and laboratory methods. Physical properties such as bulk density, water content, porosity, and drainage tests required the extraction of intact peat cores. Field methods include pumping tests, piezometer slug tests, an enclosed drainage test, and a loading test to estimate the vertical hydraulic conductivity of the catotelm.

2.4.1 Lab methods

2.4.1.1 The extraction of peat cores

Frozen cores were extracted from the fen in February and April, 2003, and in April, 2004. These cores were taken to measure physical and moisture properties at various depths in the peat. Shallow unfrozen peat cores were extracted in October, 2003 using 0.125 m diameter aluminum cylinders with sharpened edges. These cylinders were rotated and gently cut into the relatively dry fibrous peat to a depth of 0.25 to 0.4 m. During the coring, the length from the top of the core barrel to the peat inside and outside the corer was measured to ensure that there was no compression of the samples. Once the corer cut into the less fibrous peat near the water table, the peat core would usually break free from the underlying peat. Then the cylinder with the peat inside was slowly removed by hand. The cores were removed side-by-side in pairs, with one core kept intact for drainage tests, and the other cut into sections for measurement of water content and bulk density.

2.4.1.2 Bulk density and volumetric water content

The bulk density and volumetric water content of core samples were determined together in the laboratory. First the initial volume and weight of the peat cores was measured, then they were oven-dried at a standard temperature of 105 °C $\pm$ 5°C for 24 to 48 hours, and the dry core re-weighed. The volumetric water content is the ratio of water volume lost from the core to its initial volume. The bulk density is the ratio of the oven-dried mass to its initial volume. For this study, peat cores were evaluated in sections of 0.05 m thickness. The Fisher Isotemp oven used for drying the peat was monitored with a thermocouple sensor to ensure that it remained within the standard temperature range.

Some studies in the literature have used lower oven temperatures of 80 °C to prevent burning off organic matter (Zoltai et al., 2000). Standard methods (Carter, 1993) suggest that 24 to 48 hours is an acceptable duration for drying organic samples. Oven dry mass in this study was measured after 48 hours in the oven. The initial set of peat cores were extracted from the fen in February, 2003 in the frozen state. These cores were placed in the oven before they thawed, so that the oven didn't reach standard temperatures until the 2nd 24 hour period. The frozen cores extracted from the fen in April, 2004 thawed before they were oven dried for 48 hours. Peat core extracted in October, 2003 were kept in Ziploc bags at room temperature until they were oven dried. The mass of the cores was measured after 24, 36 and 48 hours to determine which duration was best. It was found that changes in mass still occurred after 24 hours. On this basis, the frozen cores extracted in February, 2003 were not comparable to later results.

2.4.1.3 Porosity

The measurement of the ash content (g/100g) of the peat in this study followed the procedures outlined by the American Society for Testing and Materials (ASTM, 1995). Small portions of core samples previously oven dried at 105°C were ground up with mortar and pestle. The ground peat was sifted through a 0.002 m sieve to produce a sample of 2.0 $\pm$ 0.05 grams in weight. A precision balance with a resolution of 0.0001 g was used for weighing. Samples were combusted in the oven at a temperature of 375 °C for one hour, followed by 16 to 20 hours at 550°C. After combustion, ash samples were weighed again.

Porosity was calculated from the particle density and bulk density parameters, using results from the ash content analysis (Carter, 1993):

$$n = 100 \times \left(\frac{PD - \rho_b}{PD}\right) \tag{2.18}$$

where, ρ_b is the dry bulk density. Particle density [kg/m^3] was estimated from ash content based on the assumption that the ash content represents the mineral fraction.

$$PD = \frac{1 + \frac{\%org}{\%ash}}{\left(\frac{\frac{\%org}{\%ash}}{1550 kg/m^3} + \frac{1}{2650 kg/m^3}\right)} \tag{2.19}$$

where, %org and %ash are the percentage of organic material and ash (mineral fraction) contained in each oven dried peat subsample, respectively. The organic fraction is assumed to have a density of 1,550 kg/m^3, and the mineral fraction has a density of 2,650 kg/m^3 (Verdonck et al., 1978).

2.4.1.4 Peat core drainage tests

Drainage tests were done in the laboratory with intact core averaging 0.3 m in length. The purpose of these tests was to estimate the storativity of layers of peat, by artificially lowering the water table and measuring the water released from storage. Prior to drainage tests in the lab, the aluminum cylinders holding the core were wrapped at the bottom with four layers of cheesecloth and taped so that the peat at the bottom would remain intact. The cylinders were tightly enclosed on either end by two acrylic plates. Rubber pads were used to waterproof the cylinder. Drainage and filling of the cylinder was done via a 1/8 inch hole cut into the centre of the lower acrylic plate, and leading to the side of the plate. A plastic three way valve was fit to the hole, to which plastic tubing was attached. Water added to the column was first boiled to remove dissolved gases and then covered while cooling. Columns were saturated for 72 hours before drainage commenced.

Following the procedure in Fetter (1994), columns were allowed to drain for days and weeks until drainage became minimal or ceased. Drainage tests commenced by lowering the outlet tubing from equilibrium, and measuring the volume of water drained in graduated cylinders. With artificial water table depths ranging from 0.05 m to 0.3 m from the top of the cores, the laboratory drainage tests mimicked the seasonal water table depth in the field. Water drained from the peat cores were the result of both saturated and unsaturated drainage. There was potential for compression of the peat cores inside their aluminum containers due to drainage of water, and this was monitored relative to a stationary surface.

2.4.2 Field Methods

2.4.2.1 Enclosure installation and field drainage test

The storativity was estimated for the upper peat layer with a field drainage test completed inside a circular enclosure in June, 2003. The cylindrical enclosure was made from a polyethylene mould, with a thickness of 0.005 m, and a height of 0.9 m. The 1.5 m diameter enclosure (Figure 2.4-1) had been inserted into the peat in October, 2002, and had frozen in over the winter. The enclosure was located between the meteorological tower and the Fen Centre site. A small section of Johnson well screen was installed in the centre of the enclosure in a pre-augured hole. At the time of the field drainage test the peat had thawed from the surface to a depth of approximately 0.4 m. The water level difference between the inside and outside of the enclosure was monitored over a period of days and weeks to be certain that there was still a barrier of frost at depth in the peat. It wasn't until June 17, 2003 that inside and outside water levels of the enclosure equilibrated, and it was no longer a closed experiment.

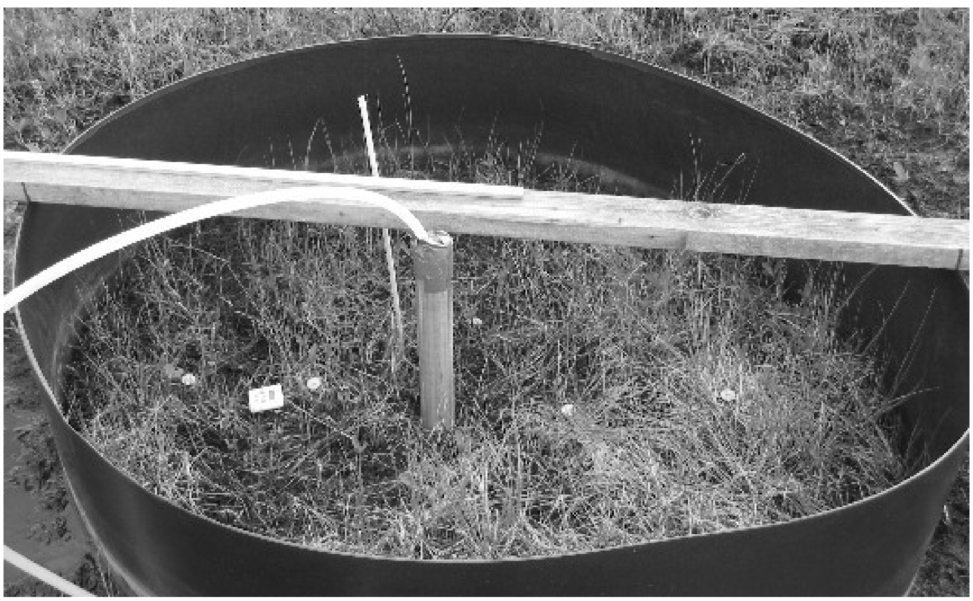

Figure 2.4-1 Enclosure used for the drainage test in thawed peat above frozen peat

On June 10, 2003 the intake of a sediment diaphragm Shurflo© pump was lowered 0.104 m below the static water table, and pumping continued until most of the water had been removed from that layer. Discharge of water from the well was timed from the initiation of pumping and quantified in buckets. When the drawdown in an observation well, placed near the edge of the enclosure, matched the well drawdown, and the discharge rate had become negligible, the test was considered complete. Subsidence of the peat above the frost table was measured at four points in the enclosure, relative to the top of the enclosure.

2.4.2.2 Piezometer installation and location

Piezometers were used to measure peat hydraulic conductivity at different depths and to measure vertical piezometric head differences during the pumping tests. Due to expectations of heterogeneity of hydraulic conductivity in the peat deposit; several replicates of piezometers were installed at depths of 0.5 m, 1.0 m, 2.0 m, and 3.0 m at the Fen Centre site. These piezometers were spaced at 0.5 m, 1.0 m, and 2.0 m distance from the central pumping well, in three directions (north, south and west). In Appendix A, the piezometers at the Fen Centre site are labelled by their various direction and radial distances from the central pumping well screen, and also by the depth of their screens below the surface at the time of installation. At the two other pumping test sites, only one set of piezometers was installed.

Piezometers were installed by creating holes in the peat with solid rods of slightly smaller diameter than the pipes, and then pushing the piezometers to the required depth. The piezometers were developed by flushing water in and out of the piezometers 100 times, inducing a head difference of 0.1 to 0.2 m. Small diameter polyethylene pipes (0.0173 m) were used for the shallow piezometers at depths of 0.3, 0.5 and 1.0 m. Most of the screens were 0.095 m in length, except for the piezometers at 2 and 3 m depths, that had screens of 0.085 m in length. Deep piezometers had smaller diameters (0.012 m), and anchors at their lower ends so they would move with the peat at a specific depth. These deep piezometers were encased with outer polyethylene pipes, separated by an air-filled annulus, in order to reduce friction from peat movement.

2.4.2.3 Slug test procedure

Falling head tests were conducted in all the shallow piezometers at the Fen Centre site from July to October, 2003, until the ground started to freeze. In August, 2004, slug tests were done in the same piezometers to test for differences in the results from falling versus rising head methods. The water level recovery versus time plots were analyzed with the Bouwer and Rice (1976) and the Hvorslev (1951) methods. The water level recovery was timed to the nearest second, and recorded manually with a weighted electronic tape. Falling head tests were also done in piezometers equipped with vibrating wire pressure transducers and head recovery was monitored with a data logger.

2.4.2.4 Pumping test procedure

Six pumping tests were conducted over the spring and summer of 2003 for the purpose of characterizing the subsurface flow properties of the upper peat. These tests were done at three sites within the open fen. The Edge pumping test site was located on the east side of the fen, just north of the raised boardwalk in 1.15 m of peat. Transect 2 pumping test site was located 10 m south of Transect 2 in the centre of the open fen. It was located in a swale covered with sedge, with slightly raised ridges approximately 5 m north and south of the pumping well. The Fen Centre pumping test site was located approximately 20 m east of the south end of Transect 2.

The following pumping test procedures for peat sites were followed.
1. Develop piezometers and observation wells at least two days in advance, depending on lag time of piezometers.
2. Monitor static water levels for one day or more prior to the test.
3. Take a level survey of the tops of the wells, piezometers and elevation sensors in advance of the test (preferably the same day).
4. Measure static water levels for all pipes, including those with transducers, immediately before the pump test.
5. Start the pump and timers.
6. Measure water levels in the nearest and shallowest wells first, followed by the rest, at regular intervals.
7. Measure discharge (the time it takes to fill a bucket of known volume) either continuously, or every few minutes at the start of the test, slowing down to every half hour or few hours as the test continues.
8. Take level surveys on the elevation sensors and peat surface points at regular intervals (every half hour to every hour).
9. Take level surveys on the tops of the piezometers and wells before the test ends, as small amounts of subsidence of the peat are expected.
10. When the water levels in the farthest piezometers (3 m or 5 m away) are no longer decreasing, the pumping test has reached a quasi-steady state, and may be stopped.
11. Regularly monitor the recovery of the water levels and peat elevations after the pump has stopped, for at least the duration of the test itself.

Three different pumps were used for the pumping tests. The low volume 12 volt diaphragm pump, made by Shurflo™, was useful in peat with lower transmissivity, such as at the Edge site. It did not produce a large enough drawdown at the Fen Centre site. A high volume gas pump was needed in the more highly conductive peat. The gas pump needed to be refueled every 1.5 hours, so it was only feasible for shorter term tests. For the 24 hour test at the Fen Centre site, a third pump powered by 110 volt AC electricity was used.

All of the pumping wells were constructed with Johnson™ well screens, that are preferred as they have a high ratio of screen to non-screen area, and these never became clogged with organic sediment. The exception was the 24 hour test, which used an electric pump that required a larger diameter plastic well screen instead of the Johnson well. The pumping well was developed by bailing sediment-laden water out of it until the water became clear.

For the Edge and Transect 2 pumping tests, observation wells were placed 0.15, 0.3, 1.0 and 3.0 m away from the well in two directions. Three screen designs were used for the observation wells. One type used a porous ceramic screen, 0.21 m in length, that was de-gassed under a vacuum and kept saturated until installation in the peat. Another was of polyvinylchloride (PVC) construction with an intake consisting of a series of 0.01 m perforations and containing a ceramic insert. The third design was slotted screens cut into polyethylene pipes. Appendix A also contains observation well specifications.

Observation wells and piezometers were developed by flushing water in and out of their screens.

Measurements of drawdown during the pumping test were made both with pressure transducers and manually with an electronic water level tape. Vibrating wire pressure transducers with very high resolution and accuracy were used in several piezometers and two observation wells at the Fen Centre site. Geocon™ Vented 4580 transducers were used in the Johnson wells at the surface, while Geocon™ Vented 4500's were used in the piezometers. Two shut-in piezometers were installed at distances of 1.0 and 2.0 m from the pumping well; these have the benefit of being sensitive to transient pressure changes in the peat (Rosenberry et al., 2003). Bentonite clay was used to seal in the vibrating wire pressure transducers near the piezometer screens at depths of 3 m, and then silica sand was packed in the piezometer above the Bentonite.

2.4.2.5 In situ loading test

A loading test was carried out in September, 2004 when the water table was above the peat surface. A rectangular plastic tub with a length of 1.42 m and width of 0.69 m was used for loading the flooded peat at the Fen Centre pumping site (Figure 2.4-2). This meant the load was not uniform over a large area so that some horizontal displacement could be expected. Vertical strain was measured at two nearby points at 3 m depths before and after the test. The container was filled quickly with water 0.235 m above outside water levels using 5 gallon pails.

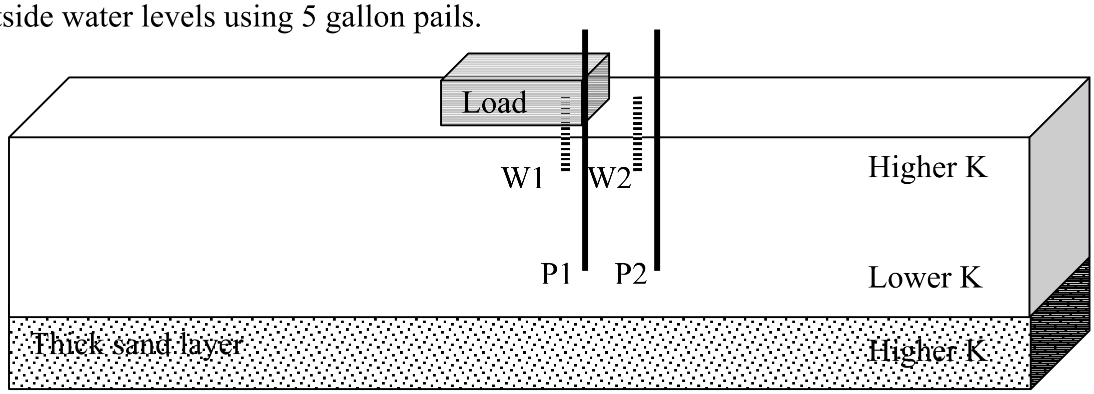

Figure 2.4-2 Diagram of the surface loading test on the peat at the Centre Fen site

Piezometric head was monitored with pressure transducers in two shut-in piezometers screened at 3.0 m depth. Open piezometers with screens at the same depth were not responsive enough for this experiment. After the piezometric head in the closed piezometers returned to normal, the container was unloaded. The pressure response to unloading was also monitored, but the test was ended and data downloaded before the recovery was complete.

2.5 Presentation of Results

There have been a multitude of physical and hydrological studies in peatlands in Canada and elsewhere over previous decades. This study provides details of larger scale field methods for use in peatlands, and compares the results from these tests with results from laboratory and smaller-scale field methods. Hydraulic properties of Sandhill Fen peat are used in the peat surface movement model in Chapter 3, and also in the estimation of water storage changes.

2.5.1 Laboratory Methods

2.5.1.1 Bulk density

Bulk density results from this study are the average of three to six cores extracted from both frozen and thawed peat, depending on the site. Ridge and Swale sites were sampled in April, 2004, while the Edge site was not. Figure 2.5-1 and Table 2.5-1 provide summaries of the mean and standard deviation of bulk density with depth and location in the fen. Mean bulk density ranges from 50 kg/m^3 to 150 kg/m^3 for the shallow cores from all sites in the fen. The bulk density may be partially dependent on depth, and is therefore plotted on the vertical axis. For all three locations of ridge, swale, and edge sites from which the cores were extracted, there is a slight increase in bulk density with depth.

The swales have significantly lower bulk densities than adjacent ridges or sites near the edge of the fen, and bulk density tends to increase with depth at all sites. Variability of the bulk density results is high, as indicated by the vertical standard deviation bars in Figures 2.5-1.

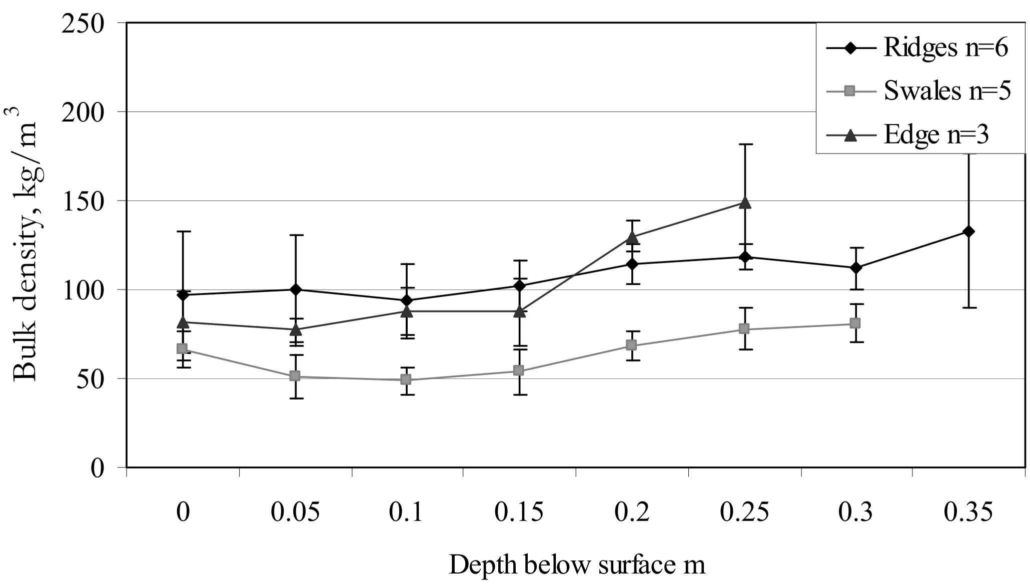

Figure 2.5-1 Mean and standard deviation of bulk density with depth and location in Sandhill Fen

Table 2.5-1 Mean and standard deviation of peat bulk density (ρ_b) and porosity (n)

Depth core	Swale		Ridge		Edge	
	ρ_b	n	ρ_b	n	ρ_b	n
m	kg m^{-3}	%	kg m^{-3}	%	kg m^{-3}	%
0-0.05	66±9	96.2	100±32	94.5	88±16	96.2
0.05-0.1	56±16	97.0	100±28	94.5	99±30	96.3
0.1-0.15	54±17	97.1	100±25	94.0	104±24	95.9
0.15-0.2	59±17	96.9	110±25	94.1	103±26	93.9
0.2-0.25	72±11	95.9	121±21	92.6	142±23	93.0
0.25-0.3	80±11	95.5	118±6	91.7	150±23	92.8
0.3-0.35	91±19	95.0	113±11	92.4	161	93.9
0.35-0.4	96		132±38		158	

Oven drying temperature and duration could affect the results obtained for bulk density using cores. As a general rule, the soil should be dried to a constant mass, but as Topp (In Carter, 1993) pointed out, soil samples may continue to lose mass slowly over several days at 105 °C, and some organic materials are volatile at that temperature. The drying time at 105 °C ranged from 24 h for the frozen cores processed in February, to 48 h for the rest of the sample sets. Both these durations of drying fall within the standard methods. The February cores have significantly higher dry weights than the other sets of cores, that may be due to a drying time of 24 hours instead of 48 hours. For consistency, they were not included in bulk density results. However, the volumetric water content results were used for comparison with other times of year.

Bulk density values from this study are of the same magnitude as those from other studies at Sandhill Fen shown in Figure 2.5-2. In general the bulk density of peat cores from Sandhill Fen was found to increase with depth. Bulk density from these four cores is quite variable, ranging from less than 50 to nearly 150 kg/m^3 in the upper 0.3 m of peat. This comparison shows that this fen peat is heterogeneous with respect to bulk density. At depths greater than 0.3 m, the bulk density of Sandhill Fen peat was in the range of 100 to 200 kg/m^3.

Differences in the values of bulk density may be attributed to differences in methods as well as intrinsic heterogeneity of the peat deposit. Zoltai et al. (2000) used lab methods that included oven drying at a lower temperature of 80 °C for 24 hours. Bauer's methods were similar to Zoltai's, with peat cores being extracted using a half-barrel MacAuley sampler. Core taken during the BOREAS campaign (Harden, unpubl.) was extracted while frozen.

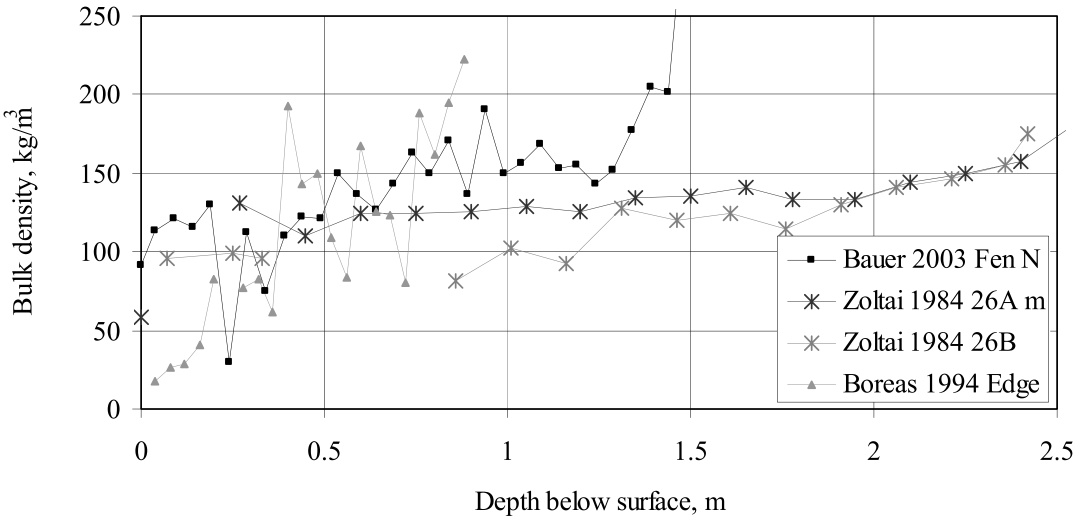

Figure 2.5-2 Compilation of bulk density data for Sandhill fen (Zoltai et al., 2000; Harden et. al., 1997 (BOREAS, 1994); and Bauer 2003

2.5.1.2 Porosity

The peat in Sandhill Fen had higher values of porosity relative to some studies (Roulet, 1991; Letts et al., 2000). Porosity is higher in the cores taken from swales than those from the edge site or the ridges (Figure 2.5-3). At shallow depths, swales have greater total pore space, that may also be an indication of greater connected pore space and higher capacity for groundwater movement.

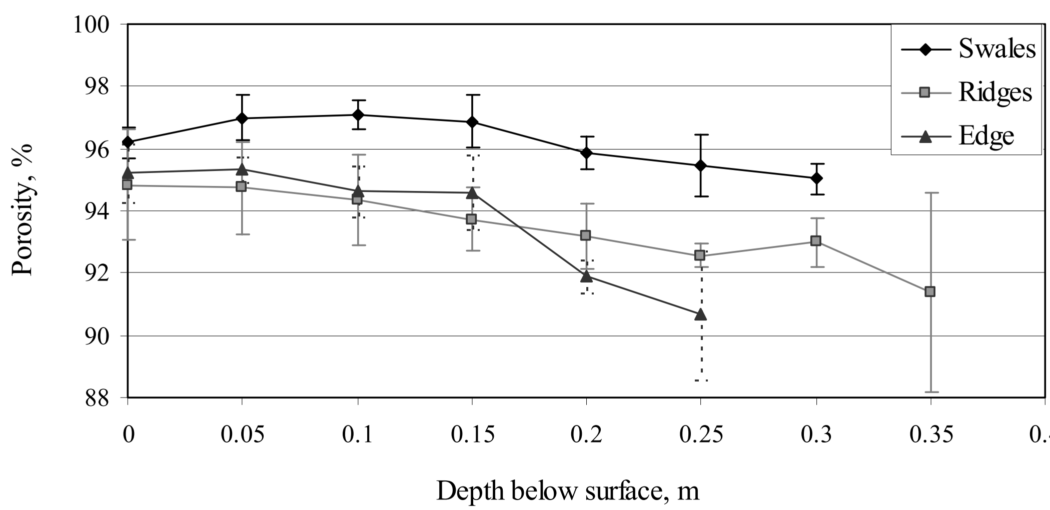

Figure 2.5-3 Mean porosity of shallow peat using cores, with standard deviations

2.5.1.3 Water content

Changes in water content are important to the water balance, particularly in months when the peatland becomes unsaturated. Cores extracted from the fen in February and October, 2003 show the decline in water content that occurred with seasonal drawdown of the water table. Volumetric water content (θ) at the field site ranged from 30% to near peat porosity values of 90% (Table 2.5-2). Swale sites, with their lower elevations, are wetter than edge or ridge sites. By the spring of 2004, the water content of shallow peat had increased again to near saturated levels.

Table 2.5-2 The volumetric water content (%) measured from peat cores in three areas of Sandhill Fen

Depth m	Feb/03 Edge	Oct/03 Edge	Feb/03 Swale	Oct/03 Swale	Apr/04 Swale	Feb/03 Ridge	Oct/03 Ridge	Apr/04 Ridge
0-0.05	78.3	22.2	90.1	27.5	45.4	38.4	28.4	67.0
0.05-.1	84.7	29.1	86.0	28.7	48.6	48.1	32.8	73.9
0.1-.15	87.4	41.0	88.2	27.4	65.0	55.4	37.4	79.0
0.15-.2	89.1	49.3	89.9	34.4	76.6	80.3	62.3	86.3
0.2-.25	84.7	71.0	87.0	57.1	82.0	90.4	75.7	86.2
0.25-.3	93.1	75.7	89.9	75.4	80.2	81.7	81.7	85.9
0.3-.35	89.0	75.6	92.5	74.8	84.8	86.9	75.3	87.5
0.35-.4	85.7		79.8			85.2	72.6	85.1

The water content of cores extracted in October, 2003 was 75 to 90% near the water table. The volumetric water content measured in cores near the water table was always less than calculated porosity. Some of the residual volume may have been taken up by interstitial gases, and/or the lower portions of the core may have been drained or slightly compressed.

The height of the capillary rise in the fibrous fen peat appears to be approximately 0.10 m, with a water table depth of 0.3 to 0.4 m. The height of capillary rise was approximated by the near-saturated water contents measured at the base of three peat cores extracted from above the water table in October, 2003. Total length of these cores were approximately 0.37 in the swale, and 0.38 and 0.42 m in the adjacent ridge. Water table depths measured from the top of these cores were measured as 0.38, 0.34, and 0.39 m, respectively.

2.5.1.4 Storativity

The storativity is the ratio of the water yielded per unit area to change in water table. The results in this section are from lab drainage tests, pumping tests, and in situ drainage tests in closed peat columns. Pressure plate analysis was attempted to evaluate moisture retention and storage at different depths, but these tests yielded unusable results and are being re-done.

2.5.1.5 Lab drainage tests on cores

Saturated peat columns of 0.3 to 0.35 m in length were allowed to drain above an artificial water table for extended periods of time (weeks to months). This was the procedure outlined for column specific yield tests given in Fetter (1994). The total water drained from the peat column divided by the volume of peat drained gives a measure of storativity. The volume of peat drained is determined by the artificial water table height. Changes of storage in compressible peat include water lost from within the peat in addition to water lost from decreasing peat volume.

The majority of the water drains in the first hours after a water table change, but small amounts of drainage continued afterward. The water table was lowered in 0.05 to 0.1 m increments. In a few of the tests, the upper peat layers yielded smaller amounts of water than the peat core beneath. Though the upper peat layers should have the lowest water retention, due to lower bulk density, they may have remained saturated even when the water table dropped to 0.05 or 0.1 m. The air entry suction value, controlling drainage of the largest pores, is not likely to be similar between peat cores at the same site, due to spatial heterogeneity of peat properties.

Storativity results from all the laboratory and field drainage tests are plotted as a function of water table depth in Figure 2.5-4. The field drainage test result is displayed as a solid line, while the laboratory test results are shown with dotted lines. The depth of the water table before and after each drainage test is shown, as well as the mean depth. Results from four different peat cores were combined together with the field trial to generate a numerical relationship between storativity and mean water table depth. Results show the heterogeneity of peat within Sandhill Fen. These variable results are to be expected with peat core extracted from swale, ridge and edge sites, that also displayed important differences in bulk density and porosity values.

The storativity shown in Figure 2.5-4 ranges from 0.4 to 0.7 near the surface, to 0.1 to 0.3 with greater depth. Storativity above the peat surface should in reality have a value of 1.0, as a drop in the water table above the surface yields 100% of the water volume. With a water table depth greater than 0.25 m, the storativity is expected to be lower than 0.3, and may be lower than 0.1, but this will vary by peat type.

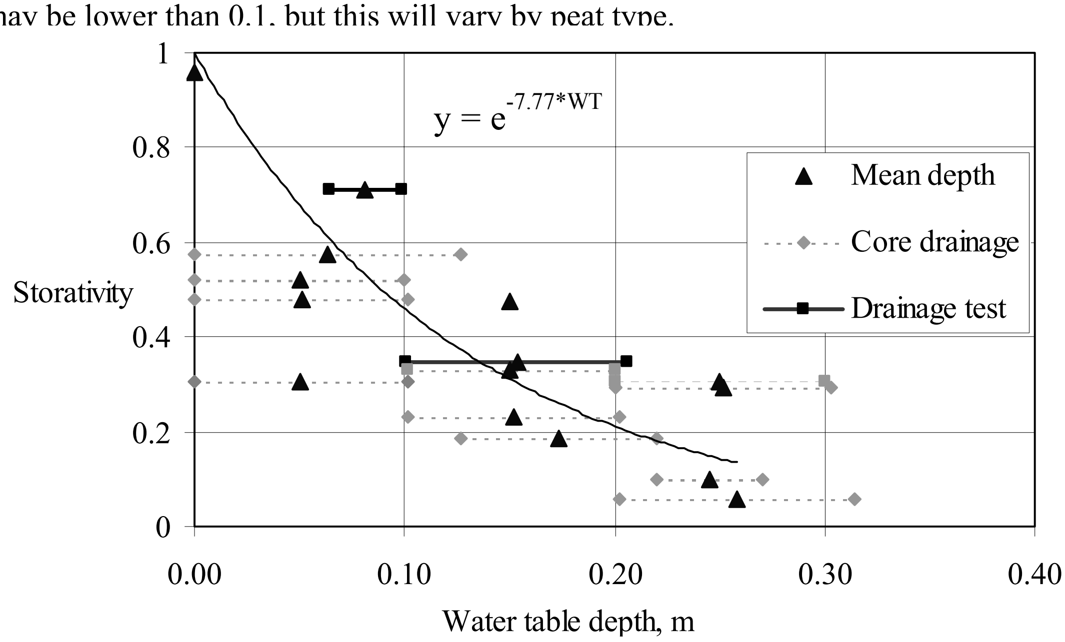

Figure 2.5-4 Estimates of storativity with depth of the water table determined with core drainage tests from edge, ridge and swale sites, and the enclosed large-scale field drainage tests

The storativity as a function of water table depth, measured with core laboratory drainage tests and a large-scale field drainage test is given in the following equation.

$$S = 1.0e^{-7.77*(WT)} \qquad (2.20)$$

In this equation, WT is the depth of the water table below the fen surface. This relationship is only applied to the upper 0.4 m of relatively fibrous peat. At water table depths greater than 0.3 m, the exponential equation may underestimate values of storativity, however additional repitions are required to verify this. This equation may be obtained in other sites through the use of relatively simple field or laboratory tests, and is expected to be similar in other fen sites. The surface of the peat represents the measured average surface of the cores or field enclosures. This equation is used in Chapter 3 to predict the amount of water retained in the unsaturated zone above the water table. Integration of the trend line in Figure 2.5-4 gives the volume of water yielded for a given change in the water table.

2.5.2 Results from field methods

2.5.2.1 In-situ drainage test

In order to estimate the storativity, a drainage test was conducted in a large-scale closed column test while the fen was still thawing in the spring of 2003. Observations of water levels inside and outside the enclosure were always different, confirming that the saturated frost layer within the peat was impermeable. Storativity calculated in Equation 2.21, is the total volume of water discharged (ΔV_w), divided by total volume of peat drained (V) defined by the water table decline.

$$S = \Delta V_w / V \qquad (2.21)$$

The discharge rate of water was measured using buckets of known volume. Total discharge from this upper peat layer was 0.0648 m^3, while the area of the enclosure was 1.77 m^2, and the change in water table was 0.105 m. Therefore, storativity was 0.349, over the water table change of 0.101 to 0.206 m (Figure 2.5-4).

During the drainage test, subsidence was measured at four points. By the end of the drainage test, the peat surface had subsided an average of 0.009 m. Compressibility [Pa^{-1}] of the acrotelm was determined from the drainage test data using the formula shown in Fetter (1994).

$$\alpha = \frac{\Delta z / b}{\rho_w g \Delta h} \qquad (2.22)$$

In this formula; Δz is the mean subsidence of 0.009 m, b is the thickness of the compressing layer measured as 0.4 m, and $\rho_w g$ [kg/m^2s^2] is the density of water times the acceleration of gravity, and the change in head (Δh) is 0.105 m. Compressibility was calculated to be 2.2 x 10^{-5} Pa^{-1}. Calculation of specific storage was then estimated using following formula:

$$S_s = \rho_w g(\alpha + n\beta) \qquad (2.23)$$

where, β is the compressibility of water of 4.485 x10^{-10} m^2/N, that is negligible, and n is the porosity. From Equation 2.23, specific storage (S_s) was determined to be 0.214 m^{-1}. As the specific storage and specific yield together contribute to total storativity, an estimate of specific yield was made from calculated storativity and specific storage. The specific yield was estimated as 0.263 by subtracting the specific storage multiplied by depth of the compressing layer from the storativity (Equation 2.1).

A reverse filling experiment; where a measured volume of water is added to the confined peat and the response of the water table monitored will allow patterns of hysteresis in storage properties to be evaluated. Enclosed drainage tests may also be feasible when there is no impermeable frozen layer if the lower peat has sufficiently low hydraulic conductivity. A preliminary test for fully thawed peat gave promising results, but further evaluation of the method for such cases is needed.

2.5.2.2 Pumping test bulk water storage

Storativity is often evaluated from pumping test analyses such as Theis (1935), and was attempted here using the Aron-Scott (1965) and Cooper-Jacob methods. A means of estimating storativity is built into many pumping tests analysis methods, although they produce errors of 20 to 30% even if all conditions of the equations are met (Kruseman and de Ridder, 1970). Storativity results from observation wells 0.15 and 0.3 m away from the pumping well were greater than 1.0, and physically impossible. This inconsistency is due to relatively high drawdown near the well, so results from any observation wells closer than 1.0 m were discarded. Even with this limitation, storativity results were variable and somewhat inconsistent between tests, ranging from 0.03 to 0.6.

The ratio of discharge to the total volume of peat drained by the pumping tests was used to calculate the storativity; this is called the volume-balance method (Nwankwor et al., 1984). Discharge rate was measured regularly during the 24 hour pumping test initiated July 31, 2003 at the Fen Centre site. Total volume of discharge from the pumping test was evaluated with use of the exponential formula of discharge rate versus time. This was integrated over the pumping test duration to determine total volume of water pumped from the peat, which was only 6.20 m^3.

The volume of the drawdown cone was determined with integration of a semi-log distance-drawdown plot. However, this calculation was done by calculating the separate volumes of a large number of cylinders above the drawdown cone, further and further from the well. With a radius of influence estimated to be 26 m, the majority of the water pumped was from the outermost edges of the drawdown cone (and possibly beyond). The total volume of peat drained during the July 31, 2003 pumping test was 11.51 m^3. The volume-balance method storativity was calculated as 0.54 and 0.56 for the two pumping tests at the Fen Centre site in 2003. Nearly 98% of total discharge was removed from the peat layer 0.05 m thick below the initial water table. Initial water table depths for the July 31 and August 8, 2003 tests were 0.119 and 0.136 m, respectively. These storativity results are somewhat higher than those obtained from the drainage tests (Fig. 2.5-4). Problems with the volume-balance method involve the assumption that all the water discharged during the pumping test was removed from the drawdown cone volume within the acrotelm, and that there is no water contribution by upward vertical flow from below the acrotelm. This may explain the high value of storativity obtained from the pumping tests.

2.5.2.3 Slug tests

Slug tests were conducted from mid-summer to freeze-up in the end of October, 2003. In total, over 50 slug tests were completed in shallow (0.5 and 1.0 m) piezometers at the Fen Centre site. Recovery of static water levels usually occurred within a few minutes. Semi-log plots of the ratio of falling head to initial head over the period of recovery were usually straight lines, with some variation between tests (Figure 2.5-5).

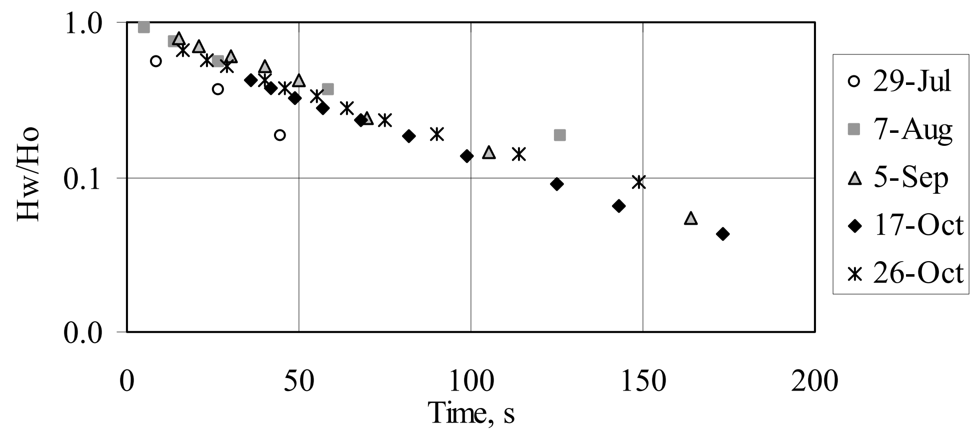

Figure 2.5-5 Piezometric head recovery for falling head slug tests repeated over the summer of 2003 for piezometer N1/1 with its intake at 1.0 m depth below the surface

Both Bouwer and Rice (1976) and the Hvorslev (1951) methods were used to generate hydraulic conductivity results. Comparison of the two methods shows that the Bouwer and Rice method gives slightly lower values and slightly smaller standard deviations (Figures 2.5-6 and 2.5-7). These results are based on 19 different slug tests in peat at 0.5 m depth, and 32 different slug tests at 1.0 m depth. Median hydraulic conductivity at these depths is 4.27 x 10^{-5} m/s and 6.11 x 10^{-6} m/s based on all tests. The distribution of hydraulic conductivity results was positively skewed by a factor of 0.6 and 1.2 for the two depths, respectively. The median hydraulic conductivity value of peat at 2.0 and 3.0 m depth was 4.87 x 10^{-7} m/s.

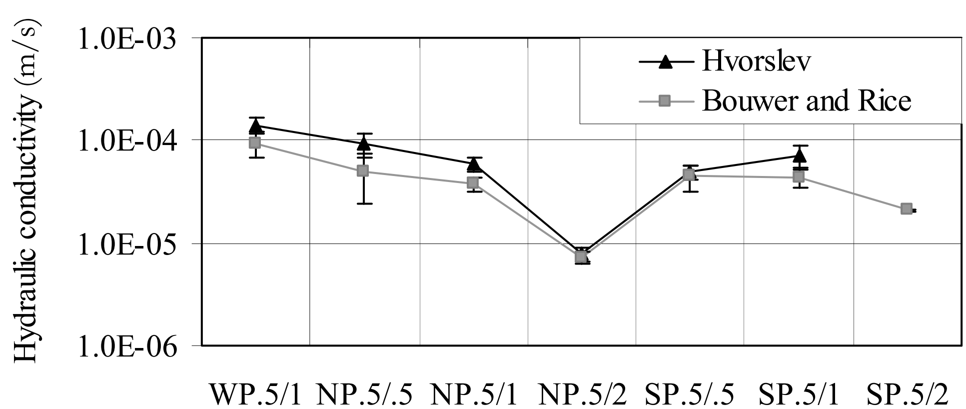

Figure 2.5-6 Mean and standard deviation of hydraulic conductivity in peat at 0.5 m depth

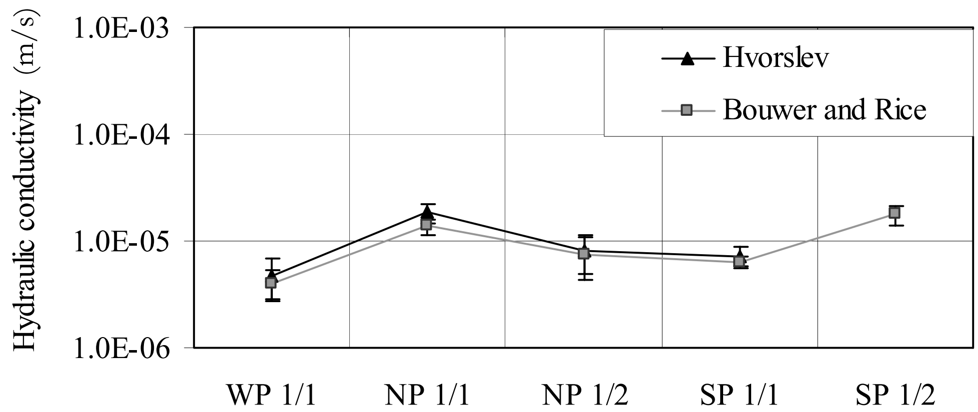

Figure 2.5-7 Mean and standard deviation of hydraulic conductivity in peat at 1 m depth

The mean hydraulic conductivity of all the tests done at each piezometer in 2003 is shown in Figure 2.5-8. The measured hydraulic conductivity decreases from the surface to a depth of about 2 m in the peat. There is some spatial variability of hydraulic conductivity at the Fen Centre site, which covers ridge and swale topography. The piezometer (NP .5/2), located in the ridge, consistently had lower hydraulic conductivity than the other piezometers at the same depth (Figure 2.5-6).

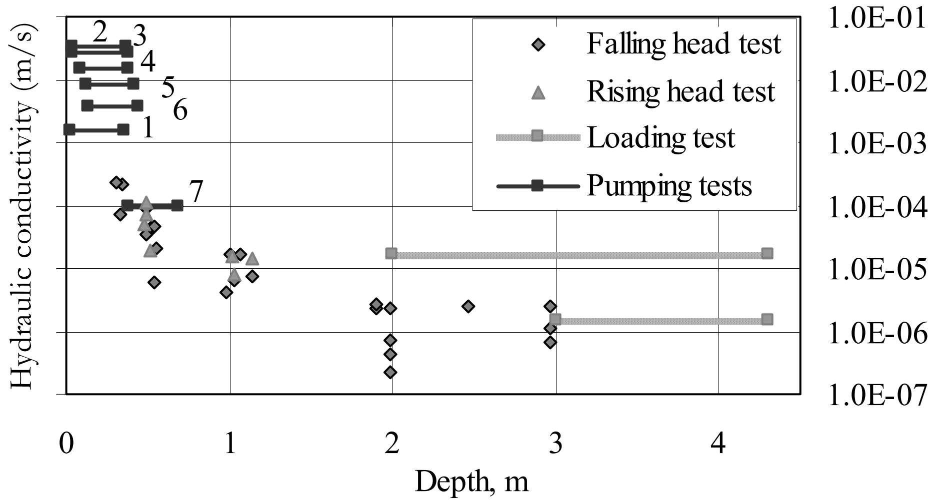

Figure 2.5-8 Mean hydraulic conductivity of pumping tests (number 1 through 7), mean slug test hydraulic conductivity of each piezometer from falling head tests, and the estimated range of vertical hydraulic conductivity from the loading test

Recent studies have shown a significant difference in hydraulic conductivity results from rising and falling head tests (Baird et. al., 2003). A series of rising and falling head tests were done in 2004 on a set of piezometers to compare the hydraulic conductivity values of the two methods. Rising head tests had 38% higher hydraulic conductivity values than falling head tests for piezometers at 1.0 m depth. Even with only five pairs of rising and falling head tests compared, bias is clearly indicated (Figure 2.5-9). In the 0.5 m deep piezometers, the mean hydraulic conductivity from rising head tests was 21% higher than for falling head tests, with 6 pairs of data.

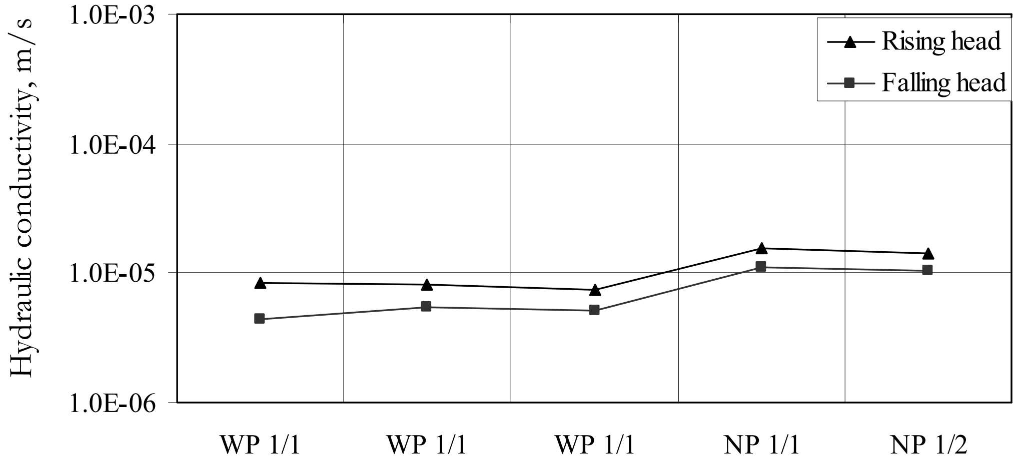

Figure 2.5-9 Hydraulic conductivity results using Bouwer and Rice (1976) comparing rising and falling head tests

To determine if the mean hydraulic conductivity was significantly different for rising versus falling head tests, the data was analyzed with the Wilcoxin test, which is commonly used with non-normally distributed paired data (McGee, 1985). The first step of the Wilcoxin test was to combine samples from both populations and rank them in ascending order. The sum of the ranks was computed, and the smaller of the two numbers used as the test statistic. As the test statistic was greater than the critical value for the 1.0 m depth slug test results, rising head results were significantly higher than falling head results. The differences between rising and falling head results were not significant at 0.5 m depth in the peat. These results had a 90% probability of being true with the alpha probability parameter equal to 0.05 (The higher the alpha, the lower the certainty). No comparisons were made of rising and falling head tests in piezometers at 2 and 3 meter depths. It is probable that the results produced by tests in catotelm peat below 1.0 m will also be sensitive to the slug test method.

The influence of the flushing method of development in piezometers was also tested using the Wilcoxin test. Developing piezometers with the flushing method caused 25% slower response times in the slug tests. However, the mean of 6 pairs of “developed” versus “not developed” samples were not significantly different with the alpha parameter equal to 0.05, using a two-tailed test.

2.5.2.4 Pumping tests

Over the winters of 2003 and 2004, the peat froze to depths of over 0.5 m. Pumping and observation wells were installed from the surface of the thawing peat to the frost table. In early June, thaw had occurred to depths of 0.25 to 0.4 m over most of the fen surface. Due to the conditions of this frost table, the water table was perched from the beginning of April to the middle of June.

Pumping tests were completed at two sites in the fen in June, 2003 using the frost table as a lower confining layer. Figure 2.5-10 shows lateral flow to a pumping well with the frost table as an impermeable barrier in the peat. The tests were repeated at the same or nearby sites in July and August, when the peat was finally thawed. The repetition of pumping tests with and without a confining layer was a good test of the feasibility of the method in measuring transmissivity of the upper peat layer.

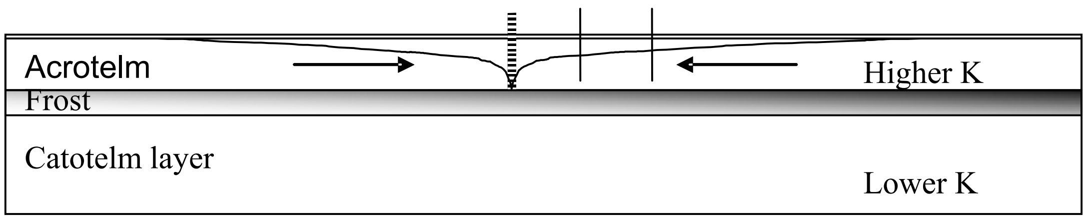

Figure 2.5-10 Diagram of flow to a well above the thawing frost table

There were several unique characteristics of pumping tests in this environment. The effective permeable zone that transmits water to the pumping well is thin – limited to the upper 0.4 m. This is due to the decrease of hydraulic conductivity with depth in the peat. In order to avoid pumping the water table down into the peat with lower hydraulic conductivity, the depth of the pump intake was set. Thus the pumping tests were constant-drawdown tests, instead of the more common constant pumping rate tests with increasing drawdown in the pumping well. The magnitude of drawdown in the observation wells was very small (0.1 m) compared to pumping tests in mineral soils. Compression of the peat was measured in several of the tests as water was pumped from the upper peat layers.

All of the pumping tests in Sandhill Fen had decreasing discharge rates over time. Figure 2.5-11 illustrates the decreasing discharge rates over time during the June 10 and July 16, 2003 tests at Transect 2 site. This may be an artifact of the decrease of peat hydraulic conductivity with depth below the surface, and the lowering of the head in the pumping well.

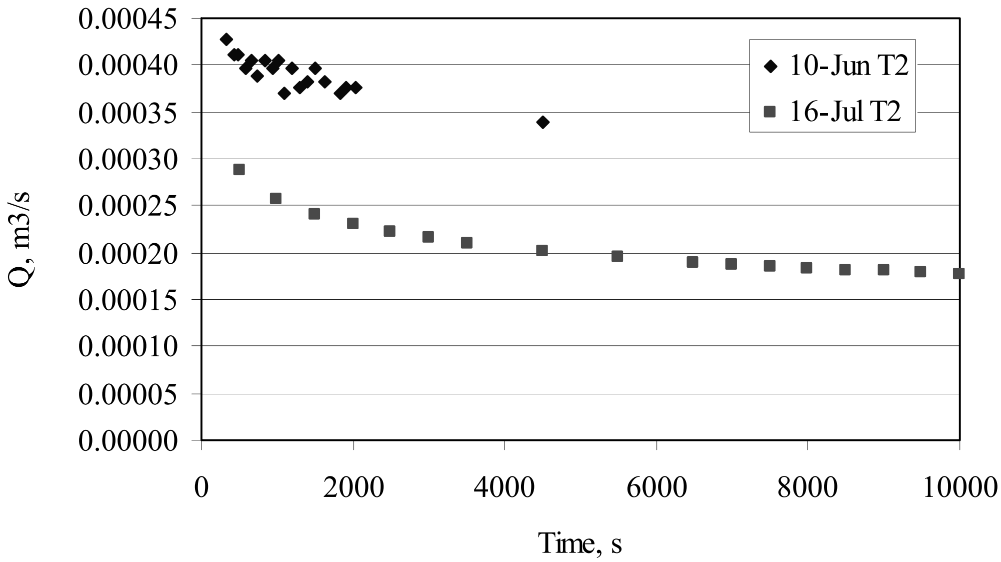

Figure 2.5-11 Decreasing discharge rates measured during pumping tests on June 10 and July 16, 2003 at the Transect 2 pumping site

The Thiem quasi-steady state (In Fetter, 1994), Cooper- Jacob Distance-drawdown (In Kruseman and de Ridder, 1970) and Aron-Scott (1965) methods were used to analyze the pumping test drawdown data.

The Aron-Scott (1965) method assumes declining discharge over time, and transient unconfined or confined flow. It is a simplified version of the analytical and graphical solutions developed by Abu-zied and Scott (1963) and Hantush (1964), where changes in discharge followed certain mathematical time-distance relationships. Shown in Figure 2.5-12, the Aron-Scott method plots the ratio of drawdown to discharge against time. Each piezometer is labeled according to its distance from the pumping well. The assumption that well storage can be neglected was verified by observations that the pumping wells were pumped dry or to a steady level within two minutes, and drawdown data was only recorded after this time.

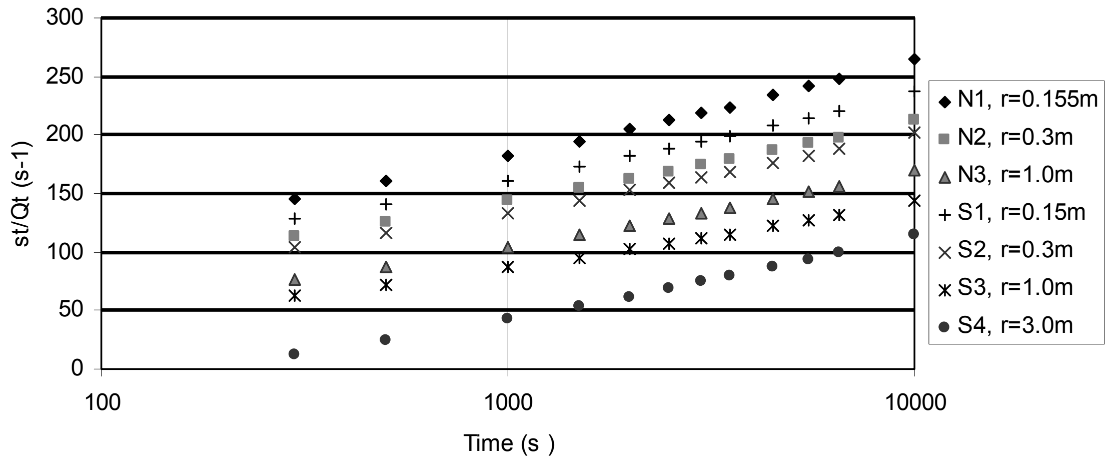

Figure 2.5-12 Aron-Scott (1965) method showing the ratio of drawdown to discharge versus time after pumping began on June 10 at the Transect 2 site

For pumping tests affected by evapotranspiration or atmospheric pressure changes, it would normally be necessary to make corrections to drawdown data. An alternative approach used in this study was to apply methods of analysis to the drawdown data that did not require these corrections. The difference in drawdown over time is uniform in observation wells as shown by the data for wells W1 and W2, located one meter apart, for a 24 hour pumping test completed at the Fen Centre site (Figure 2.5-13). Therefore the Thiem and Distance-drawdown methods could be applied to the data, as it gives results dependent on the difference in head at pairs of observation wells.

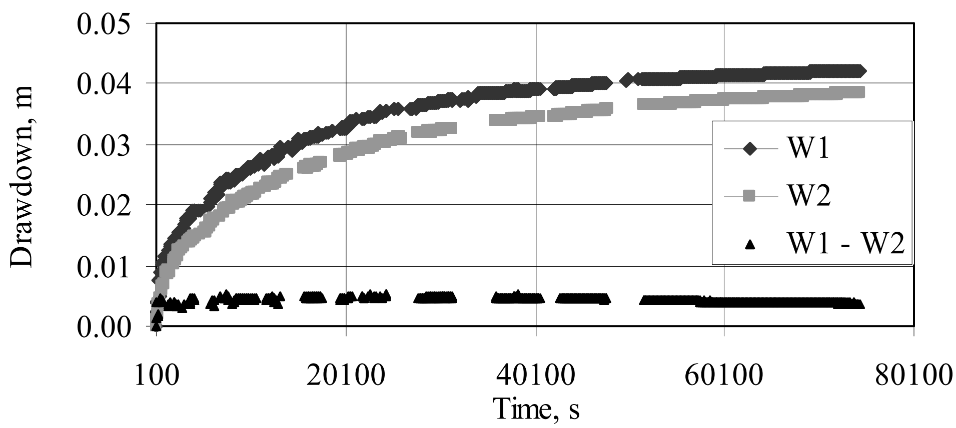

Figure 2.5-13 Drawdown in observation wells 1.0 and 2.0 m from the pumping well, assuming constant static water level, and the difference in drawdown of W1 and W2, recorded with Geocon^{TM} vibrating wire pressure transducers during the 24 hour pumping test on July 31, 2003 at the Fen Centre site

The use of Thiem and Cooper-Jacob Distance-drawdown methods eliminates the need for making corrections to the drawdown data for evapotranspiration or barometric pressure changes. The distance versus log-drawdown plot for a test on June 3, 2003 shows uniform slopes from 1000 s to 5,000 s, that indicates the robustness of the method (Figure 2.5-14). The results were obtained from data from five observation wells at the Edge site pumping test.

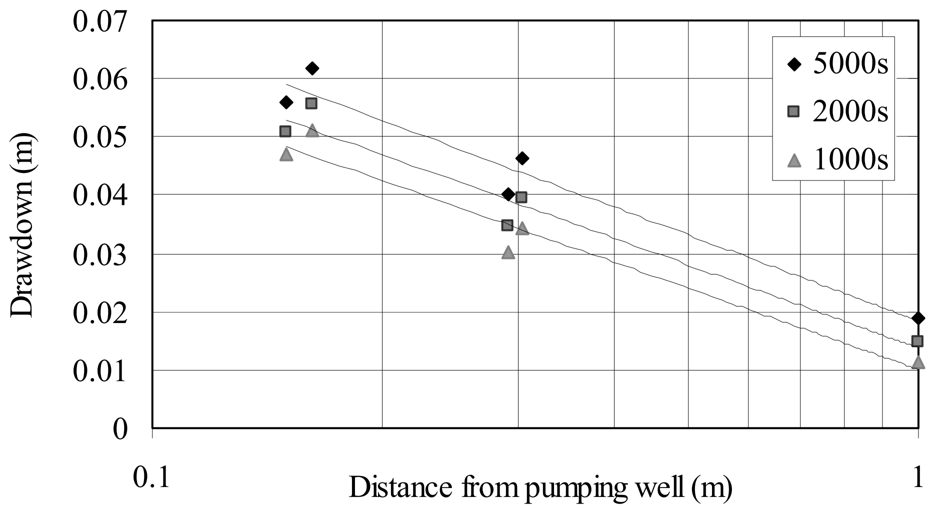

Figure 2.5-14 Distance versus drawdown of five observation wells, at three points in time, during a pumping test on June 3, 2003

Information describing the pumping tests completed at Sandhill Fen is shown in Table 2.5-3. Transmissivity results are from the Distance-drawdown method. Measurements of pumping rates and drawdown data for all the tests are presented in Appendix B. For early tests (numbers 1 to 3) above frozen peat, the saturated depth above the frost table of 0.35, 0.37 and 0.38 m, respectively, were used to calculate the hydraulic conductivity. For tests 4 through 7 in thawed peat, the entire saturated thickness of peat could not be used to calculate the hydraulic conductivity from transmissivity results, as this was not the layer of peat contributing water to the pumping well. An effective saturated thickness of the peat of 0.3 m was used instead of the total peat thickness to calculate the hydraulic conductivity. It was assumed that this upper 0.3 m thick layer of peat is contributing water to the pumping well. Mean hydraulic conductivity results from individual pumping tests using the Distance-drawdown method are compared with slug test results in Figure 2.5-8.

Table 2.5-3 Details of pumping tests in the 2003 season and Distance-Drawdown transmissivity results

Test no.	Location	Date 2003	Duration (hours)	Frost depth (m)	Discharge Rate @ end (m^3/s x10^{-4})	WT depth (m)	T mean & stdev (m^2/s x10^{-4})	K (m/s x 10^{-4})
1	Edge	June 3	1.5 h	0.35	0.9	0.040	4.8 + 0.15	15
2	T2	June 3	0.8 h	0.37	0.83	0.04	86 + 1.3	261
3	T2	June 10	3.3 h	0.4	3.4	0.028	88 + 3.1	260
4	T2	July 16	3.0 h	Thawed	1.75	0.067	56 + 5.5	186
5	Centre	July 31	25 h	Thawed	0.6	0.119	30 + 4.5	100
6	Centre	Aug 8	3.5 h	Thawed	0.58	0.136	17 + 1.8	56
7	Edge	Aug 13	3.3 h	Thawed	0.0066	0.384	0.34 +0.008	1.1

On June 3, 2003, pumping tests were completed at the Edge site (no.1) and site T2 (no.2). While the water table was at a similar depth below surface at both sites, drawdown in observation wells at the Edge site was much greater, suggesting much lower transmissivity at this site. Testing at site T2 was repeated the following week (no. 3) with a higher-volume pump. Distance-drawdown results from June 3 and June 10, 2003 confirmed that mean transmissivity was an order of magnitude higher in peat near the centre of the fen (8.8 x 10^{-3} m^2s^{-1}) than at the Edge site (4.8 x 10^{-4} m^2s^{-1}).

Mean transmissivity results for pumping tests numbered 1 and 3 through 7 are compared in Figure 2.5-15. Results from three methods are shown: Thiem's (1906) confined steady state method, Aron-Scott's (1965) transient unconfined method, and the Cooper-Jacob Distance-drawdown method. The Distance-drawdown method gives transmissivity results that are consistently higher than the other methods. The low standard deviation of the transmissivity results indicates that the results are nearly uniform. Over the summer, the water table dropped into peat with lower hydraulic conductivity. This caused the transmissivity to decrease with each pumping test.

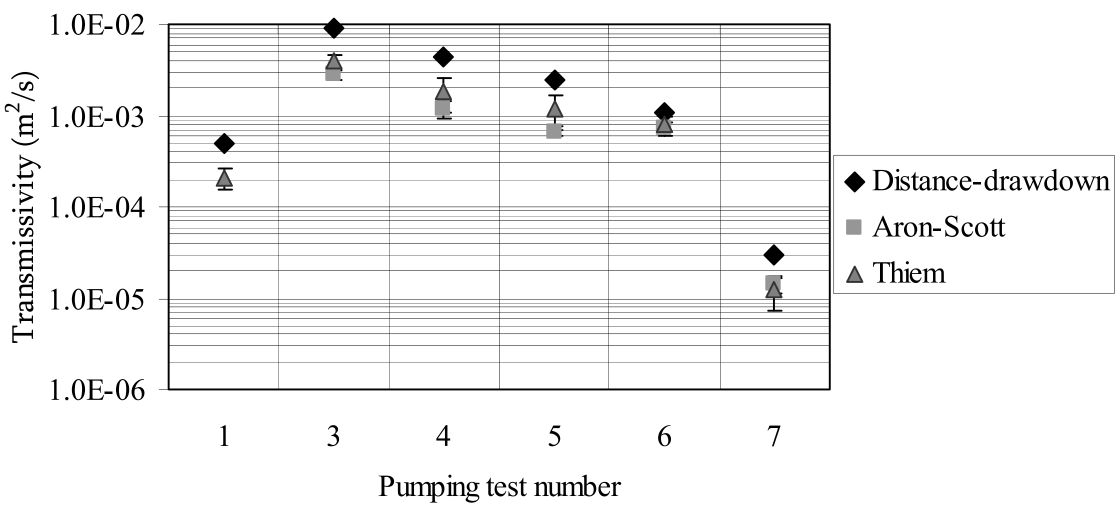

Figure 2.5-15 Mean pumping test results for Sandhill Fen peat using three methods

Anomalous piezometric head readings at depth in the peat were observed during pumping tests in thawed peat. Drawdown measured in deep piezometers at depths of 3.0 m showed the same response as wells at the surface. Raw vibrating wire pressure transducer data for a 24 hour pumping test is shown in Figure 2.5-16, for a surface well and a 3 m deep shut-in piezometer. These were both located 1.0 m from the pumping well. Despite some lag in the head response, the magnitude is similar. The influence of daily evapotranspiration and possibly daily temperature effects is shown in this figure. The numerous transient peaks in water levels are an artifact of apparent mechanical loading by an observer.

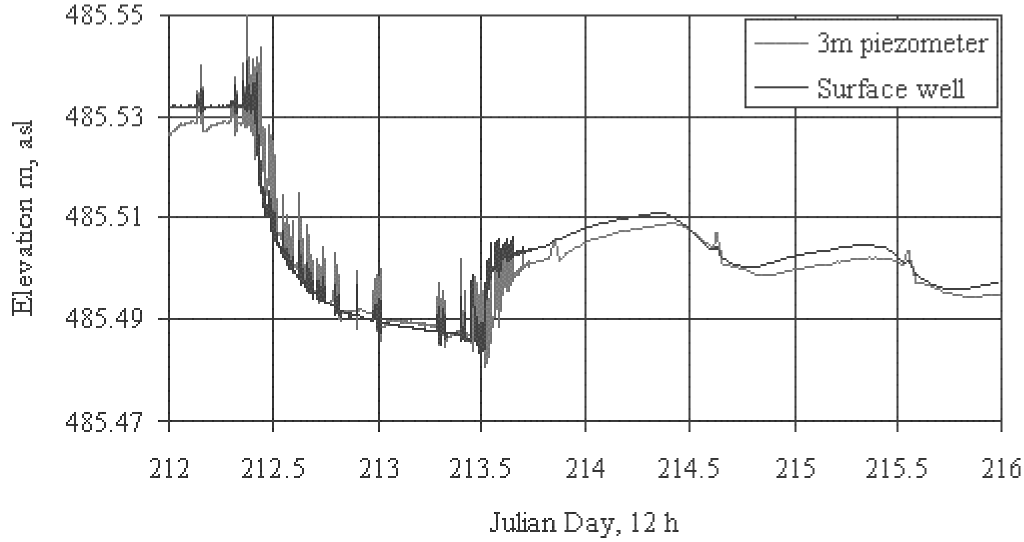

Figure 2.5-16 Vibrating wire pressure transducer data during and following the 24 hour pumping test for a surface well and a 3 m deep piezometer at the Fen Centre site

Strain gauges were installed at different depths at the Fen Centre site to estimate compressibility using short-term pumping tests. These gauges were constructed in a similar manner to those described by Price (2003). Although these strain gauges (elevation sensors) did measure subsidence of the peat during the pumping tests, these movements were on the scale of millimeters. Measurements of vertical elevation sensor movement with the laser level were limited by an accuracy of 2 mm under ideal conditions. The small water table drawdown during the pumping tests induced only slight changes in effective stress. Due to these factors, compressibility was not estimated based on pumping test induced changes in stress and strain.

2.5.2.5 Loading test

The loading test estimated hydraulic diffusivity and vertical hydraulic conductivity over the depth of low hydraulic conductivity peat. When a load was applied, shallow observation wells W1 and W2 showed an instant increase in piezometric head. Figure 2.5-17 shows the piezometric head of the closed piezometers and wells six hours prior to and throughout the loading test. In the low hydraulic conductivity layer there was a slow recovery (called the un-drained response), as the piezometric head was elevated for a longer period of time. Drainage from this layer would have occurred upwards into more permeable peat, and downwards into underlying substrate sand. Dissipation of piezometric head took over 2.5 hours in the two closed piezometers screened at 3 m depth.

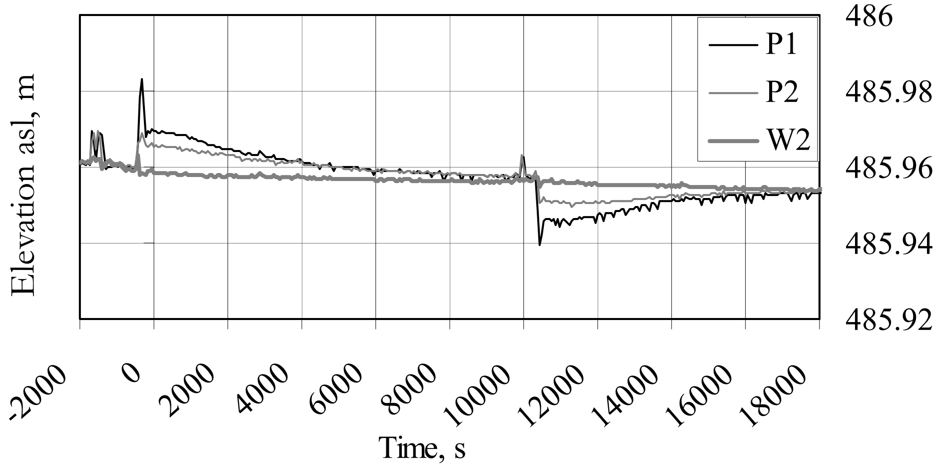

Figure 2.5-17 Vibrating wire pressure transducer data for two 3 m deep packed piezometers 1 m and 2 m from the centre of the applied load, and for the surface well 2 m away, September 21, 2004

The exponential decline of piezometric head after loading was accurately measured in the two closed piezometers. There was some noise in the datasets due to the high frequency of measurements (every minute) that was smoothed by taking the average of three data points, so that each point in time represented the average pressure over three minutes. The head in a surface well (W2) was subtracted from the piezometric head in piezometers P1 and P2 (Figure 2.5-17), to get the change in head imposed by loading. The well (W1) one meter from the center of the load was not used to correct the piezometer P1 because the slope of the loading phase over time was different than that of the unloading phase.

The change in piezometric head from static conditions was plotted versus time on a semi-logarithm chart (Figure 2.5-18). The negative slope was equivalent to -4.286/ τ (van der Kamp and Maathuis, 1985). Slopes of the two head versus time curves were similar for the closed piezometers. Inserting the slope of the lines into Equation 2.6.1 resulted in characteristic response time values of 19,000 s for P1 and 17,900 s for P2.

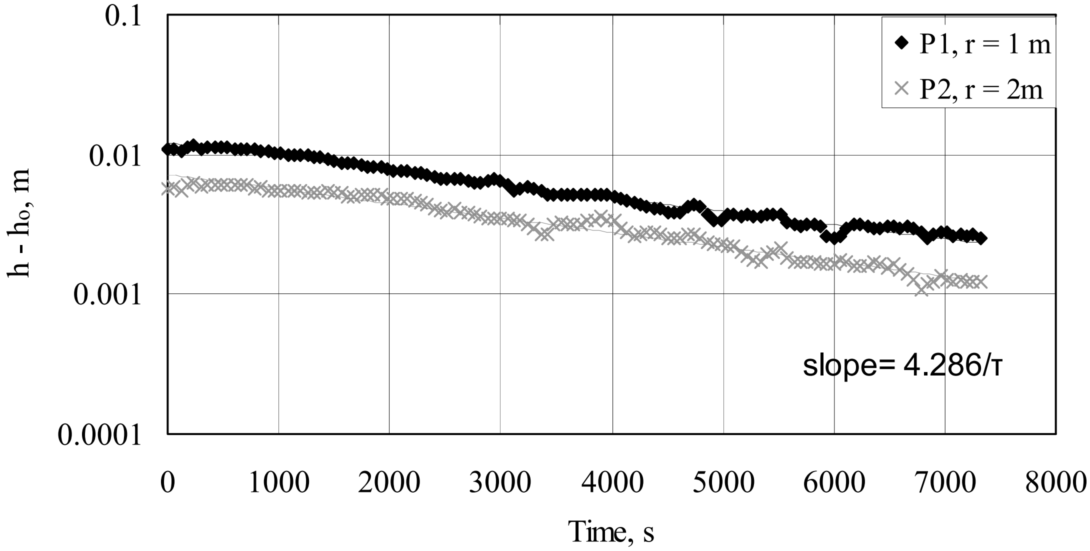

Figure 2.5-18 Change in log-head over time in closed piezometers at three meter depths after loading

In order to calculate the hydraulic diffusivity (Kv/Ss), the characteristic response times (τ) and estimated thickness of the low hydraulic conductivity peat (D) was required. The characteristic response times were calculated from the slope of the lines in Figure 2.5-18 (Equation. 2.17). At the time of the loading test, peat at the Fen Centre site was 4.4 $\pm$ 0.1 m thick. The thickness of the low hydraulic conductivity peat was defined by comparing test results from the slug tests at depths of 0.5, 1.0, 2.0 and 3.0 m. The upper boundary of this layer was assumed to be between 1.0 and 3.0 m, while the lower boundary was the substrate sand. Given that slug test hydraulic conductivity results decreased an order of magnitude between 1.0 and 2.0 m depth, it was more likely that the upper boundary was at least 2.0 m deep.

The hydraulic diffusivity is smaller when the smaller thickness was assumed. The thickness of the low hydraulic conductivity peat was assumed to have an upper limit of 2.0 or 3.0 m depth below the peat surface. Mean hydraulic diffusivity ranged from 0.00030m^2/s to 0.00032m^2/s with D representing the layer from 2.0 m depth to the substrate sand (D = 2.4 m). Hydraulic diffusivity was 0.00011m^2/s when D represented the 3.0 m depth to the sand (D = 1.4 m).

In order to calculate vertical hydraulic conductivity the specific storage of the deep peat was needed. While the subsidence of the peat at depth was measured before and after the load test, it was only measured at two points. An independent estimate of specific storage was used based on compressibility determined from seasonal subsidence described in Chapter 3. Specific storage of the 2.0 to 3.0 m peat layer was 0.052 m^{-1}, and it was 0.014 m^{-1} from 3 m of depth to the substrate sand. Using these values, the mean vertical hydraulic conductivity ranged from 1.5×10^{-6} to 1.6×10^{-5} m/s, using a D value of 1.4 m and 2.4 m, respectively. Estimates of hydraulic diffusivity and vertical hydraulic conductivity results are compared above in Table 2.5-4.

Table 2.5-4 Estimates of hydraulic diffusivity (Kv/S_s) and vertical hydraulic conductivity of Fen Centre site peat

Piezometer	Slope	T (s)	D (m)	K_v/S_s (m^2/s)	S_s (m^{-1})	K_v (m/s)
P 1m	-0.000226	18,900	2.40	0.00030	0.052	1.59E-05
P 2m	-0.000239	17,900	2.40	0.00032	0.052	1.68E-05
P 1m	-0.000226	18,900	1.40	0.00010	0.014	1.49E-06
P 2m	-0.000239	17,900	1.40	0.00011	0.014	1.58E-06

The estimated thickness of the low hydraulic conductivity layer and also the specific storage influenced vertical hydraulic conductivity results. Increasing the specific storage from 0.0144 m^{-1} to 0.052 m^{-1} will increase estimates of vertical hydraulic conductivity by 114%. Figure 2.5-8 shows depth integrated results from the pumping tests, slug tests and loading test. Probable limits of vertical hydraulic conductivity are represented by the four loading test points in the figure. The results suggest that the vertical hydraulic conductivity is greater than or similar to horizontal hydraulic conductivity.

2.6 Discussion and Conclusions

2.6.1 Peat properties

There are significant differences of physical properties between sites in the fen, as predicted by morphology, vegetation zones and peat depth. Results from the coring of swale, ridge and edge sites show that swale sites have significantly higher porosity and lower bulk densities. Swales have more homogeneous peat qualities, that are matched by their more uniform topography.

The patterns of hydraulic properties with depth are similar to those previously described in the literature. The variation of hydraulic characteristics with depth is important to hydrological modeling (Bradley, 1996). Porosity and storativity decrease with depth in the peat. Bulk density results were comparable to previous studies at the site, increasing with depth below the surface. Results from Sandhill Fen were compared to a classification of peat qualities by Letts et al. (2000). Depending on which hydraulic parameter is used, the upper 0.5 m layer of Sandhill Fen peat could be classified as either fibric or hemic peat, when compared to the classification given by Letts et al. (2000).

It has been observed elsewhere that the volumetric water content of saturated peat is somewhat less than its porosity (Quinton and Hayashi, 2004), though this may be an artifact of the methods used on cores. All peat core removed from the fen was measured to have volumetric water contents 5 to 15% less than porosity. It is possible that some of the water drained from the bottom of the unfrozen saturated peat cores as they were being removed from the fen. Another possibility is the existence of trapped gases in both frozen and unfrozen peat, that prevents complete saturation with water.

Other studies have directly or indirectly measured gas content within saturated peat to be 5 to 10% (Beckwith and Baird, 2001), 9% (Reynolds et al., 1992), and 9 to 13% of the total peat volume (Rosenberry et al., 2003). Gas bubbles, mainly composed of methane are produced by anaerobic decomposition in saturated peat (Reynolds et al., 1992; Price, 2003). These interstitial gases have an impact on the hydraulic properties measured in the field and in the laboratory (Price, 2003), reducing the hydraulic conductivity (Reynolds et al., 1992; Beckwith and Baird, 2001), storage coefficients (Rosenberry et al., 2003), and influencing peat volume in the field (Price, 2003). Kellner et al. (2004) showed that zones of excess pore-water pressure may deflect groundwater flows driven by hydraulic gradients.

While the volumetric water content of Sandhill Fen peat near the water table was less than its porosity, the effect of this gas volume on the results from field tests is not certain. Transmissivity and storage properties of the upper peat measured with pumping tests likely characterized peat containing free-phase gas. There was no obvious evidence of over-pressuring of the peat by free-phase gas content, observed in data from vibrating wire pressure transducers installed in closed piezometers through the summer and fall of 2003. For example, Figure 2.5-16 shows no anomalous piezometric head measurements at depth in the peat over a period of four days. The occurrence and ebullition of free-phase gas occupying water conducting pores may reduce hydraulic conductivity (Beckwith and Baird, 2001; Rosenberry et al., 2003; Price, 2003). This study also didn't observe large ebullition events through the monitoring of the peat surface movements.

2.6.2 Water storage

Storage properties influence such processes as the water table response to rainfall events, the seasonal soil moisture regime, and therefore also the rate of evapotranspiration. Drainage tests done with Sandhill Fen peat mimic the range of negative pressure created by natural water table fluctuations. The majority of water is drained within 24 hours from an imposed water table change, although slow and intermittent drainage may continue for weeks. Price and FitzGibbon (1987) performed specific yield tests on peat that ended after 24 hours. The results in this study are comparable to those in the literature which impose suction values from atmospheric pressure to 1.0 m (.01MPa) to estimate specific yield (Boelter, 1968; Letts et al., 2000). Under natural conditions, water tables in fens rarely experience negative pressures of 1 m.

Combining field and lab drainage tests to determine storage properties offers a solution when volumetric water content data are lacking. The retention of water increases with depth in the peat. These storativity results will be used in Chapter 3 in estimating the volume of water retained in peat above the water table. The relationship of water table depth and storativity described here is limited to water table depths of less than 0.4 m below the surface. While these results were expected to be heterogeneous, more certainty may be obtained by additional drainage tests, and will be strengthened by future water retention results attained by pressure plate tests.

Field scale tests of storativity have the advantage of representing a large volume of peat. Field drainage tests are viable if the existence of a lower confining layer can be confirmed. By lowering the pump intake incrementally below the static water level, a storativity with depth relationship could be established. Reverse experiments where a measured volume of water is added to the enclosure will allow any patterns of hysteresis in storativity to be identified. During a preliminary filling test in thawed peat on July, 2003, leakage out of the base of the enclosure was quite slow. With further testing it is possible that enclosed drainage or filling tests may be useful tools to assess storativity of the upper peat.

By measurement of total vertical volume changes of the peat with drainage or filling tests in the field, the specific storage component could be estimated. The compressibility of 2.2×10^{-5} Pa^{-1} measured with this method was similar to an independent estimate from seasonal compression of the fen. From this experiment, the specific yield of the peat in the field enclosure was 0.26, which fits well with the range of results from laboratory drainage tests on cores. This specific yield value matches Boelter's (1968) values for hemic peat as presented in Letts et al. (2000).

Storativity results with the volume balance method were significantly higher than field and laboratory results for the same depth of the water table. Although drawdown was measured in a large number of observation wells, there was still difficulty in estimating the radius of influence. Estimation of the volume of the drawdown cone is dependent on having enough data far from the well. Contributions from the capillary fringe layer are accounted for with this method, although these will be more important in more highly decomposed peat. With pumping tests performed in thawed peat there is potential for vertical upward flow to the pumping well. Any leakage from below would increase discharge and produce higher storativity estimates. Therefore the volume-balance method associated with pumping tests in thawed peat is not recommended.

The enclosed drainage test could generate storativity for the peat from the water table to the depth of the frost. Estimating storage from the results of pumping tests required calculation of the volume of peat drained and total discharge. Only if there were several observation wells far from the pumping well could a reliable logarithm-distance-drawdown plot be generated. If the frozen peat isn't deep enough to hold a perched water table for a significant amount of time the in-situ test of storativity won't be feasible.

2.6.3 Slug tests

Slug tests were used in characterizing the hydraulic conductivity of the deeper, less conductive peat. Slug test methods require the piezometer intakes to be a certain depth below the surface for the results to be valid (Dawson and Istok, 1991). The hydraulic conductivity is so high in the upper 0.3 m of peat that it is nearly impossible to measure the hydraulic conductivity by this method. Hydraulic conductivity decreases with depth by at least three orders of magnitude; from 10^{-4} at 0.3 m depth to 10^{-7} m/s at a depth of 2.0 and 3.0 m. Results varied between piezometers due to the expected spatial variability of peat properties, and were somewhat less variable for repeated tests in individual piezometers.

Slug tests are much more problematic than pumping tests with regard to susceptibility to disturbance or clogging of the screens. More care must be taken to ensure that the peat around the screens will be representative of the undisturbed peat surrounding it. Both compression of the peat and gaps created near the screens will cause the hydraulic conductivity of the piezometer tests to be misrepresented. Piezometer installation by augering holes may also cause disturbance of the original peat structure. There was no significant effect of developing the piezometers by flushing water in and out of the intakes. Clymo (2004) and Baird et al. (2004) also found inconsistent results from bailing water out of piezometers in preparation for slug tests.

There was no significant difference between falling and rising head slug tests in the shallow piezometers at depths of 0.5 m. However, this study found falling head tests gave significantly lower hydraulic conductivity results than rising head tests for the piezometers screened at 1.0 m depth. Even this significant difference didn't have as noticeable an effect on the general trend of hydraulic conductivity with depth as did spatial variability. These same effects would be conceivable in the peat at 2.0 and 3.0 m, but this possibility wasn't tested.

The peat subsided during the summer and fall of 2003, during which time a series of slug tests was conducted. There was no obvious decrease in hydraulic conductivity in the peat in the slug tests repeated over this period. Compression of the peat may also influence the recovery rate during a slug test (Baird and Gaffney 1994). Anomalous results were not obvious in the straight line semi-log plots of piezometric head during the slug tests. In spite of potential problems with slug tests, hydraulic conductivity results in the peat within 1.0 m of the surface are trustworthy.

2.6.4 Pumping tests

Pumping tests are widely used in quantifying the transmissivity of hydrogeological units because they provide representative and reliable estimates (Kruseman and de Ridder, 1970). Pumping tests performed above a confining layer such as a frost table give more concrete values of hydraulic conductivity as the saturated depth is known. Otherwise estimation of the effective saturated depth relies on independent measures of hydraulic conductivity from cores or slug tests. Transmissivity in the centre of the fen was ten times higher than at the Edge site, although the depths of the perched water table at the two sites were similar.

Use of pumping tests and slug tests are complementary, because pumping tests are able to measure transmissivity at the water table, while slug tests can be performed at greater depth. With the high water table common in fens, the hydraulic properties of near surface layers are most important to groundwater flow. Pumping tests perform poorly in deposits with low hydraulic conductivity such as in the catotelm peat, as discharge becomes very small. When the water table rises above the peat surface, pumping tests will primarily draw water from above the surface and no longer evaluate transmissivity of the peat. The conditions of the peat around the observation well screens are not as vital to the results of pumping tests as they are for slug tests.

It is beneficial to apply methods of analysis that conform as closely as possible to the actual site conditions. However, peat is such a highly variable material that a very strict approach to pumping tests and their equations makes little sense (Van der Schaaf, 2004). All the pumping tests completed in the peat were constant head and not constant discharge. This allowed the advantage of minimizing drawdown in a thin layer of peat with high hydraulic conductivity. Lowering of the drawdown cone into peat with lower hydraulic conductivity is a likely cause of the decreased discharge over time. As well, dewatering of the more conductive upper layers will decrease transmission of water to the well and lower the transmissivity results.

Water levels measured over a period of hours or days will be influenced by barometric pressure changes and daily evapotranspiration patterns that lower the water table. As well, subsidence in the vicinity of the pumping well is likely to occur within hours of the drawdown of the water table, and this may affect the slope of the drawdown curve over time. With the small drawdown encountered in peat, water level measurement error may influence results. Precision was improved by having the same water level tape and observer taking the measurements for all the pumping tests. Recharge may occur from the pumping cone intersecting a stream, from having the discharge hose too close to the site, or from breakthrough of a thin frost layer beneath the peat in spring, and this also will affect the drawdown in observations wells measured over time. Variations in pumping rates over time may also affect water levels measured. Without careful corrections it will be difficult to differentiate these various effects on the drawdown vs. time plots from pumping tests.

Decreasing discharge rates are accounted for in the analysis of the Aron-Scott (1965) method, although the drawdown over time data is still sensitive to outside factors such as evapotranspiration and compressibility. For approximations using the Thiem method, pairs of observation wells were monitored and late-time drawdown data was only used if there was a constant hydraulic gradient between the two wells, indicating that quasi-steady state conditions existed. These conditions are easy to identify with pressure transducer datasets. The Distance-drawdown method was least sensitive to the slope of the drawdown curve over time, and the myriad of factors already mentioned that can affect it.

There may be several reasons for the decrease in measured values of transmissivity over the spring and summer in the fen. The transmissivity results were affected equally by the hydraulic conductivity and saturated thickness. Based on slug test results, the hydraulic conductivity in the peat decreased with depth. Therefore, when the water table was drawn down over the summer of 2003, the thickness of the saturated peat of high hydraulic conductivity declined. Lowering of the water table and depletion of soil moisture increased the effective stress of the peat deposit and caused subsidence. There was no consistent evidence of decreasing hydraulic conductivity due to peat compaction based on slug test results repeated over the summer and fall of 2003. However, open piezometers may alter the natural and dynamic gas content of the peat by acting as vents for the release of gas to the atmosphere, and thereby be unable to detect changes in hydraulic conductivity over time (Kellner et al., 2004).

Pumping tests completed in thawed peat demonstrate the characteristics of radial flow, although it is possible there is some influence from vertical flow. Other authors have modeled flow to wells in vertically heterogeneous aquifers by treating the radial flow component near the surface analytically, while employing a finite difference technique to the vertical flow component at depth (Hemker, 1999). However, there was very little or no vertical gradient measured between piezometers screened at various depths in the peat. During slight drawdown of the water table during pumping tests, the piezometric head at depth was lowered by the same magnitude. Increased effective stress from water losses caused small amounts of strain. The complex response of thawed peat deposits to pumping tests requires further study.

Subsidence of the peat during pumping may contribute water to the well, increase peat density and decrease hydraulic conductivity. Price (2003) measured a decrease of hydraulic conductivity by half in undisturbed peat with 0.5% strain over a dry season. Measured strain of the thick Sandhill Fen deposit from pumping tests was less than 0.01 m. If the average porosity of the upper peat is 0.95, and the average void ratio 19, then a change in the total peat volume of 0.01 m would result in a change in the volume of pores of 0.19 m. The effect of changes in void ratio on hydraulic conductivity was not measured in this study, but has been modeled in the studies by Lang (2002) and Kennedy and Price (2004).

2.6.5 Loading test

Short term loading tests obtain information about the vertical hydraulic conductivity of deep catotelm peat that is not otherwise easily acquired. The rate of recharge to and from the peat from the underlying sand deposit is controlled in part by the vertical hydraulic conductivity. The hydraulic diffusivity ranged from 1.1 $x10^{-4}$ m^2/s to 3.2 x 10^{-4} m^2/s depending on the assumed thickness of the low hydraulic conductivity layer. Using independent estimates of specific storage ranging from 0.014 to 0.052 m^{-1}, the bulk vertical hydraulic conductivity was between 1.5 x 10^{-6} and 1.6 x 10^{-5} m/s. Estimates of specific storage were based on seasonal subsidence of peat layers in 2003. In light of low characteristic response times, there is no evidence for a confining layer at the lower peat/sand interface. If there was a confining layer at the base of the peat and not a sand formation, all of the water in the less conductive peat would have had to drain upwards, and the vertical hydraulic conductivity above the confining layer would be four times higher, which seems unlikely considering that the vertical hydraulic conductivity would then be an order of magnitude higher than horizontal hydraulic conductivity.

These vertical hydraulic conductivity values were unexpectedly higher than estimates of horizontal hydraulic conductivity obtained with deep slug tests. The primary reason for this, is the use of equations assuming only vertical movement of water during the dissipation of excess head. In Figures 2.5-17 and 2.5-18 there is evidence of lateral gradients away from the center of the load, even at 3 m depth in the peat. Thus a portion of the excess head was dissipated laterally, causing a quicker characteristic response time than would be the case for only vertical flow. In the evaluation of hydraulic properties of peat at depth, the loading test is recommended as a low-disturbance method that may be completed in a short period of time. However, three dimensional flow equations should be used with a surface load of small dimensions, or else the load should be of large dimension over the surface compared to the piezometric measurement points.

This study adds to the field of peatland hydrology the potential exploitation of new field methods and a description of what may be expected. The characterization of peat hydraulic conductivity using pumping tests and loading tests can be accomplished in a short period of time with highly accurate instrumentation, and causes minimal disturbance to the site. The use of the frost table as a confining layer presents an opportunity to evaluate both storage and flow properties of the upper peat layer without complications from the catotelm peat and underlying mineral substrate.

Hydrological modeling of boreal regions containing significant areas covered by peatlands should make use of hydraulic properties unique to these surface deposits. The depth of the water table below the surface depends on the characteristics of the peat described in this study. Water table depth, soil moisture content, and peat type are known to influence many other aspects of peatland hydrology. Hydraulic properties have an impact on groundwater flow through the peatland, seasonal peat temperatures, the energy balance at the surface, and the production of greenhouse gases.

3. Hydrological observations and modeling of peat surface elevation change

3.1 Introduction

The distribution of peatlands has changed substantially during the Holocene in response to changing climate (Halsey et al., 1998). Climatic changes will likely result in substantial change in the hydrology of boreal and sub-arctic regions (Waddington et al., 1998). These changes are not expected to be evenly distributed throughout the year, for example, increased winter temperatures will cause snowmelt and runoff to occur earlier in the year (Burn et al., 2004). The exchange of mass and energy among the major peatland forms and between them and the overlying atmosphere is poorly understood (Quinton and Hayashi, 2004). These regions are still under-represented in the Soil-Vegetation-Atmosphere (SVAT) modeling literature (Letts et al., 2000). An improved understanding of mass and energy exchanges among peatland types will improve the ability to understand and therefore predict climate-induced changes to the water cycle (Quinton and Hayashi, 2004).

The hydrology of Boreal peatlands may be influenced by a variety of anthropogenic and natural events. In the future, forestry and hydroelectricity production are expected to affect the drainage patterns and the extent of peatlands more than peat mining (Rubec, 1996). Sandhill Fen site is surrounded by forestry cut blocks of varying age, and the potential impact on hydrology of changing and cutting the surrounding Black Spruce (*Picea mariana*) forest has yet to be examined. Fires have an impact on 1850 km^2 of peatland annually in western Canada, and with warmer and/or drier conditions the burning of peatland areas would likely increase (Turetsky et al., 2004).

Seasonal frost plays an important role in the hydrology of northern peatlands. Peatlands are the only environments that preserve scattered permafrost in southern boreal regions (Williams and Smith, 1991) and seasonal frost often endures well into the summer. These sites may be the first indicators of environmental changes from climate warming, or else demonstrate the resistance of these systems to climate changes.

The purpose of studying peat surface movements has often been to improve water and land surface management programs. Minimizing subsidence in order to sustain land above sea level is a very important management issue in both the Netherlands and Venice, Italy (Gambolati et al. 2003; de Lange and van der Linden, 2004). In the Netherlands a model was created to determine if previous water management policies were working. Ditching and drainage practices cause subsidence from consolidation and shrinkage, and irreversible losses of unsaturated peat to oxidation (Dasberg and Neumann, 1977; Silins and Rothwell, 1998; Price and Schlotzhauer, 1999). A simulation model was developed by Kennedy and Price (2004) for assessing the impact of various peat extraction techniques and the efficiency of re-wetting scenarios in restoration of cutover peat bogs.

The subsidence and rebound of peat maintains the water table relatively close to the peat surface (Price, 2003). This provides a more stable moisture regime for the vegetation inhabiting the fen. Increasing water table depth has been related directly to decreasing evapotranspiration in fens (Ingram, 1982), therefore a high water table promotes evapotranspiration. Studies have shown that the removal of the upper layer of peat for commercial purposes results in irreversible changes of its hydrologic behavior (Schlotzhauer and Price, 1999). Peatlands that have an adjusting surface may emit higher amounts of methane annually, and are generally less affected by moisture changes (Moore et al., 1990; Roulet, 1991). Sustained saturation due to these adjusting surfaces will reduce peat oxidation (Price, 2003). Even slight changes in elevation of the peat surface may influence the quantity of surface runoff.

The objectives of this chapter are to present hydrological observations from the study of Sandhill Fen and to use this data, in concert with hydraulic properties from Chapter 2, to estimate water storage at three sites, and simulate the movement of the peat surface, based on water table changes.

Through measurement of hydrological and thermal variables, this study characterizes the annual subsurface hydrology of a seasonally frozen patterned fen in central Saskatchewan. During this period the fen underwent both a drying and a wetting cycle, that allows greater insight into the functioning of undisturbed peatland than would be possible under more uniform conditions. Peat surface, water table, piezometric head, frost table, soil temperature, and snow course elevations were measured along transects representing three distinct areas of the open fen. Changes in seasonal water table elevation and peat hydraulic properties were used to estimate water storage in the peat over time at three study sites.

A major portion of this study involves predicting a change in peat surface elevation relative to change in the water table. Peat thickness was measured at three study sites, and three 100 m transects in order to monitor change through time and differences between sites. Observations were also made along 100 m transects. Procedures for measuring peat surface and volume changes were similar to studies by Roulet et al. (1991) and Price (2003). Strain was also measured in the summer and fall of 2003 at a site in the centre of the fen. Simulation of annual changes of peat thickness will be made using a monthly model based on the stress-strain concept, and a dataset of regular hydrological and thermal observations and hydraulic properties. This model will be useful in predicting the elevation of the peat surface relative to the water table.

3.2 Literature Review

3.2.1 Studies of frost in peat

Persistent seasonal frost is common in peatlands south of the permafrost zone (Brown and Williams, 1972). This has been attributed to the low conductivity of organic soils relative to mineral soil and the effect of seasonal variations in water content on the thermal conductivity of peat (Riseborough and Burn, 1988). Once the water contained in peat freezes, its thermal conductivity increases four-fold, and heat can more easily transmitted through it (Oke, 1987).

The total moisture content in organic soils is higher than in mineral soils, in both the frozen and unfrozen condition (Williams and Smith, 1991; Nyberg et al., 2001). As well, the fraction of soil water remaining unfrozen at temperatures below the freezing point was 10 to 15% by volume in organic soil, compared to 5 to 7% in the mineral soils (Nyberg et al., 2001). In spite of these higher amounts of unfrozen water in frozen organic soils, there have been several accounts of impermeable frost in peatlands, that may increase spring runoff.

In the spring, the height of the saturated frost layer relative to the surface affects the magnitude and timing of snowmelt runoff (Quinton et al., 2003). At the onset of spring melt runoff, the relatively impermeable frost table is usually within 0.1 m of the surface, and in the zone of high hydraulic conductivity (Quinton and Hayashi, 2004). As the surface begins to thaw the peat has a larger capacity to store and transmit water (Roulet and Woo, 1988).

Seasonal frost in peat takes longer to thaw than in mineral soils. The rate of thaw is affected by radiation, convection and evaporation at the surface, depth and density of the snow cover, and the thermal properties of the soil (Brown & Williams, 1972). Thaw rates in a dry bog hummock were slower than in a hollow (Fitzgibbon, 1981). Relatively warm snowmelt water accumulating in swales and pools contributes to the more rapid thaw of those areas (Brown & Williams, 1972).

The effect of frost table formation and dissipation on peat volume should be considerable in highly porous peat, especially if the pore spaces are saturated. Vertical expansion or shrinkage of the peat (Δz) [m] is governed by the density of the water (ρ_w) and ice (ρ_i). Roulet (1991) used a formula similar to this to calculate the maximum shrinkage in peat volume when frozen water melts.

$$\Delta z = n\left(\frac{\rho_w}{\rho_i} - 1\right)\Delta FT \qquad (3.1)$$

Where, ΔFT (m) is the difference in frost table thickness from the first month of observation minus the frost depth of the following months, and n is the average porosity of the upper peat. This formula assumes that all of the pore water freezes, and doesn’t contain unfrozen water adsorbed onto organic particles. Pavlova's (1970) study in a different peat types estimated there were significant amounts of unfrozen water at temperatures near zero.

3.2.2 Snow pack

Winter snow pack is a key factor in water basin planning (Fetter, 1994), and is important for surface energy exchanges, frost penetration, and for plants and animals that depend on it for cover (Brown et al., 2000). The maximum snow accumulation in the late winter measured on snow courses is sometimes used as a predictor of the annual contribution of snowmelt to streamflow. The snow pack adds an important insulating layer to the peat, that reduces further heat loss and restricts frost penetration (FitzGibbon, 1981). Goodrich (1982) found that doubling the snow cover from 0.25 to 0.5 m increased the minimum ground surface temperature by 7 degrees.

Snow course surveys are commonplace in hydrological studies in all terrain types as they determine the balance of snow accumulation and losses to sublimation and blowing snow over the winter. Measures of snow water equivalent using snow depth distributions and density are important in estimating the amount of moisture that will become snowmelt and spring runoff. It has been found through various studies that the minimum ideal length for snow surveys is about 80 to 100 m, depending on topography. Over this length, the standard deviation of snow depth stabilizes (N. Neumann, personal communication).

3.2.3 Changes in water storage

The water storage function of peatlands is important, as it determines the availability of water for evapotranspiration and the depth of the water table, which contributes to runoff. The total storage available in a patterned wetland is greater than the depression storage of other fens (Quinton and Roulet, 1998). Water storage in the peat depends on water table depth and storage properties (Ingram, 1981).

3.2.4 Compressibility and specific storage

The phenomenon of *Mooratmung* (mire breathing) was observed and noted from the early part of the century in German bogs and Russian mires as an oscillation of the peat surface over the seasons (Ingram, 1981). It is the low amount of mineral sediment and ash in peat soils that contributes to their highly compressible and easily disturbed nature. This phenomenon occurs in response to changes in water storage, and can be significant on daily time scales in floating peatlands, floating mats, or those connected to tidal regimes (Ingram, 1981; Nuttle et al., 1990; Roulet, 1991). In many other peatland sites, deformation of the peat is important on the seasonal scale (Price and Schlotzhauer, 1999; de Lange and van der Linden, 2004).

A survey of numerous Ontario peatlands found fen water tables to be nearer the surface than other peat types (Riley and Michaud, 1987; Roulet, 1991), presumably deformation of peat was the mechanism. Peatlands that compress in response to water level recession, will maintain a wetter surface for the vegetation, and sustain higher evapotranspiration rates (Price, 2003). Surface adjustment in peatlands has a significant effect on their hydrological, biogeochemical, and biological processes (Nuttle and Hemond, 1988). Peat subsidence is known to increase moisture retention and lower hydraulic conductivity (Roulet, 1991; Chow et al., 1992; Price and Schlotzhauer, 1999). This decrease in hydraulic conductivity as the peatland dries may be an important self-preservation mechanism (Price, 2003).

As the peat surface isn't a reliable reference point in measuring water table changes, it must be measured in relation to a stationary bench mark (Roulet et al., 1991). Defining the “surface” of peatlands is difficult due to their variable micro-topography. In response to this problem, Roulet et al. (1991) constructed bog shoes of hollow P.V.C piping that covered over a meter squared, and moved vertically with the peat. These were used in concert with water table wells, and all were connected to a data logger to track changes in peat surface and water table elevations.

Movements of the peat surface result from volume changes throughout the peat deposit. Price (2003) constructed vertical rods anchored into the peat deposit at different depths to gauge strain in different peat layers. Conventionally one dimensional peat consolidation is measured in the lab by loading (Hanrahan and Walsh, 1965; Lang 2002; Kennedy and Price, 2004).

Specific storage (S_s) [m^{-1}] is the portion of total water lost or gained by compression or expansion of the saturated peat. In certain settings, the specific storage component of total storage is more important than specific yield (Nuttle et al., 1990; Schlotzhauer and Price, 1999). It is related to the compressibility of the peat as shown in Equation 2.20 (Fetter, 1994). Plotting compaction versus drawdown data from an aquifer pumping test can give estimates of specific storage in confining units (Burbey, 2000).

Deformation of the peat occurs through processes of shrinkage above the water table, compressibility below the water table, oxidation, and long term consolidation, also called secondary compression (Price and Schlotzhauer, 1999; Price, 2003). Deformation of an undisturbed peat deposit may occur from changes in water table and water content, snow accumulation, and the production and ebullition of gases (Price, 2003; Rosenberry et al., 2003). The majority of annual changes in peat thickness occur in the upper acrotelm peat layer (Price, 2003). In some soils, deformation due to moisture losses may cause shrinkage cracks to form near the surface, indicating three dimensional stress changes. However, Price (2003) observed only one dimensional volume change in peat.

Shrinkage is the reduction of pore volume above the water table. Shrinkage of the peat is sometimes irreversible (Kennedy and Price, 2004). Shrinkage may occur at a slower rate than changes in water content, but volume changes can be significant (Price, 2003). Over the long-term in the Netherlands, peat oxidation was found to account for 50% of peat subsidence. Oxidation is an irreversible process whereby organic matter mass is lost and Carbon dioxide is released (Gambolati et al. 2003).

Compression is usually partitioned into both primary and secondary consolidation processes, that may or may not be reversible. Primary consolidation is the volume change of the peat below the water table that causes equivalent changes in water storage.

Secondary consolidation is a slower process that involves irreversible compression of the peat due to rearrangement of the soil structure under load (Kennedy and Price, 2004, and is a function of the void ratio. When a soil undergoes a higher stress than it has previously encountered, its compressibility will be decreased. Compressibility it is strongly affected by the previous loading history of the hydrologic unit. When peat undergoes higher effective stress than it has previously encountered and it surpasses its pre-consolidation pressure, then the consolidation rate is higher and there is increased strain per unit effective stress (Kennedy and Price, 2004).

Re-arrangement of soil structure is due to changes in effective stress, not changes in total stress (Freeze and Cherry, 1979). The concept of effective stress was introduced by Karl Terzaghi in 1936; "All measurable effects of a change of stress, such as compression, distortion and a change of shearing resistance are due exclusively to changes in effective stress". The effective stress is the distribution of load carried by the soil. In peat deposits even small changes in effective stress will cause subsidence. Effective stress (σ') [Pa] is calculated from the total stress and pore pressure as follows.

$$\sigma' = \sigma - u \qquad (3.2)$$

The total stress (σ) applied downwards on a plane through a saturated porous medium is balanced by the effective stress (σ') and pore pressure (u) upwards. Changes in water table result in changes in effective stresses below the water table.

3.2.5 Peat surface models

A hydrological model was coupled to a surface subsidence model designed to describe the response of the subsurface to variations in ground water and surface water (de Lange and van der Linden, 2004). Roulet (1991) created a water balance model that accounted for changes in storage and specific yield, but not specific storage. Their model predicted peat surface movements of a floating fen for a given change in water table. Negative changes in storage were better correlated with peat surface changes than rising water storage. A model simulating flow in cutover peat systems (FLOCOPS) developed by Kennedy and Price (2004) simulated summertime trends in peat thickness, water table, moisture content, and pressure head, and made adjustments for changes in hydraulic properties.

3.3 Site Description

Section 2.3 gives a complete description of the study site.

3.4 Methods

A series of hydrological observations were made from the fall of 2002 to the fall of 2004. Observations involved measurements of peat surface, water table, frost table and piezometric head elevations, as well as peat temperatures in the upper 1.4 m. Taken together; these observations help to characterize the year-round hydrology of the patterned fen site. For the purposes of characterizing the compressibility of the peat, strain was measured over the season at the Fen Centre site. These results are later applied in a model of peat elastic behavior, and in calculations of water storage.

3.4.1 Transect surveys

Linear transects of 100 m length were established at three sites to capture the spatial variation of peat surface, frost table, snow accumulation, and water table. Flag markers were spaced out every 0.5 m for the first 20 m, every meter from 20 to 50 m, and every 2 m for the northernmost 50 m. These intervals were intended to capture the variation in scale of fen micro-topography. Benchmark-piezometers anchored into underlying sand marked the ends of these transects.

Peat surface, water table and frost table elevations were measured at 100 points along three transects representing different topographic zones of the fen. A Sokkia rotating laser level (LP 30 model) with a range of 200 m in all directions was attached to the top of iron benchmark pipes using a threaded coupling (Figure 3.4-1). The accuracy of the laser signal decreased with distance. As most of the surveying required for the study was done within 20 m of the laser level; accuracy and precision were generally within 0.002 m. Surveys beyond 50 m had an accuracy of approximately 0.01 m. The signal accuracy was negatively influenced by wind gusts, but when the laser level unit was jarred beyond its self-leveling range, the signal would stop. Wind error was reduced by taking longer measurements at each survey point to allow gusts to pass, and avoiding level surveys during the windiest parts of the day.

In the spring, the receiver was attached to a frost probe with 0.01 m delineations. The depth of the frost table, water table (if above the surface), and peat surface were measured relative to the laser level elevation. Once the frost had dissipated only the peat surface elevation was measured (and water table if present), using a measuring rod with 0.001 m increments. Survey points along transects were marked with roofing nails inserted into the surface of the peat so that repeated surveys would occur at exactly the same points.

Figure 3.4-1 Laser level and receiver set up along transects

3.4.2 Bog shoes

Peat surface movements were measured using bog shoes and transect surveys on a weekly and monthly basis. Bog shoes can be used to make precise measurements of vertical peat surface movements relative to a stationary benchmark. The bog shoes were modeled after the design given in Roulet et al. (1991). They consist of hollow CPVC pipes that rest on and move vertically with the peat (Figure 3.4.2). The area of peat covered by the bog shoe at Fen Centre is $0.56 m^2$, and for the Edge and Partially Treed sites the bog shoes cover $0.18 m^2$ of surface. They were situated next to the three main study site benchmarks so that true elevations could easily be obtained. The Fen Centre bog shoe was located on the border of a ridge and a swale, and away from all pathways. These simple instruments are reliable for showing the seasonal trends of peat surface movements.

Figure 3.4-2 Initial Bog shoe and benchmark set up at the Fen Centre site

3.4.3 Measurement and calculation of strain

Measurements of strain and estimates of effective stress were used to determine the compressibility of layers at different depths in the Sandhill Fen peat. Strain measurements relied on measuring the relative movements of the peat at depth. As described by Price (2003), in order to determine changes in thickness of individual peat layers, the change in thickness of the lower layers were deducted at each time step. A series of elevation sensor rods were anchored at depths of 0, 0.3, 0.5, 1.0, 2.0, and 3.0 m. Elevation sensor rods were surveyed with the laser level in the summer and fall of 2003.

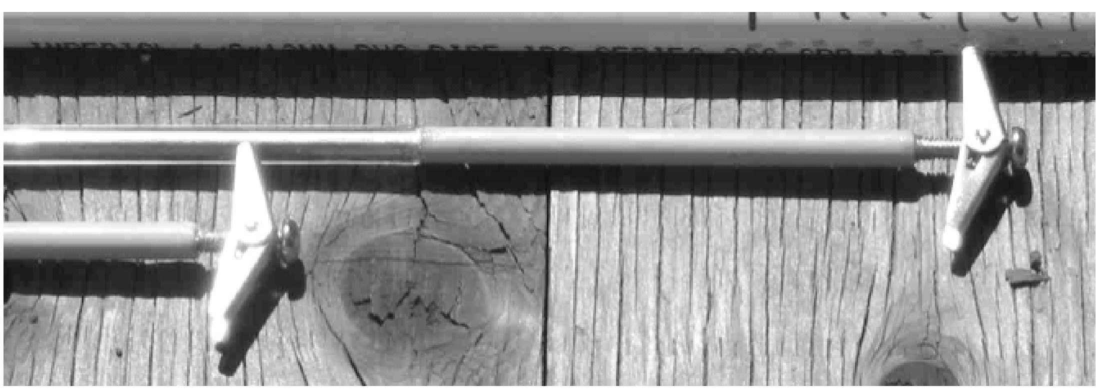

Figure 3.4-3 Elevation sensors installed in the shallow peat

Elevation sensor rods of two different designs were used, as depicted in Figures 3.4-3 and 3.4-4. Large drywall anchors were used to hold the shallow elevation sensors in place. These were screwed partially onto short sections of threaded rod of the same size, that were secured to hollow plastic tubes. Small diameter dowels were inserted inside the tubes for stability during installation. They were pushed just beyond the depth of interest, through pre-made holes, then twisted and pulled upward to engage the anchor outward. The deep elevation sensors installed at 2.0 and 3.0 m depth were designed to work in combination with piezometers. An outer plastic pipe casing of 0.025 m diameter covered an inner pipe screened 0.1 m at the bottom, with an anchor attached. The whole unit was pushed to the desired depth, whereupon the inner piezometer/anchor pipe was held in place while the outer casing was raised 0.1 m to expose the piezometer intakes.

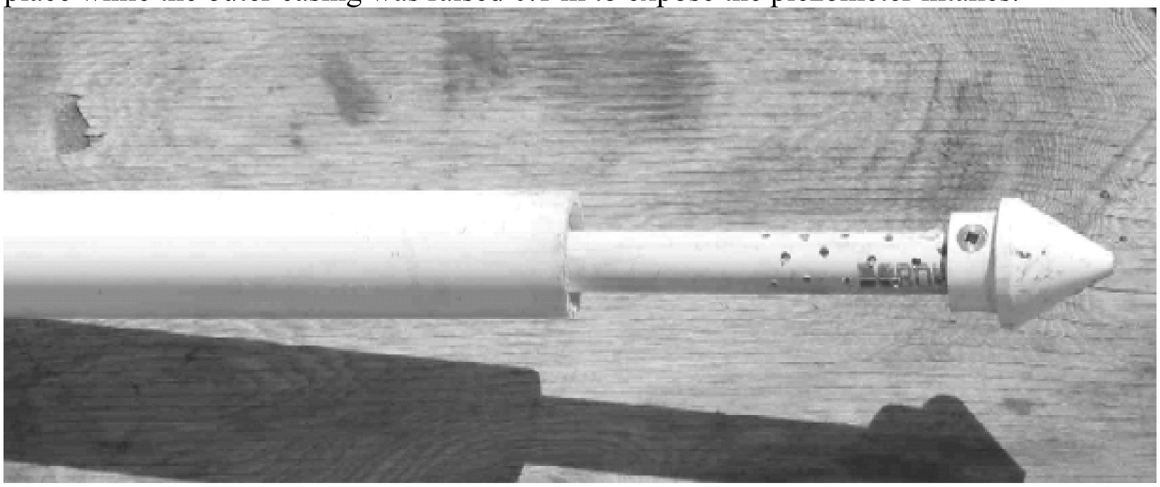

Figure 3.4-4 Settlement sensors installed in the peat at 2 and 3 m depths

Strain was calculated for peat layers from the surface to the underlying sand, at every set of elevation sensors. Strain (ε) is calculated as the change in thickness of the layer, divided by initial thickness of the layer (b_o).

$$\varepsilon = \Delta z_1 - \Delta z_2 / b_o. \qquad (3.3)$$

In Equation 3.3, z_1 and z_2 are the change in elevation of the sensors at the top and bottom of the layer, respectively.

Measurements of strain relied on the accuracy of the level surveying method. During ideal conditions, with low wind speeds, and close proximity to the laser level, accuracy was 0.002 m. With greater distance, accuracy was lessened. In conditions of higher wind speed, the laser level affixed to the top of the benchmark pipes vibrated, and this decreased precision of the measurements. The laser level automatically ceased if the unit was forced off its level by the wind.

3.4.4. Hydrological observations

3.4.4.1 Installation of Piezometers and Benchmarks

Piezometers were installed in the sand layer beneath the peatland in order to monitor changes in piezometric head over the seasons. These iron piezometers were also designed to serve as benchmarks. Piezometer nests were installed at the Fen Centre and Transect 2 pumping sites. Most piezometers were constructed of PVC or CPVC plastics. Intakes for the piezometers were at various peat depths, and consisted of numerous slotted openings or circular perforations.

Six benchmark-piezometers were installed at either end of the three 100 m transects in the open fen. The benchmarks were fixed into the sand below the peat by fluting welded around the bottom of the piezometer (Figure 3.4-5). The pipes were pushed through pre-augured holes in the peat, and then rotated into the sand layer in the direction of the fluting. The pipes on the north end of the transects were secured 0.5 m into the sand, while those on the south ends were secured at least 1.0 m into the sand. The benchmark/piezometer at the south end of transect one on the east side, was set to a depth of 2 m. Elevation above sea level for these benchmarks was obtained through extensive surveying from a local datum benchmark on Highway 106. Periodic surveys through the study period confirmed that the elevation of these benchmarks was stationary.

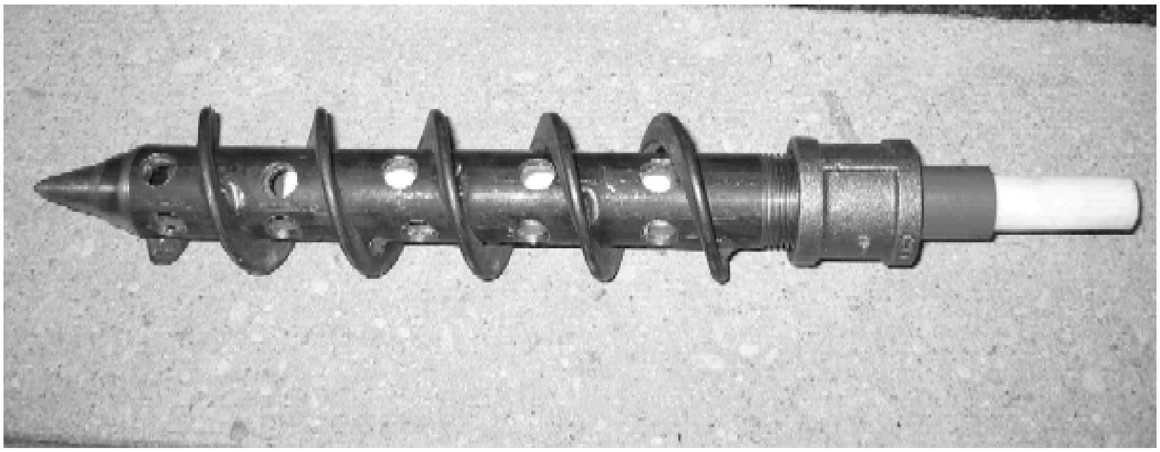

Figure 3.4-5 Fluting welded at the bottom of the benchmark piezometers to anchor them in place

3.4.4.2 Water level measurement

The water table and piezometric head was monitored at several sites weekly or bi-monthly during the frost-free seasons. As the elevation of the benchmark pipes was known, measurement made from the top of the pipes to the piezometric surface inside the pipe or the surface water level outside the pipe gave water table and piezometric head elevations. If the water table was below the peat surface, water table elevation was measured inside shallow wells with screens extending to the surface, located beside the benchmark pipes.

Measurements were made with an electronic water level tape. The piezometric head was also measured with Geocon© vibrating wire pressure transducers at various peat depths in the centre of the fen. Through the winters and much of the study period, piezometric head in the sand below the peat was monitored with Solinst© Levelloggers. These are self-contained units suspended inside the piezometers that give piezometric head data. During the frost-free seasons piezometric head at the benchmarks was also measured manually.

3.4.4.3 Snow surveys

In the winter of 2003, snow course surveys were completed at 2 m intervals for three transects in the fen. The depth of the snow pack was measured to the nearest 0.01 m using a frost probe. To determine density, the snow pack was sampled with a hollow MSC standard snow sampling tube, at five random points along each transect. Samples were kept in Ziploc bags and accurately weighed in the lab. The density of five snow tube measurements on each transect was averaged. The average density of five points and the depth at each point were used to calculate the snow water equivalent in millimeters.

3.4.4.4 Thermocouple strings

Peat temperatures and the depth of the frost were characterized using thermocouple strings installed at the main fen study sites. Type T thermocouples were soldered together, wrapped around a fiberglass rod, and shrink-wrapped with plastic to secure and protect the sensors from the elements. Thermocouples were placed at depths of -0.05 m, 0 m, 0.05, 0.1, 0.2, 0.3, 0.5, 0.75, 1.0, and 1.25 m on each rod. The tops of the rods were made of yellow aluminum, and may have been susceptible to heating due to solar radiation. To avoid this, the aluminum portions were wrapped in white rubber tape. Thermocouple strings were placed at the south end of transects and connected to data loggers to record annual hourly temperatures data for ridge, swale (at Fen Centre site) hummock and hollow (at the Partially Treed site) and the Edge site peat.

3.4.4.5 Zero degree depth

The temperature of the soil between the thermocouples was interpolated using the average of two adjacent points. The zero-degree depth was interpolated to the nearest 0.05 m for the period of the study at three sites. It was assigned to the depth with a negative temperature closest to 0°C. Thus the actual zero-degree depth might have been slightly deeper than that estimated. The depth of thaw was estimated as the interpolated depth with a positive temperature closest to 0°C. Therefore, the depth of thaw might be slightly shallower than shown. This was a sufficient level of interpolation to infer the depth of freezing.

3.4.5 Water storage calculation

Water storage above and within the peat was estimated at three study sites from November, 2002 to September, 2004. This calculation includes the water held in the peat (both above and below the water table), the water ponded above the surface, and the water stored as snow on the surface. The total water storage at each site (TS) [m^3/m^2] was estimated as the combined volume of the ponded water per square meter of surface area (b_{PW}), the water within the peat (b_p), and the water stored as snow, measured by the snow water equivalent (SWE).

$$TS = b_{pw} + b_p + SWE \qquad (3.4)$$

Ponded surface water was calculated as the difference in water table and peat surface elevation. The snow water equivalent measured (from numerous snow surveys) the amount of snow accumulated on the ground each month, not the total snowfall.

The quantity of water in the unsaturated layer above the water table was estimated from a relationship of storativity and water table depth described in Section 2.5.1.5. The relationship of storativity versus water table depth was determined with a field drainage test, and a series of laboratory drainage tests on cores extracted from ridge, swale and edge sites in the fen. The equation is:

$$S = S_0 e^{-7.77\,(WT)} \qquad (3.5)$$

Where, S is storativity, S_0 is the storativity value with the water table at the surface, equal to 1.0, and WT is the water table depth, to a maximum of 0.4 m depth. The volume of water removed from the upper layer of peat may be calculated by integrating Equation 3.5:

$$V_w = \int_{Z=A}^{Z=B} S dz = S_0 M (e^{-A/M} - e^{-B/M}) \quad (3.6)$$

where, M is a characteristic depth range of the water table, equal to 1/7.77, over which the storativity changes by e^{-1}, V_w [m^3] is the volume of water lost by drawdown of the water table from the surface, A and B are the initial, and the final water depth below the surface, respectively, and z is the depth below the elevation of the peat surface, when the water table was at the average peat surface.

Seasonal measurements in the fen determined that water table depth and peat compression are related. When the water table falls below the surface, the peat surface elevation decreases. Surveys measuring the strain of the peat with depth at several points at the Fen Centre site, took place four times from July to October, 2003. From this data, it was recognized that most of the compression of the peat, that occurred in concert with water table decline, was in the upper peat layer (the acrotelm). A relationship of acrotelm thickness and water table depth was developed, based on these four surveys. The base of the compressing layer of peat was set to 0.4 m below the surface, while the water table was at the surface. If the water table fell below the surface, the upper peat layer would compress to less than 0.4 m. These changes of thickness, in response to water table depth, were assumed to be equivalent for compression and rebound. The change in acrotelm thickness was estimated, based on a measured peat subsidence, and the thickness of the acrotelm as a function of water table depth is defined by:

$$D_a = 0.4 - 0.0671 * WT \quad (3.7)$$

where, -0.0671 is the negative slope of the water table depth-peat volume change plot. This relationship is also used in the peat surface modeling described in Section 3.5.4 to determine changes in acrotelm thickness based on the calculated water table depth.

The total amount of water stored below the surface of the peat, b_p, is equal to the amount of water in the catotelm b_c plus the amount of water in the acrotelm b_a, $b_p = b_c + b_a$. These two layers may be considered separately because the acrotelm is subject to freezing and desaturation while the catotelm is rarely affected by freezing and drying.

The water in the catotelm, b_c is equal to the thickness of the catotelm D_c minus the volume of solids per unit area in the catotelm D_{sc}. The catotelm thickness is equal to the total peat thickness D_p minus the acrotelm thickness D_a. Therefore $b_c = D_p – D_a – D_{sc}$. The total peat thickness and the changes of thickness can be measured by means of peat probing and bog shoes. The acrotelm thickness can be estimated by Equation 3.7. The equivalent column of water in the catotelm can be calculated if the peat surface movement and water table depth are known.

The water in the acrotelm can be calculated from the storage change – water table relationship (Equation 3.6) because this relationship gives an estimate of the total amount of water lost from the acrotelm by shrinkage, compaction and pore drainage and thus takes the changes of acrotelm thickness into account. The total amount of water in the acrotelm, b_a is therefore equal to the water in the acrotelm at zero water table depth (0.4 m - D_{sa}) minus the water lost by water table drawdown, i.e.: $b_a = 0.4 – V_w – D_{sa}$, where D_{sa} is the volume of solids in the acrotelm per unit area [m^3/m^2].

The total amount of water within the peat, as a function of peat thickness and water table depth can now be written as:

$$b_p = D_p – D_a(WT) + 0.4 – V_w(WT) – (D_{sc} + D_{sa}) \tag{3.8}$$

and using equations 3.6 and 3.7 this relation can be written as :

$$b_p = D_p + 0.067*WT – S_o*M(1- e^{-WT/M}) – D_s \tag{3.9}$$

Therefore, the total amount of water in the peat is equal to peat thickness, plus the change in acrotelm thickness as a function of water table depth, minus the water lost by water table drawdown, minus the amount of soil solids.

The volume of soil solids in the peat ($D_s = D_{sc} + D_{sa}$) was calculated from the particle density (Carter, 1993), mass of the solid fraction of peat cores, and peat thickness. The volume of peat solids in the upper 0.2 m was significantly less than for the deeper peat. The volume of the solid fraction of the peat below a depth of 0.2 m was assumed to be equal to that of core sections taken from 0.2 to 0.4 m depth. The true volume of solid peat in the field is likely to be a gradient, increasing with depth as the other peat properties change with depth, and displaying heterogeneity, however for simplicity D_s is divided into two layers.

3.4.6 Peat surface movement model

Fluctuations in water storage are primarily responsible for the changes in effective stress responsible for volume change in the peat during the frost-free season. However, in a seasonally frozen peat deposit, a ubiquitous impermeable frost layer may form at the water table, beginning in the fall. Due to the characteristics of this frost layer, pressure changes beneath the frost may or may not represent changes in water storage. Thus, the advantage of framing the model around estimates of effective stress are that the model incorporates measured piezometric head independent of water table changes, and the weight of snow accumulated on the surface. An additional component of the model accounts for the phase change of water, which causes volume change.

Inputs to the model are monthly water table elevations, piezometric head measurements at the base of the peat, and an initial measurement of peat thickness. Estimates of the depth of frost and the snow water equivalent in a given month are optional. There are two important formulas in the model; one to calculate monthly effective stress for the entire peat thickness, and a second to calculate the resulting peat surface movements. The remaining calculations built into the model primarily determine the thickness of the frozen and unfrozen peat, and the portion of the acrotelm layer that is unsaturated. The thickness of the catotelm or acrotelm layer in a given month is based on calculated changes of these layers in the previous month.

Assumptions associated with this peat surface movement model include the following: 1) The acrotelm and catotelm layers are homogeneous with respect to compressibility 2) The mineral substrate beneath the peat deposit is incompressible, 3) Lateral stress and strain are negligible and 4) The compressibility of the peat with subsidence is the same as it is for expansion, and is constant, 5) The frost layer is assumed to be impermeable and not compressible, 6) There is no change in water storage in frozen peat, and 7) The catotelm remains saturated.

For the model, the peat profile was divided into two layers, loosely defined as the acrotelm and catotelm. The base of the acrotelm layer was assumed to be 0.4 m. Compressibility measured for the upper peat during the enclosed drainage test was 2.2 x 10^{-5} Pa^{-1}, which is comparable to results using the seasonal stress-strain method of 2.5 x 10^{-5} Pa^{-1}. The compressibility of the catotelm layer at each site was calculated using a weighted average of peat compressibility with depth from 0.4 m to the substrate sand. Compressibility of the lower layer at the three sites were; 5.5 x 10^{-6} Pa^{-1} at the Fen Centre site, 9.5 x 10^{-6} Pa^{-1} at the Partially Treed site, and 1.2 x 10^{-6} Pa^{-1} at the Edge site.

The total stress calculated for the peat surface model accounts for surface water and snow. The depth of snow water equivalent in meters (SWE) is multiplied by the density of water and the gravitational constant. The depth of the perched water table (PWT) was the measured height of the water table above the peat surface in spring.

$$\sigma = \rho_{sat} g(D_c + D_a) + \rho_u g D_u + \rho_w g SWE + \rho_w g PWT \qquad (3.10)$$

Here, D_c, D_a, and D_u are the thickness of the catotelm, acrotelm and unsaturated peat layers, respectively. Saturated peat (ρ_{sat}) and unsaturated peat layer densities (ρ_u) are calculated for the model from estimates of density of the water and peat in each layer. For the calculations of monthly water table depth in the model, the nearest value of peat unsaturated density was assigned using a nested if-then statement. Calculated ρ_u ranges between 359 and 991 kg/m^3 when the water table was 0.05 m to 0.4 m below the peat surface.

The change in the monthly peat surface elevation (ΔD_p) [m] was calculated from the change in monthly effective stress, multiplied by the compressibility, and the thickness of the acrotelm and catotelm layers.

$$\Delta D_p = \Delta\sigma'(\alpha_a D_a + \alpha_c D_c + \alpha_a D_u) + (0.089 \times 0.6 \times \theta F) \qquad (3.11)$$

In Equation 3.11, $\Delta\sigma'$ is the change in effective stress (Pa), and α_a and α_c are the compressibility of the acrotelm and catotelm peat, respectively (Pa^{-1}). Seasonal shrinkage of the unsaturated peat was not reliably measured, and was assumed to be equal to the compression of the saturated peat.

The second term of Equation 3.11 is the frost component of volume change, important in cold regions. In Equation 3.12, θF is the depth of frost [m] multiplied by the volumetric water content.

$$\theta F = S_R \times D_{uf} + 0.9 \times D_{satf} \quad (3.12)$$

Here, D_{uf} and D_{satf} are the unsaturated and saturated depths of frost. S_R is the specific retention calculated using the depth of the water table, porosity, and the storativity. The saturated water content was set to 0.9, that is an average value of porosity measured in peat at the base of the cores extracted from the fen.

Volume expansion of the peat due to pore ice formation was estimated on a monthly basis. It is dependent on the thickness of the frost table, the change in density of water when it freezes, and the volumetric water content of frozen peat. When the continuous peat temperature data were converted to monthly averages, it was assumed that the peat below 0°C was frozen. The depth of the 0°C interface was used to estimate the depth of the frost table (FT). Due to interpolation between thermocouple sensor depths, the accuracy of the frost table depth was within 0.05 m. Frost table depths used for the model were the average of observed data from the winters of 2003 and 2004.

As pore water freezes over a range of temperatures, Pavlova's (1970) study in a sedge fen estimated there to be significant amounts of unfrozen water at temperatures near zero. Average monthly peat temperatures in Sandhill Fen were between -2 °C and 0 °C for most of the winter. Using Pavlova's empirical formula, 35% to 43% of the fen water would have been unfrozen at those temperatures. A correction factor of 0.6 was applied to the unfrozen pore water volume estimate. Under the influence of frost expansion alone, the peat surface in the model would rise as the frost depth increased and subside with the onset of thaw.

In addition to using estimates of effective stress to determine changes in the thickness of the acrotelm, described above, a form of Equation 3.7 was used to estimate the total change in acrotelm thickness from month to month, based on water table changes. When the water table is at equilibrium at the surface, the acrotelm should have a thickness of 0.4 m.

One possible further development of this empirical method would estimate changes of acrotelm thickness over time using Equations 3.7, and only require calculations of change in effective stress for the catotelm layer. The monthly change in effective stress in the catotelm would then be the result of changes in total stress (water storage) and measured piezometric head. An advantage of this method would be in avoiding calculations involving the density of saturated and unsaturated peat. However, this would restructure the model significantly, and may be attempted as a further study outside this master's thesis.

3.4.7 Model validation

Validation of the peat surface movement model required a better method than the R-square value, that is commonly used as a measure of correlation. The main problem with the magnitudes of R and R^2 is that they are not consistently related to the accuracy of prediction (Willmott, 1982). Therefore, a combination of summary and difference measures were employed to evaluate the model, as described in Willmott (1982) and used to evaluate portions of the CLASS model presented by Comer et al. (2000). The slope and intercept of a scatter plot of observed versus predicted monthly peat surface changes was used in addition to the mean observed and mean predicted values to generate these summary and difference measures. The index of agreement (d) is a descriptive measure between 0 and 1 that provides information on the agreement between observed (O_i) and predicted (P_i) values.

$$d = 1 - \left[\sum_{i=1}^{n} \left(P_i^{'} - O_i^{'} \right)^2 / \sum_{i=1}^{n} \left(\left| P_i^{'} \right| + \left| O_i^{'} \right| \right)^2 \right], 0 \le d \le 1 \qquad (3.13)$$

Here $P_i' = P_i$ – mean O and $O_i' = O_i$-mean O (Willmott, 1982).

Another important measure is the root mean square error (RMSE), which is a method of determining the average difference or error between observed and predicted values.

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} \left(P_i - O_i \right)^2 \right]^{0.5} \qquad (3.14)$$

In these equations, n is the number of observed or predicted values. RMSE [m] doesn't describe the size of the average difference or the nature of the differences (Willmott, 1982). Two related measures explain the portion of RMSE that is systematic and unsystematic error, and these are also in units of meters.

$$RMSE_s = \left[\frac{1}{n} \sum_{i=1}^{n} \left(P_i^{'} - O_i \right)^2 \right]^{0.5} \qquad (3.15)$$

$$RMSE_u = \left[\frac{1}{n} \sum_{i=1}^{n} \left(P_i - P_i^{'} \right)^2 \right]^{0.5} \qquad (3.16)$$

In Equation 3.15, the systematic error should approach zero and the unsystematic error (Equation 3.16) should approach the RMSE value in a "good" model, although all three measures should be low (Willmott, 1982). Differences described by $RMSE_s$ may be corrected by adjusting the model parameters (Comer et al., 2000). As unsystematic error measures the potential accuracy of the model formulation, high $RMSE_u$ may require changes in the model's structure.

3.5 Presentation of Results

3.5.1 Hydrological conditions 2002 to 2004

3.5.1.1 Precipitation

The observations compiled in this study make up important datasets that describe the hydrological behavior of Sandhill Fen over two very different annual cycles. Beginning in 2002 there was a region-wide shortfall of precipitation from normal levels, which resulted in lowering of the water tables surrounding and within Sandhill Fen. Figure 3.5-1 shows average cumulative precipitation from three stations for the two years of the study, compared to the normal cumulative precipitation for the years 1961-1990 (Environment Canada, 2004). Annual precipitation was nearly 100 mm short of normal conditions. In 2004 rainfall exceeded the normal climate levels by the beginning of July, and annual cumulative precipitation was 150 mm greater than normal. Within the fen precipitation showed the same inter-annual patterns. However, the Belfort gauge and the alter shield that improves its measurement showed significantly less precipitation than surrounding regions during the first season, but was similar from January to June, 2004.

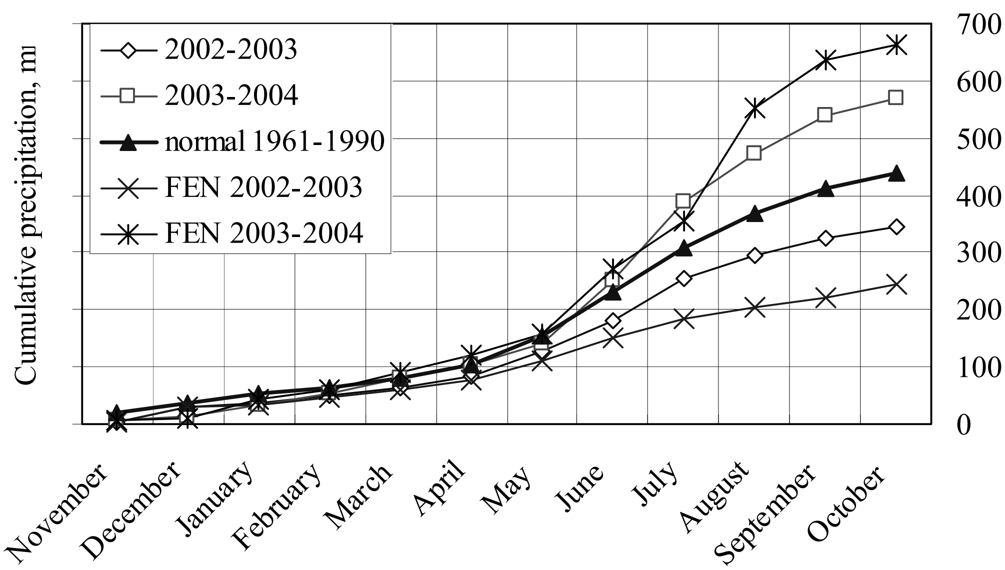

Figure 3.5-1 Average regional cumulative precipitation over the hydrological year compared to the average regional normal precipitation from 1961-1990 for Prince Albert, Nipawin, and Waskesiu stations, and data from Sandhill Fen

The data in Figure 3.5-1 are plotted for the hydrological year, which begins in November and ends the following October. In this region, the accumulation of snow usually begins in November, and impacts the amount of water available the following spring for runoff. Precipitation in the region appears to have impacted annual streamflow. In 2003, flow in White Gull Creek, adjacent to Sandhill Fen, was the lowest on record since 1994. In contrast, streamflow in White Gull Creek was the highest ever recorded in 2004 (Environment Canada, 2004).

3.5.1.2 Snow accumulation

Snow survey results are shown in Figure 3.5-2 as mean water equivalent, and standard deviation. For 2003 the snow water equivalent in the middle of March was 75 mm for Transect 1, 63 mm for Transect 2, and 86 mm for Transect 3. In both 2003 and 2004, the Partially Treed site (Transect 3) had the highest snow water equivalent, and the wind-scoured Fen Centre site (Transect 2) had the lowest. In the winter of 2003, regular snow surveys were conducted at the Edge transect in the fen. Results from surveys at the Edge site were applied to other sites in the fen.

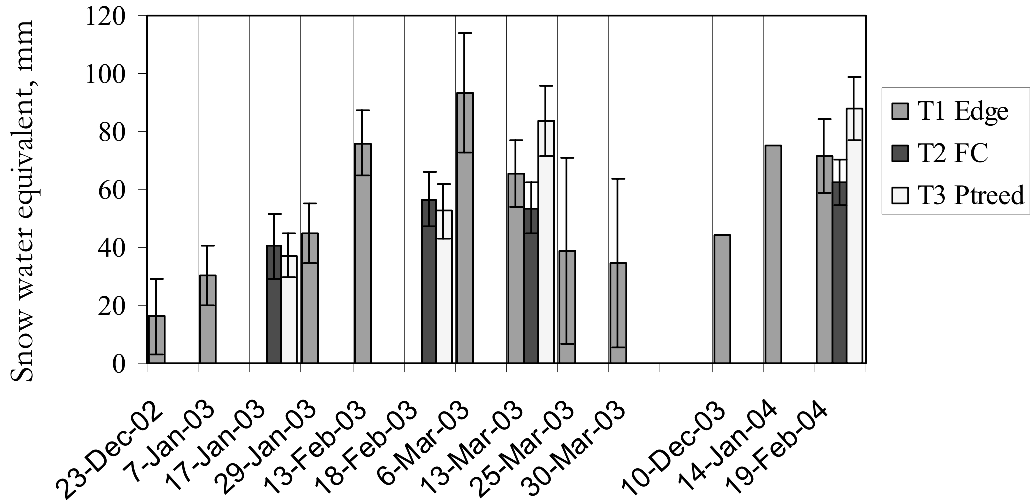

Figure 3.5-2 Mean and standard deviation of snow water equivalent (mm) for three fen transects

3.5.1.3 Frost and thaw

Thaw data collected with frost probe surveys in the spring of 2003 are shown for three 100 m transects (Figures 3.5-3 to 3.5-5). The patterns of thaw are relatively uniform over each of the transects. In 2003 a significant amount of thaw had occurred by April 30th. By the middle of June, thaw had progressed to a depth greater than 0.4 m. Where frost persisted into July at the Edge site (Transect 1), it was associated with large hummocks.

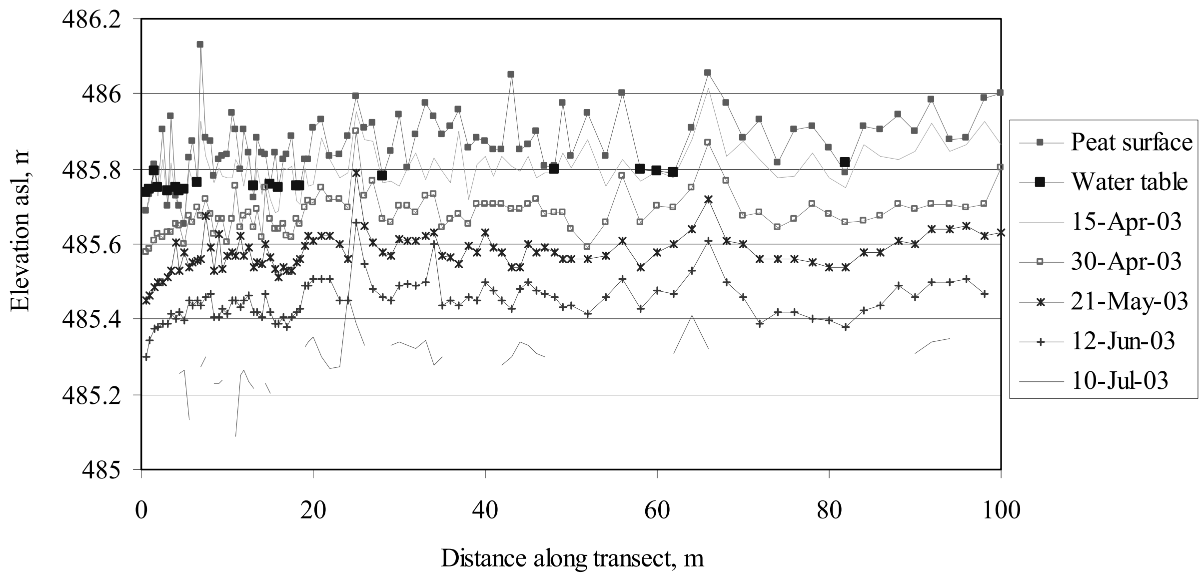

Figure 3.5-3 Progression of thaw along Transect 1 (Edge site) in the spring of 2003, with peat surface and water table elevations shown for April 15

Combined water table, peat surface, and frost table elevation data are shown for April 15, 2003 at each site. This illustrates the presence of a perched water table that was completely independent of piezometric head levels in nearby piezometers. The water table at all three sites slopes from north to south with a gradient of approximately 1:1000. The height of the water table relative to the peat surface illustrates the general 'wetness' of each of the sites. Generally the Fen Centre site (Transect 2) with its swale and ridge topography was the wettest, due to the lower elevation of the surface.

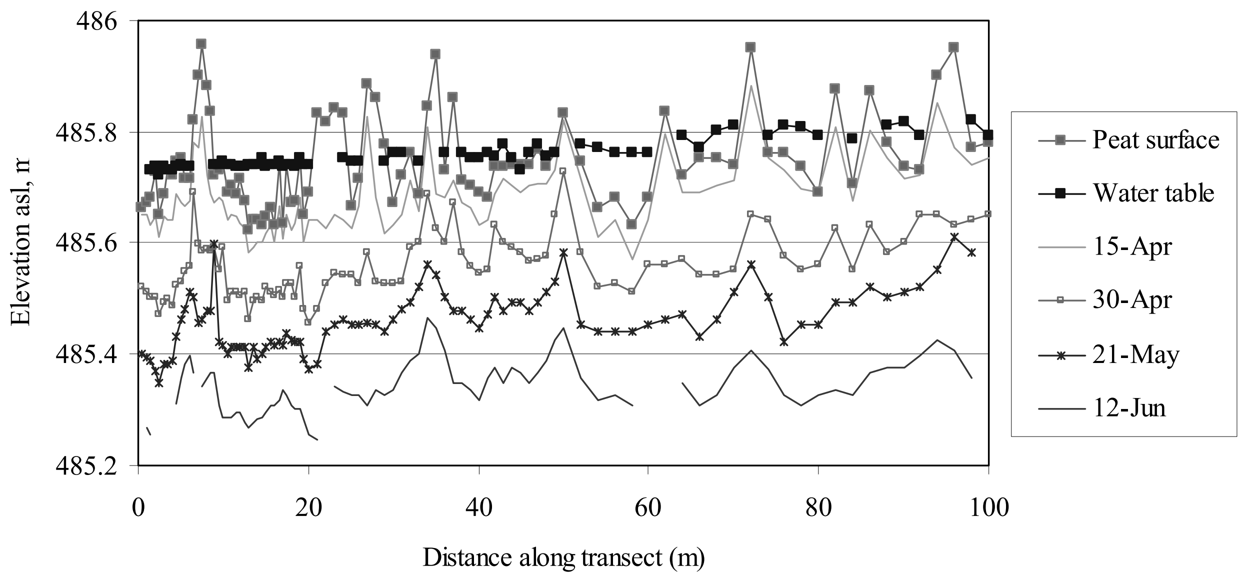

Figure 3.5-4 Progression of thaw along Transect 2 (Fen Centre site) in the spring of 2003, with peat surface and water table elevations shown for April 15

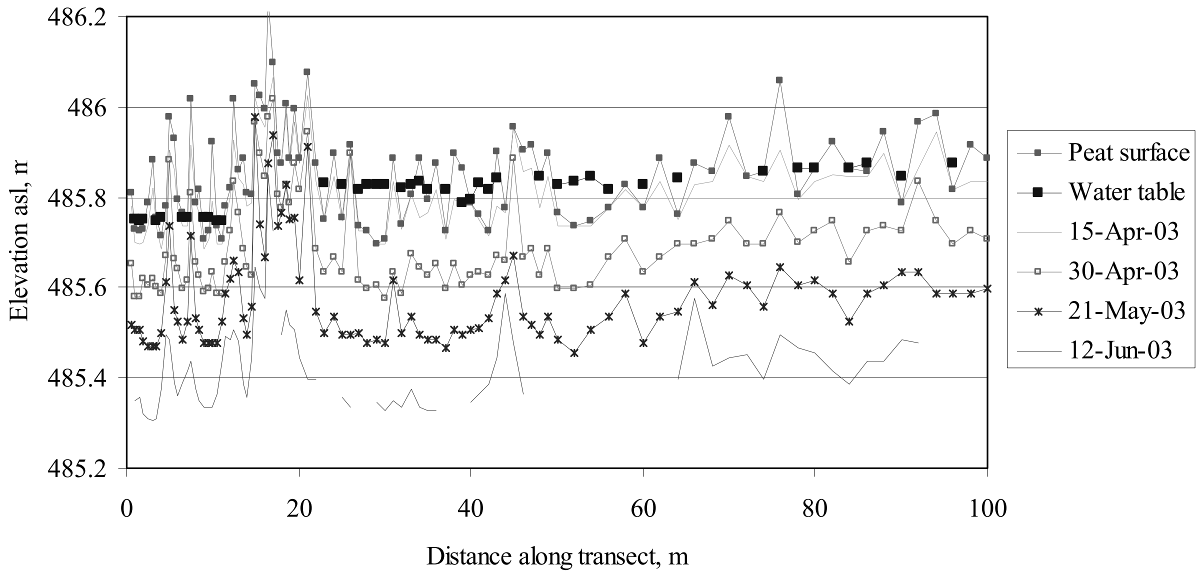

Figure 3.5-5 Progression of thaw along Transect 3 (Partially Treed site) in the spring of 2003, with peat surface and water table elevations shown for April 15

Frost table elevations were measured at 100 points for the three transects. Figure 3.5-6 shows a comparison of mean thaw depth for three sites in 2003, based on the transect surveys. The mean thaw depth among the three transects are similar for all the surveys; however, frost was persistent along Transect 1 even into July. Mean monthly thaw depth data at each site was used in the peat surface model.

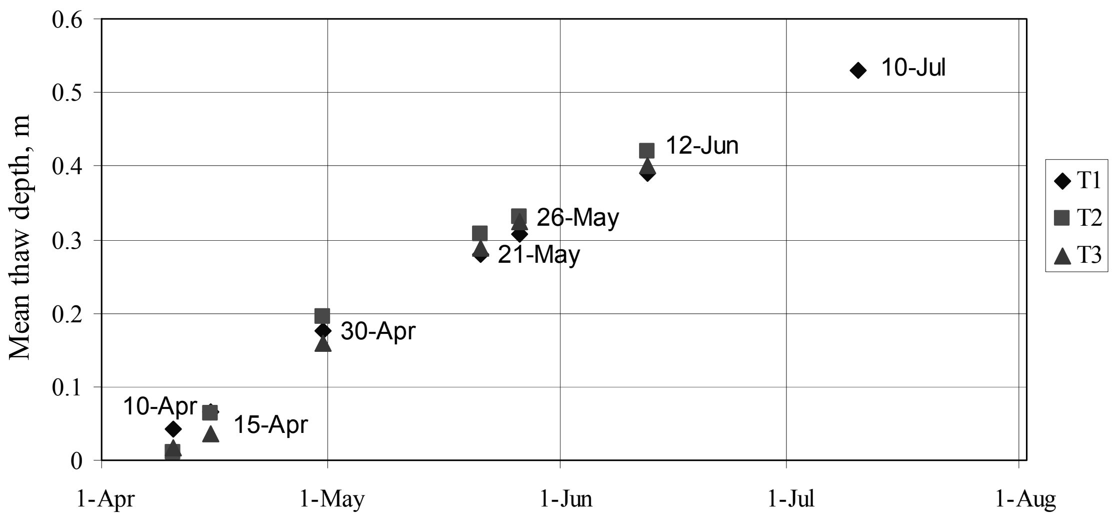

Figure 3.5-6 Mean thaw depth of frost table over the spring of 2003 along three separate transects (Edge, Fen Centre, Transitional treed)

3.5.1.4 Zero-Degree Depth

Figure 3.5-7 shows the mean monthly zero degree depth for five sites in Sandhill Fen, for the winter seasons of 2002-2003 and 2003-2004. The ridge and swale locations are adjacent to Transect 2, the hummock and hollow locations are adjacent to Transect 3, and the edge location is located near Transect 1. The monthly zero degree depth for all sites was comparable within 0.1 m, except for the Transect 3 hummock site. This thermocouple string was in a large exposed hummock beside a tamarack tree (*Larix laricina*). The depth of frost below the surface was deeper in the hummock than the other sites through the winter. It was also the last thermocouple site to contain frozen peat in June and July at depths of 0.8 to 1.0 m. If the top 0.2 m of the hummock were removed, the thermal regime of this site would be similar to the other four with respect to zero degree depth. The ridge site of Transect 2 showed the peat temperature patterns as the hummock site of Transect 3, but on a smaller scale. The maximum zero-degree depth below the surface was approximately 0.6 m for all five sites the first season of the study, and 0.5 m the second season.

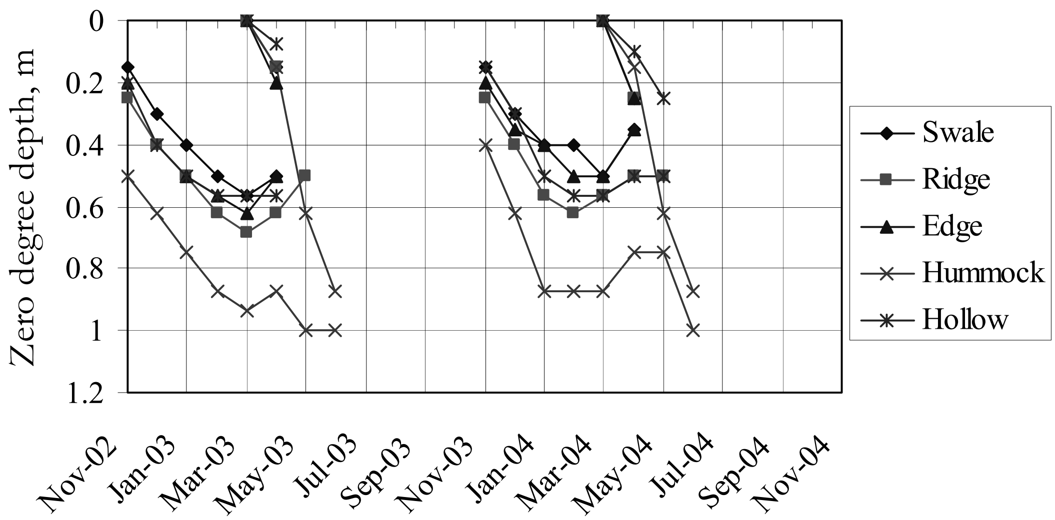

Figure 3.5-7 Monthly zero-degree depth based on mean half hourly temperatures from thermocouple measurements at five sites in the fen

In May and June, monthly thermocouple data for most sites showed the absence of negative temperatures, even though the frost probe surveys consistently showed a solid frost table. The zero-degree depth of the peat thawing in April was deeper than the thaw depth determined with the frost probe surveys along the 100 m transects. This may be due to some conduction of heat along the metal-tipped fiberglass rods to which the thermocouples were attached. Disturbed areas beside the benchmark pipes or boardwalks also caused these areas to thaw the quickest.

3.5.1.5 Water table and piezometric head

The water table and piezometric head elevation was measured from the fall of 2002 to the fall of 2004 on a regular basis (Figure 3.5-8). Measurements were taken relative to stationary benchmarks within the fen at the three study sites. Water table elevations were measured manually outside the benchmarks, from the period of snowmelt in spring, to the late fall. Although the water table at the three sites was similar in the spring, after a dry summer of 2003, the water table at the Edge site declined most significantly.

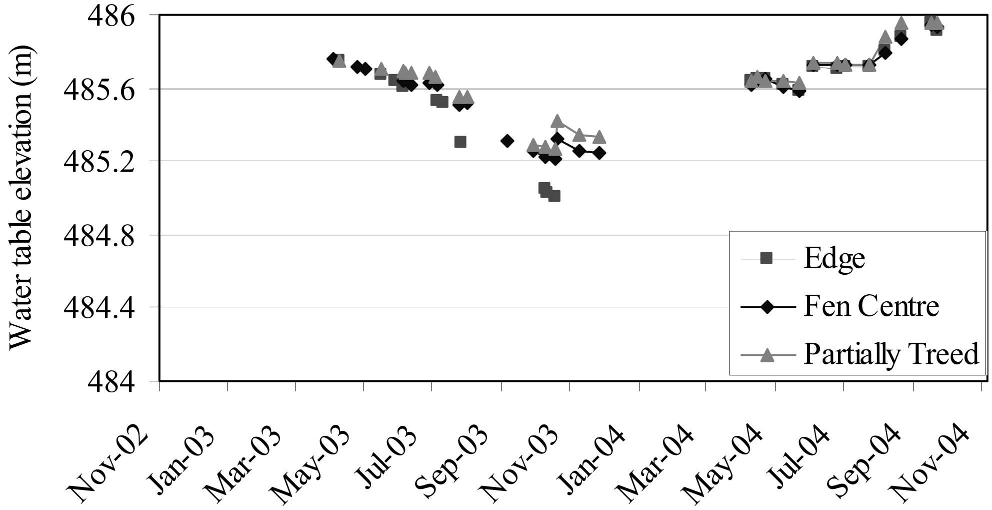

Figure 3.5-8 Measurements of water table elevations over time at the three study sites in Sandhill Fen

Piezometric head elevations were measured inside the benchmark pipes, that also functioned as piezometers (Figure 3.5-9). The intakes of the benchmark-piezometers were beneath the peat, in the underlying sand. As ground frost did not penetrate to the depths of the benchmark-piezometer intakes, pressure transducers installed in them recorded the piezometric head throughout the winters. Seasonal trends and the magnitude of piezometric head were similar for the Fen Centre, Edge, and Partially Treed sites. The Edge site consistently had a lower piezometric head elevation than the other two sites to the west. Seasonal trends show declines of piezometric head in the winters of 2002 to 2003, and 2003 to 2004. Piezometric head rises again in the springtime. In the dry summer of 2003, the piezometric head at all the sites declined, while the wet summer of 2004 showed increasing piezometric head elevations, due to inter-annual differences in precipitation.

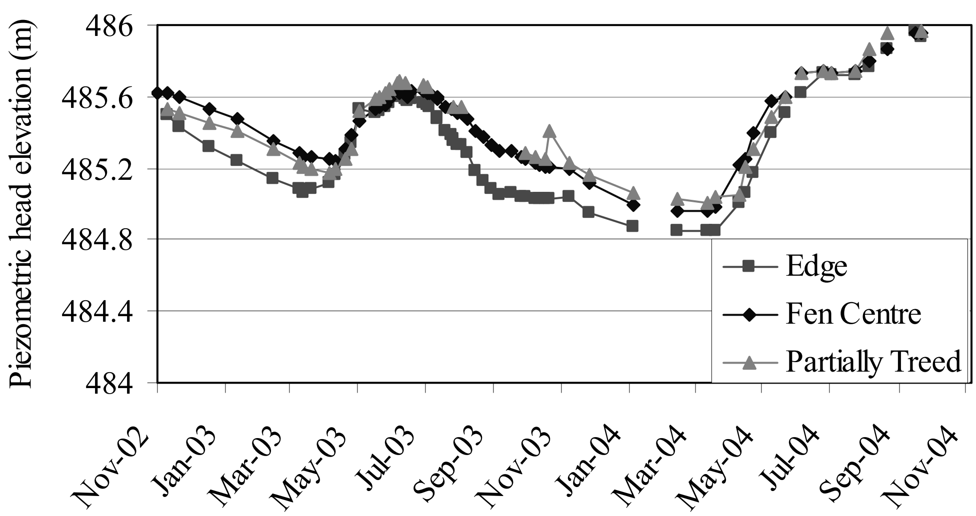

Figure 3.5-9 Measurements of piezometric head elevation over time at the three study sites in Sandhill Fen

3.5.1.6 Peat surface movement

An underlying question was whether the peatland surface moved as one entity, or if the hummocks and hollows moved independently. From topographic surveys along the transects, it was found that the high and low points of the peatland moved in tandem. Peat surface elevation data collected for the three transects over time is shown in Appendix C as graphs and in tables. While only the first 20 m of transect data from the south end is shown in the figures, the surveys covered the full 100 m in length.

Peat surface elevation surveys were important for verifying that the bog shoe data was representative. The ridge and swale topography occurred on a larger scale than hummocks and hollows. The peat surface elevation from all the transect surveys was compared with the elevation at the bog shoe sites (Figure 3.5-10). BST1, BST2 and BST3 are the bog shoes measuring peat surface elevations at the primary study sites south of Transects 1, 2, and 3, respectively. Mean peat surface elevation along the first 20 m of three transects are shown in comparison to the bog shoe elevations. Peat surface movements measured along transects 1 and 2 match well with the bog shoe movements. However, the mean elevation of Transect 3 continued to diverge from the bog shoe elevations measured over the period of the study. The elevation of the benchmark for Transect 3 was stationary through the study period, as verified with optical surveys. There is no known systematic error to explain this divergence, however it may be related to the position of the bog shoe on a hummock.

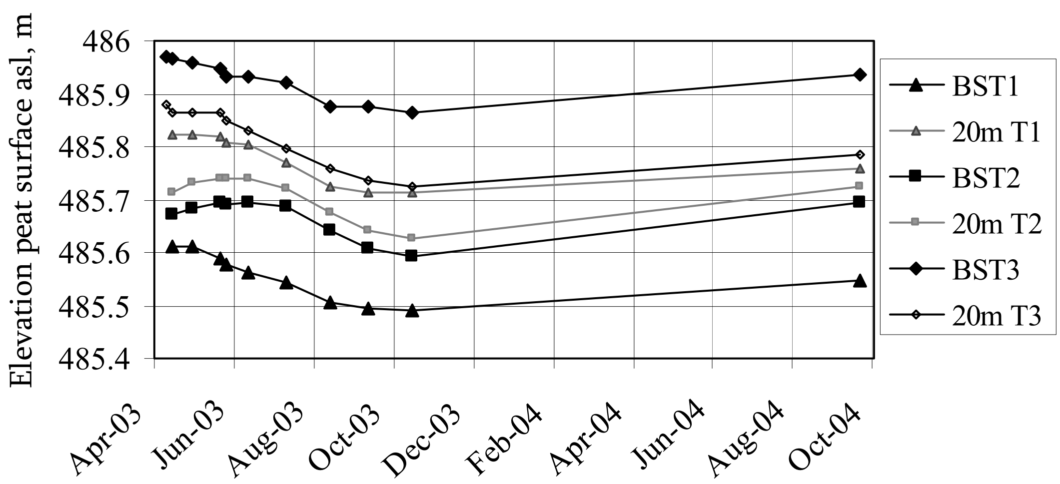

Figure 3.5-10 Elevation of the peat surface compared for three bog shoe sites and the mean elevation of the first 20 m of their corresponding transects

Peat surface movements are shown for three study sites in Figure 3.5-11. Elevations represent the average surface movement of the peat in the area of the bog shoes. Coinciding with the spring rise of piezometric head, there was peat surface rebound at the Fen Centre site. In contrast, the Edge and Partially Treed site bog shoes started subsiding in May. This subsidence coincided with both the thaw of the frost from the surface and lowering of the water table. Total subsidence at the Edge site from mid-April to the beginning of July was 0.065 m.

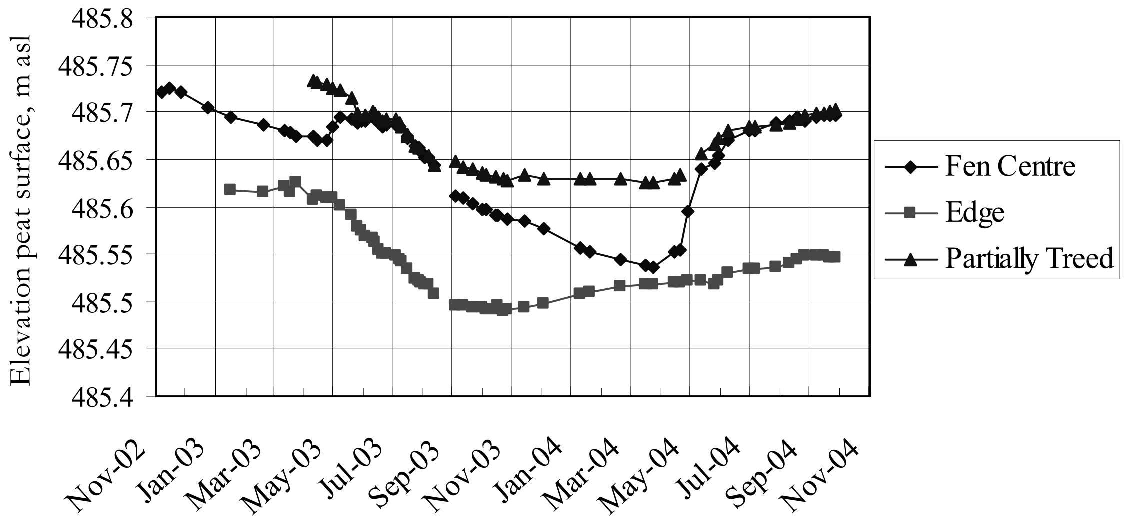

Figure 3.5-11 Change in peat surface elevation measured at bog shoes at three sites in Sandhill Fen

Subsidence of the three sites over the summer and fall of 2003 were similar, in the range of 0.1 m. The rate of compaction is reflected in the steepness of the elevation change over time plot. The months of July and August showed the highest rates of compaction, conforming to a period of scarce rainfall and high evapotranspiration. In the fall subsidence continued at a reduced rate at all sites.

These data in Figure 3.5-11 show important differences in the timing and magnitude of volume changes between the three sites. For example, the Edge site showed the most rebound during winter because the peat is thin there and froze throughout most of its thickness. At the Fen Centre site, subsidence of the peat continued over the winter and overwhelmed the rebound due to freezing of the acrotelm. Rebound of the surface in the spring and summer of 2004 was greatest at the Fen Centre site, and occurred most quickly there.

Peat surface change is highly related to water table change during periods of prolonged drying or wetting of the fen site. Figure 3.5-12 and 3.5-13 show the relationship of peat surface elevation change to water table decline, and water table rise, respectively. Water table decline in the summer of 2003 is shown for the period from June 17 to October 26, 2003. Water table and peat surface elevation increases are shown for the period of April 15 to September 27, 2004. Linear correlation of water table decline and subsidence measured with bog shoes at the three study sites produced R-square values of between 0.88 and 0.99, and standard error values of between 0.003 and 0.01 m. The high R-square values suggest that water table change is the primary control of peat surface change during the frost free period. The significance of these relationships is a result of the extreme drying and wetting phases that characterized Sandhill Fen in 2003 and 2004. The magnitude of peat thickness change was greatest at the site with the thickest peat; the Fen Centre site.

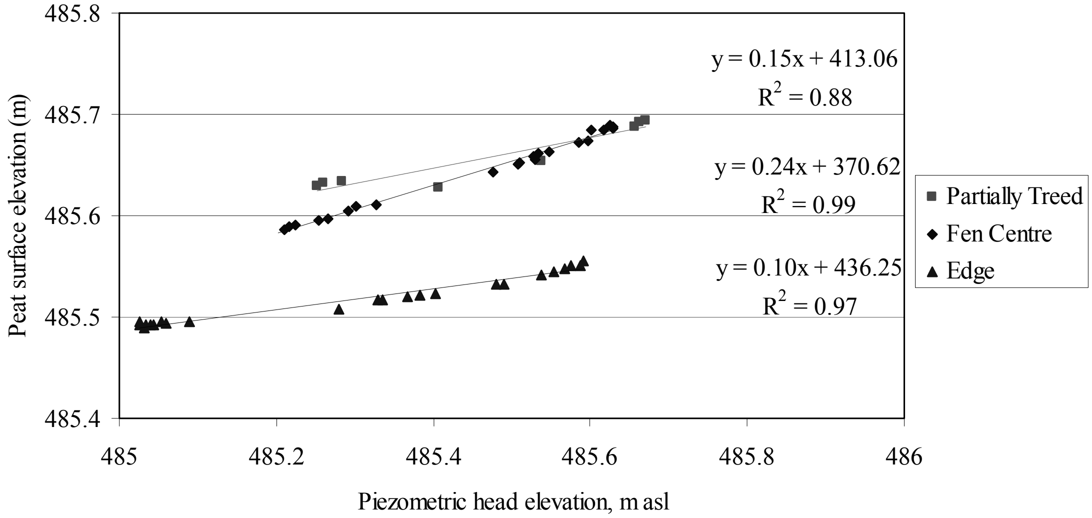

Figure 3.5-12 Relationship of peat surface elevation and water table decline during the dry summer of 2003

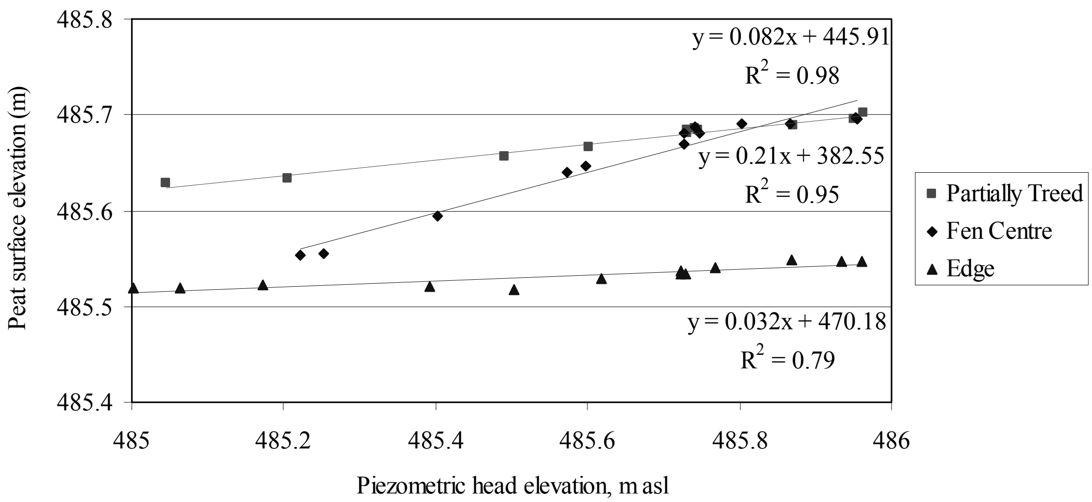

Figure 3.5-13 Relationship of peat surface elevation and water table rise during the wet summer of 2004

Heavy rainfall in the summer of 2004 caused the water table to overtop the peat surface over most of the open fen. With the rising water table, the peat expanded vertically. The ratio of peat expansion to the rising water table elevation was not as great as that of subsidence to water table decline. By the end of the summer of 2004, all three sites rose to the elevations they were measured at in June, 2003. However, by the end of that summer the water table was 0.3 m higher than in June, 2003. These observations showed that seasonal peat subsidence in 2003 was greater than rebound in 2004.

3.5.1.7 Strain

Vertical strain of the peat was measured with elevation sensor rods anchored at different depths. These were surveyed relative to the nearest benchmark on four occasions from July 30 to October 17, 2003. This coincided with a period of drought so that the compaction of the peat was significant. The change in elevation (Δz) of each sensor was calculated relative to its first surveyed elevation on July 30, 2003. Figure 3.5-14 shows the relative change in elevation of the sensors. The average movement of all the sensors at each depth is highlighted by the connected lines. Movement of the peat is greatest at the surface, decreasing in each layer at greater depth. The average movement of these four surface points and the bog shoe were used to estimate strain of the surficial peat.

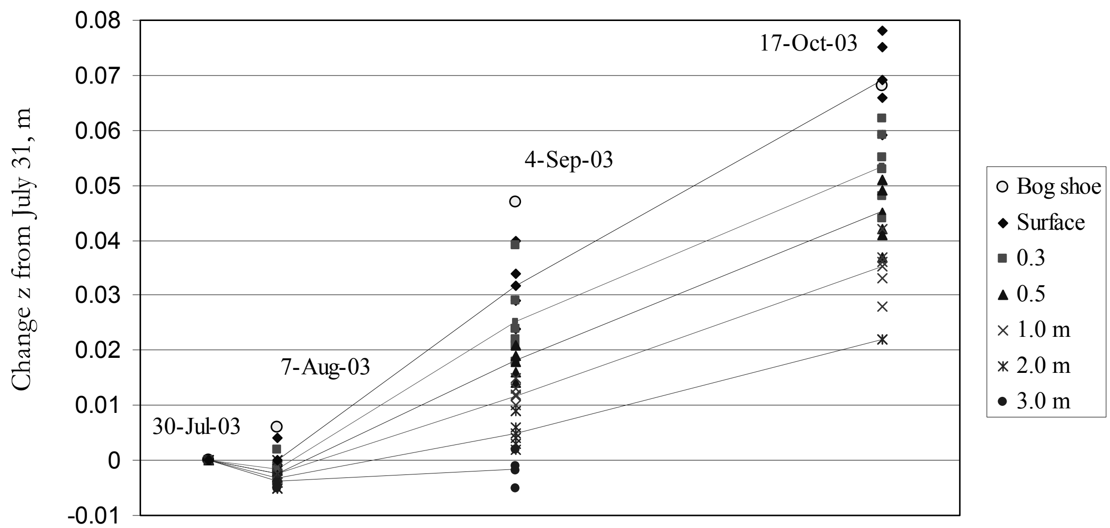

Figure 3.5-14 Movement of the bog shoe and all the elevation sensors relative to July 31, 2003, the mean elevation change of each depth is shown by connected lines

Due to the reduced accuracy in using level surveys even at these short distances, and the variability of movement of elevation sensors, the average strain measured at each depth in the different locations was used. The standard deviation of the strain values was relatively high for all depths.

The average and standard deviation of the strain of each layer is shown in Figure 3.5-15. As expected, the strain accumulates over time, with the highest strain experienced near the surface. For the layers at and below 0.5 m, strain over the period of subsidence was less than 2%. Above 0.5 m, strain increased to 4 to 6%. The upper 0.3 m became completely unsaturated by October, so that strain in the upper layer is likely the result of negative pore pressures, and processes of shrinkage.

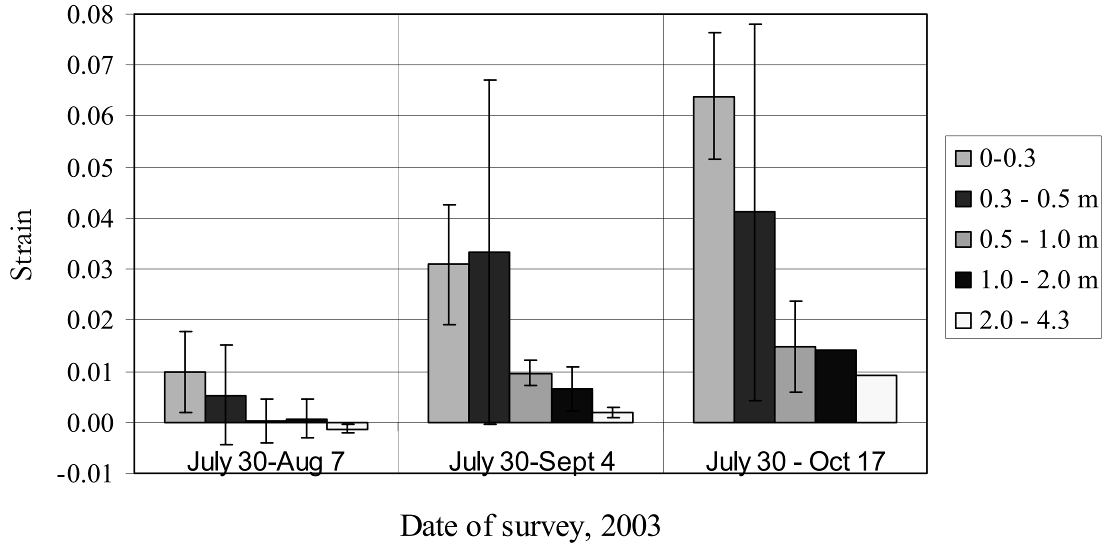

Figure 3.5-15 Mean and standard deviation of strain of peat layers

3.5.1.8 Summary data

Combined hydrological and peat temperature observations of the three fen sites are shown in Figures 3.5-16 to 3.5-18. In the frost free period, piezometric head below the peat was near the same elevation as the water table. During parts of the summer the piezometric head was slightly higher than the water table, indicating a small upward gradient, likely induced by evapotranspiration. The piezometric head was isolated from the water table as freezing progressed in late fall. Through the winter the head at all sites dropped significantly as the depth of frost increased. Late in the spring, the piezometric head increased again to pre-winter levels. The spike of head in late October, 2003 at Fen Centre and the Partially Treed site was measured both manually and with level-loggers, and coincided with a snowfall event.

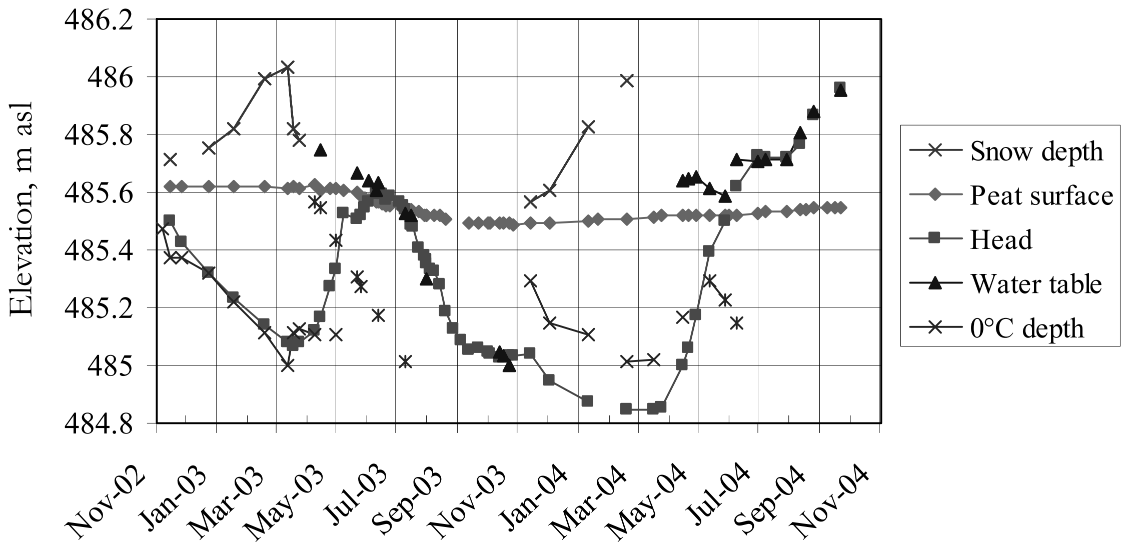

Figure 3.5-16 Hydrological observations at the Edge site during the study period

While the piezometric head, peat temperature, and snow depth were measured continuously at the fen site, the results shown are only for the days that peat surface measurements were made. More complete data sets of these observations are displayed in Appendix D. The monthly zero-degree depth data displayed in these summary figures are based on the same mean half-hourly data used in Figure 3.5-7. There were two thermocouple strings installed at the Fen Centre and Partially Treed sites, but only data from the Fen Centre swale and Partially Treed site hollow are shown here.

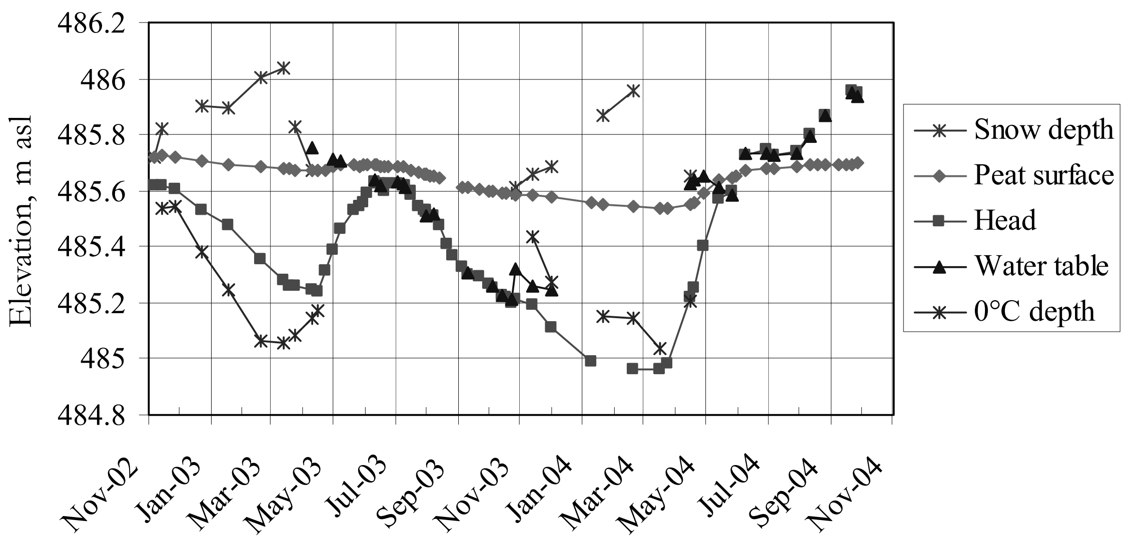

Figure 3.5-17 Hydrological observations at the Fen Centre site during the study period

Peat surface data shown for the Partially Treed site were measured from the bog shoe located on a hummock beside the benchmark/piezometer. For this reason the water table was low relative to the top of the hummock for most of the study. The bog shoe was only installed at the Edge site in January, 2003 and at the Partially Treed site in April, 2003. For the Edge and Partially Treed sites, the elevation of the peat surface for the winter of 2002 was set equal to the first measurement.

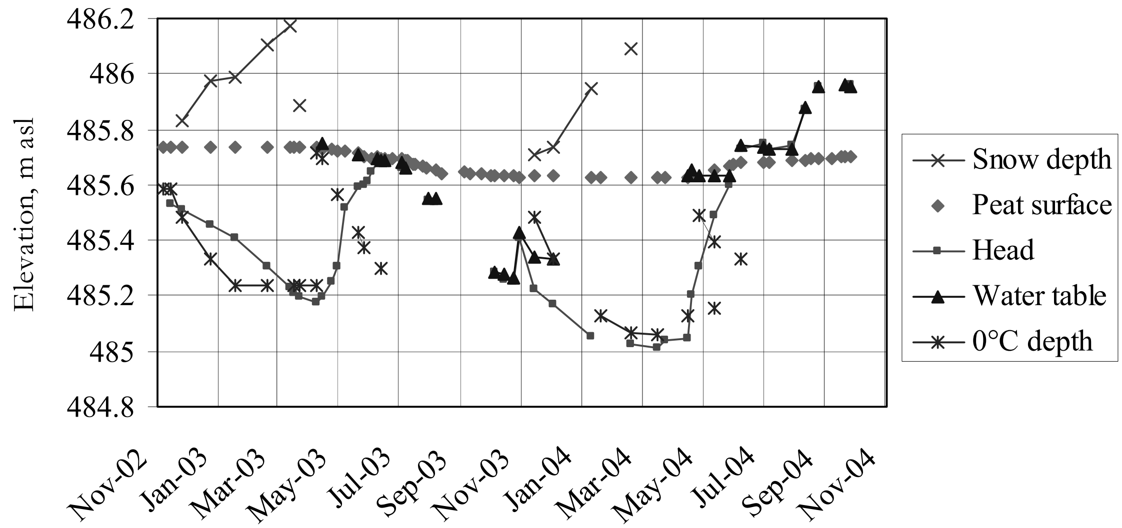

Figure 3.5-18 Hydrological observations at the Partially Treed site during the study period

3.5.2 Seasonal water storage

Total water storage was calculated for three sites using Equation 3.4. This is the sum of water stored above the peat surface, unsaturated and saturated water within the peat, and snow water equivalent in the winter (Figure 3.5-19). Snow water equivalent was calculated from snow surveys on a monthly basis the first season. For the winter of 2003-2004, it was measured regularly at one of the sites, and these estimates were used for the other two sites. Water stored above the peat surface was measured by water table height relative to a datum. During the winter months, the piezometric head was below the peat surface, and this was assumed to be equivalent to the water table.

All three sites in Figure 3.5-19 show the same patterns of reduced storage in the dry summer and fall of 2003, and replenishment in June of 2004 as precipitation increased significantly. It was assumed that storage within the peat did not change over the winter, so the thickness of the unsaturated layer was set to a mid-November value. The only change in water storage in winter was due to snow accumulation. The peat layer that was unsaturated through the winter was assumed not to become saturated in the spring until it thawed. Due to these assumptions, the calculation of water storage was more trustworthy during the frost-free season.

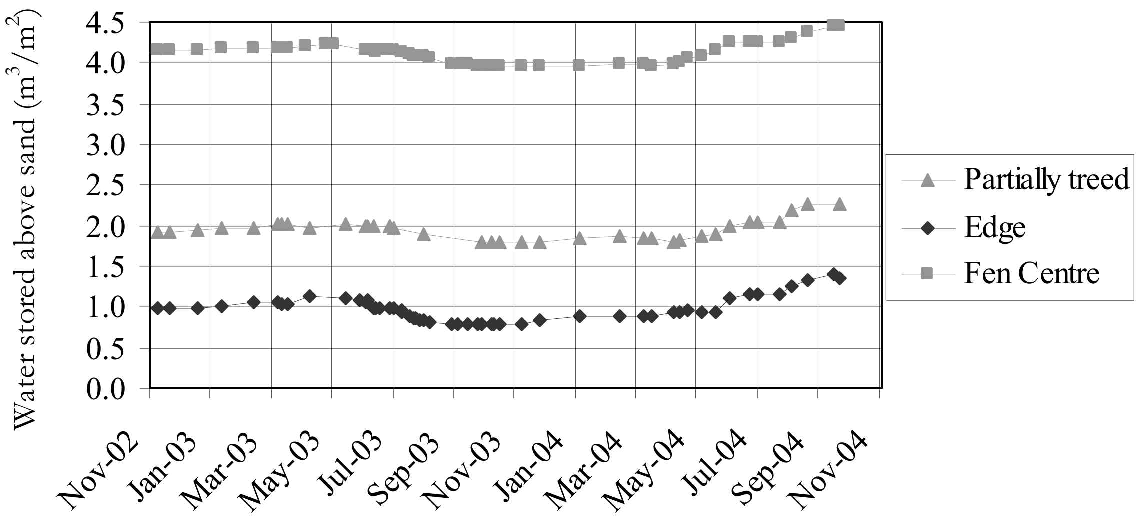

Figure 3.5-19 Daily and weekly measurements of total water stored above and within the peat at three sites in Sandhill Fen

For the study period the change in water storage at the three sites is compared in Figure 3.5-20. In 2003, storage was most depleted at the eastern Edge site, and least depleted at the Partially Treed site (PT) to the west. The depth of the water table became greatest at the Edge site. With the high precipitation beginning in June, 2004, all fen sites quickly recovered their water losses and surpassed initial storage values by 0.3 m.

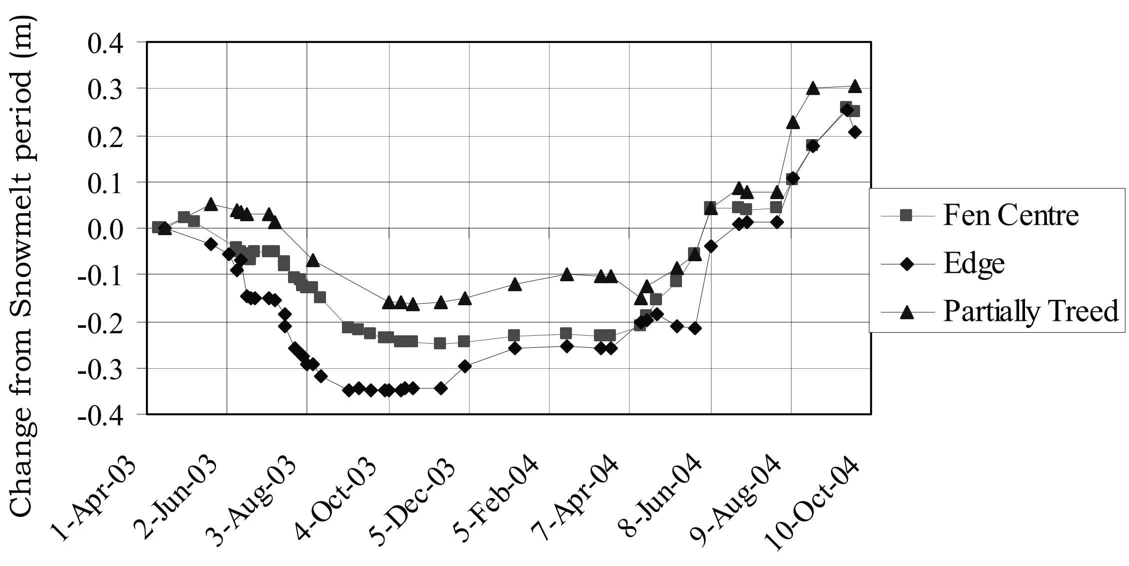

Figure 3.5-20 Change in spring and summer water storage at three sites

3.5.3 Compressibility of Sandhill Fen peat

Compressibility quantifies the ability of the peat to expand and contract in response to effective stress changes. Water table change influences total stress on the deposit and pore pressure height within the peat. Above the water table, the loss of moisture reduces the total stress, but also has negative pore pressures. The accumulation of snow on the peat surface creates a load and increases total stress. Effective stress was calculated for the top of each peat layer. The compressibility of the peat layers is equivalent to the slope of the effective stress-strain plots shown in Figure 3.5-21.

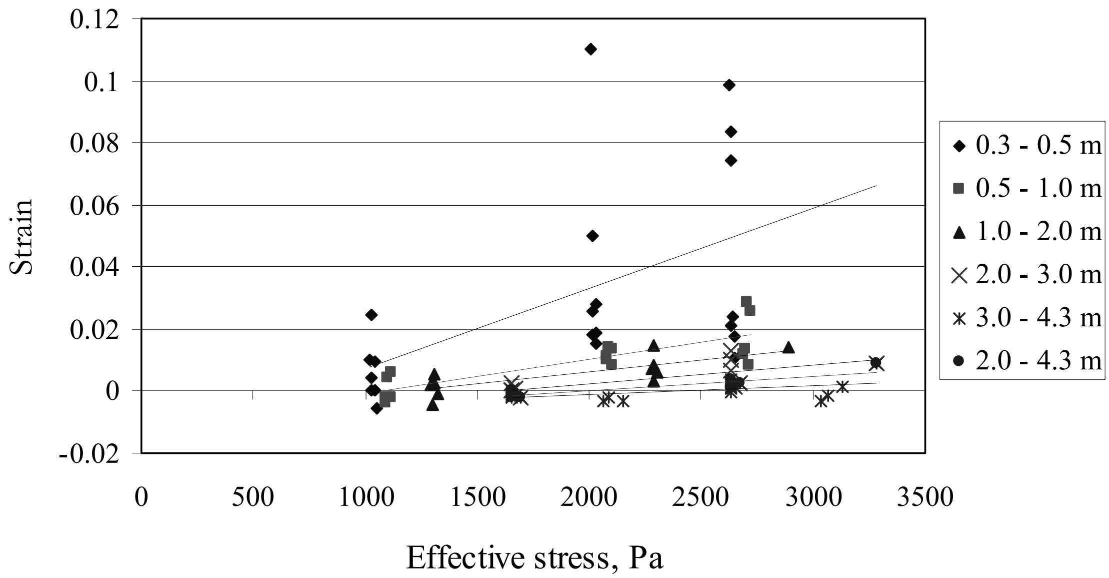

Figure 3.5-21 Effective stress versus volumetric strain measured with elevation sensors at the Fen Centre site in 2003

Compressibility was estimated to be highest near the surface (Figure 3.5-22). Calculations of effective stress were based on the overlying stress of saturated and unsaturated peat layers. The layer at a depth of 0.3 to 0.5 m had a compressibility of 2.5 x 10^{-5} Pa^{-1}. At 0.5 to 1.0 m, the compressibility measured was 1.1 x 10^{-5} Pa^{-1}, and at 1.0 to 2.0 m it was 8.1 x 10^{-6} Pa^{-1}. The deepest layers from 2.0 to 3.0 m and 3.0 to the sand were based on five sensors had a compressibility equal to 5.4 x 10^{-6} Pa^{-1} and 1.5 x 10^{-6} Pa^{-1}. Compressibility measured for the upper peat during the enclosed drainage test, was 2.2 x 10^{-5} Pa^{-1}(Chapter 2), which is comparable to results using the seasonal stress-strain method.

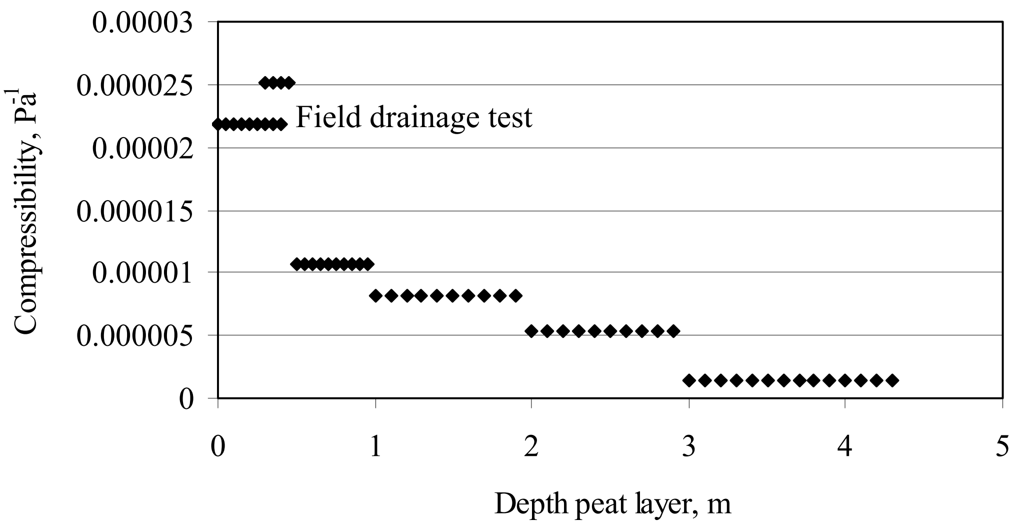

Figure 3.5-22 Compressibility estimated with depth in the peat

3.5.4 Peat surface movement model results

The model results are compared to observed monthly changes in peat surface elevation at the Fen Centre site in Figure 3.5-23. Results of the model are based on changes in calculated effective stress due to change in water table and unsaturated storage, and account for expansion due to frost formation. Predicted and observed peat surface elevations are a good match at the Fen Centre site in the summer and fall of 2003. Divergence of the model occurs after snowmelt in the spring, as it overestimates the rebound of the peat by over 0.05 m. Modeled and observed data converge by the fall of 2004. Although the model doesn't explain spring thaw processes, it does predict peat surface change well the rest of the year.

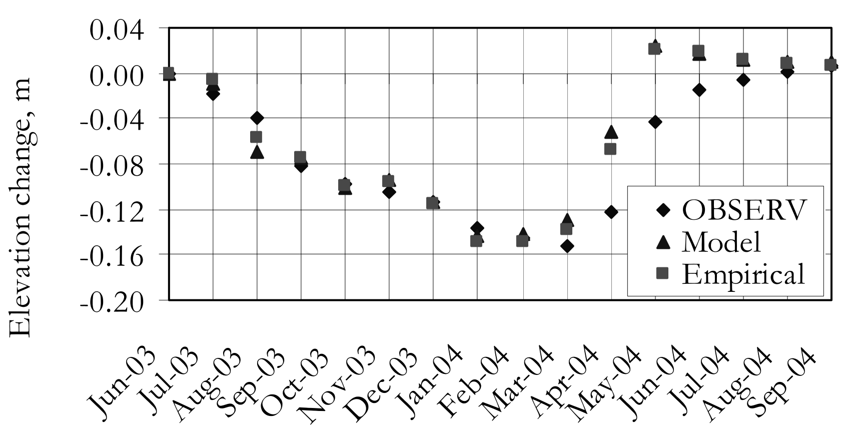

Figure 3.5-23. Results of a peat surface movement model compared to mean monthly observed peat thickness for a site in the centre of Sandhill Fen

The use of an empirical method to define changes in acrotelm thickness instead of using effective stress is also shown in Figure 3.5-24. Measured changes in peat acrotelm thickness and water table depth or height above the surface were used to generate a linear relationship. The cumulative change in acrotelm thickness was generated from the same techniques for measuring strain, described above in Section 3.5.2. When the water table was at equilibrium at the surface, the acrotelm was given a thickness of 0.4 m. Acrotelm thickness change is equal to -0.0671 times the change in water table depth. This was used to estimate the acrotelm thickness from month to month, that was then used in the calculation of effective stress. This slightly simplified method performed virtually the same as the one that estimated the effective stress.

The same model was applied to the Partially Treed and Edge research sites in the fen. They show the same general patterns as for the Fen Centre site, but don't match the observed changes in peat thickness as well. The Partially Treed site model overestimates the change in elevation during the summer of 2003 by 0.02 m (Figure 3.5-24). It exhibits greater subsidence in the winter than what was measured, and greater rebound in spring. The Partially Treed site modeled and observed peat surface elevations converge in the fall of 2004. The Edge site model shows a higher elevation than observed, and this may be due to the lack of rebound of that site compared to the others.

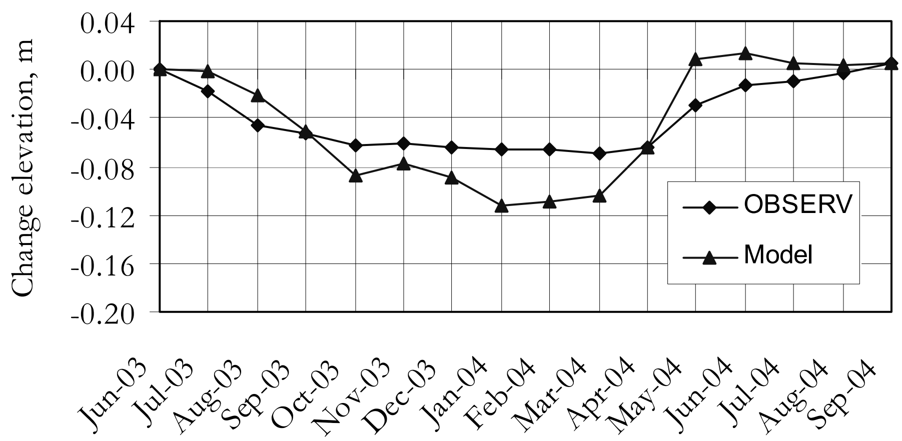

Figure 3.5-24. Results of a peat surface movement model compared to mean monthly observed peat thickness for the Partially Treed site

The Edge site was located in shallow peat of approximately 1 m in thickness. This site still experienced over 0.06 m of subsidence by the fall of 2003, comparable to that which occurred at the Partially Treed site. Although this site was assumed to have the largest compressibility overall based on the weighted average of the catotelm, its shallowness prevented the model from estimating larger changes in elevation. By the end of the summer the model was within 0.01 m of observed subsidence. As noted earlier, the Edge site didn’t rebound as much as the other two sites during the wet summer of 2004. The model suggests that rebound occurred quickly in the late spring of 2004 when water levels rose significantly, and that rebound was as large as subsidence. As shown in Figure 3.5-25, the Edge site peat began to increase in thickness early in 2004, even though frost expansion was accounted for. This was the only site that increased in peat elevation over the winter, by about 0.03 m.

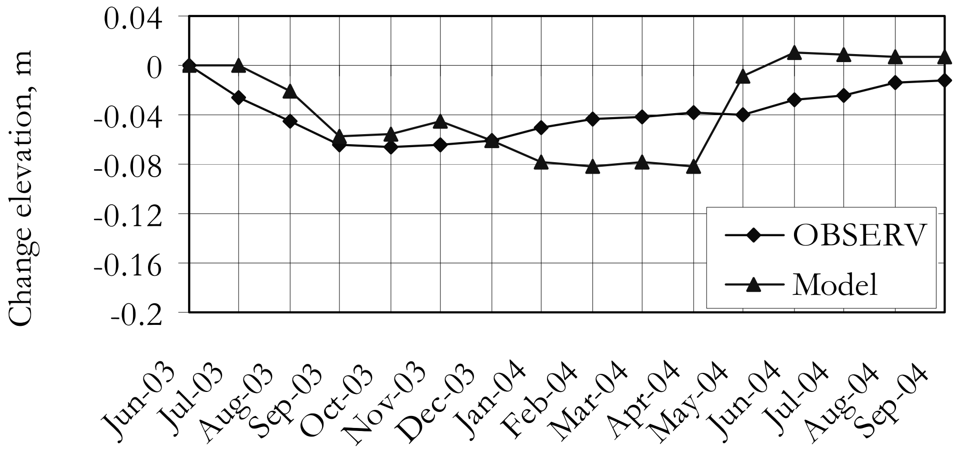

Figure 3.5-25. Results of a peat surface movement model compared to mean monthly observed peat thickness for the Edge site

It is important to describe the model results using quantitative measures of agreement between predicted and observed values. Table 3.5-1 shows the mean observed and predicted values, root mean square error (RMSE), systematic and unsystematic differences ($RMSE_s$ and $RMSE_u$), the index of agreement (d), and the R-square value for comparison. The level of agreement between predicted and observed peat surface movement is largest at the Fen Centre site and lowest at the Edge site. As shown in the table, the R-square values are not consistent with the other measures of model validity.

Table 3.5-1 Quantitative measures of peat surface movement and model performance

Site	Mean O_i	Mean P_i	RMSE	$RMSE_s$	$RMSE_u$	d	R^2
Fen Centre	-0.071	-0.057	0.029	0.013	0.025	0.937	0.832
Partially treed	-0.041	-0.046	0.026	0.016	0.019	0.873	0.841
Edge	-0.041	-0.036	0.028	0.012	0.028	0.702	0.494

All three measures of average difference between predicted and observed peat surface movement are relatively low, between 0.01 and 0.03 m. The unsystematic error is slightly larger than the systematic error at all three sites. This indicates that improvement could be made to the model's formulation, rather than to the adjustment of parameters. Still, making adjustments to, and providing natural limits for, the model parameters is useful for understanding peat behavior.

3.5.5 Sensitivity analysis

Modifying model variables such as snow depth and quantity of unfrozen water in the frozen peat shows the response of peat thickness to changing winter conditions. Higher amounts of snow loading increases total stress on the peat and increases effective stress and subsidence. Having 0.2 m of snow water equivalent is approximately equal to 2 m of fresh snowfall if the density of snow is 100 kg/m^{-3} (Pomeroy and Gray, 1992). Snow density measured along three transects in the fen in February, 2004 averaged 160 kg/m. The high snow water equivalent depicted in Figure 3.5-26 would then be equivalent to a very large snow accumulation of 1.25 m depth. As the figure shows, the effect of measured snow accumulation on peat thickness change in the winter of 2003-2004 was moderate.

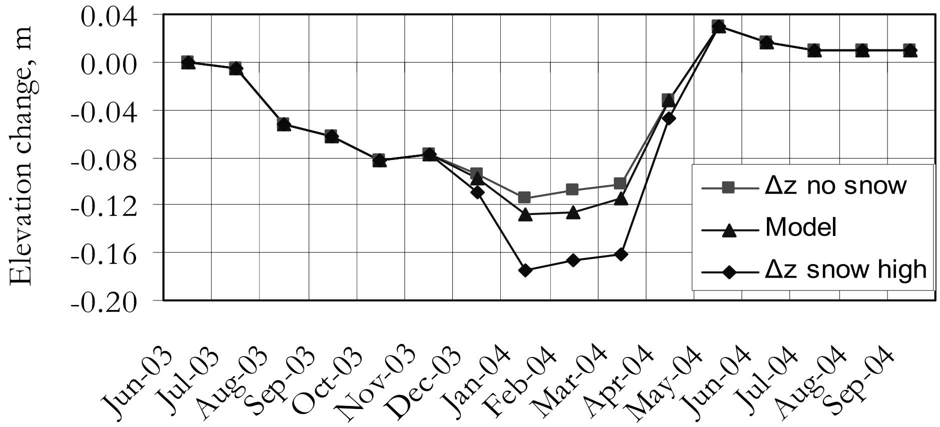

Figure 3.5-26 Sensitivity analysis of adjusting the snow water equivalent at Fen Centre for measured values (Model), no snow loading, and loading of 0.2 m SWE

The unfrozen water content in the peat is known to influence peat volume changes (Pavlova, 1970). The assumption of 40% unfrozen water content within the frozen peat may be variable between sites, due to differences in peat properties or pore water chemistry. This was varied in the Edge site model by assuming that 1) there was no unfrozen water content, and 2) that there was 60% unfrozen water content in the frozen peat. The amount of expansion was directly related to the amount of frozen water. With the unfrozen water content set to zero (a decrease of 40%), the model simulated additional peat expansion of 0.015 m. Increasing the unfrozen water content by 20% decreased peat expansion by the same amount.

Testing the sensitivity of the peat thickness model results to compressibility was done in two ways. First, the compressibility of the catotelm layer was varied from the calculated value by 50% in each direction, while acrotelm compressibility remained the same. Secondly, the compressibility was made uniform for the peat deposit, and set equal to the catotelm and acrotelm values. Acrotelm compressibility used for the model was 2.5 x 10^{-5} Pa^{-1}, while catotelm compressibility was 5.5 x 10^{-5} Pa^{-1}.

As shown in Figure 3.5-27, changes in catotelm compressibility by 50% in each direction had a significant effect on changes in peat thickness during periods of subsidence. The 50% decrease in compressibility of the catotelm caused decreased change in peat thickness by 0.05 m during the dry fall and winter of 2003. With increased compressibility of this layer, peat thickness change increased subsidence by 0.05 m. With a deeper peat deposit such as at the Fen Centre site, the thickness and compressibility of the larger layer is more important. Decreasing the catotelm compressibility for the Partially Treed site model produced better agreement when compared with observed peat thickness change.

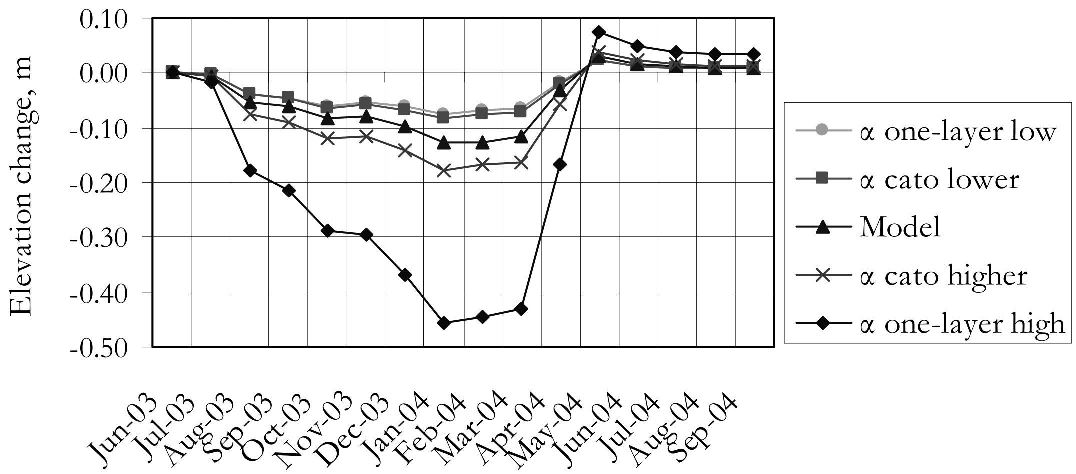

Figure 3.5-27 Sensitivity analysis of compressibility at Fen Centre comparing results of adjusting the catotelm compressibility by an order of magnitude, and creating uniform peat compressibility equal to the acrotelm or catotelm value

With a uniformly high compressibility the accumulated subsidence over the fall and winter of 2003 was extreme compared to the original model results. Subsidence of 0.5 m for this period would be highly unlikely, and would be matched by an equal amount of rebound in a short period of time in the spring. Assuming the compressibility of the acrotelm was equal to the catotelm value, the opposite scenario occurs. Changes in peat surface elevation would be less than the original model results by at least 0.05 m. It should be noted that for all values of compressibility, the peat surface elevations converge by the fall of 2004.

Increasing the peat storativity (S) values in the acrotelm layer influenced peat thickness changes over time. In the model, this decreased the overall amount of subsidence, and generally increased the amount of rebound. Increasing the storativity means less water is retained in storage with a change in water table depth, that slightly decreases the peat density of the unsaturated layer (D_u). This is because the density of water is much greater than the bulk density of peat. Increasing the storativity in the model caused the average difference of the RMSE parameter to increase, and the index of agreement (d) to decrease for the model of the Fen Centre site. This indicated less agreement between observed and estimated values.

3.6 Discussion and Conclusions

3.6.1 Hydrology

Characterization of peatland hydrology involved year round observations. Datasets of the hydrology and subsurface thermal regime, combined with physical and hydraulic properties of the peat give the basis for understanding the functioning of Sandhill Fen. These datasets and methods may be applied in future studies involving hydrological modeling, groundwater flow properties in peat, or investigations of an ecological nature.

Precipitation and evapotranspiration drive water table changes in the peat, although drainage processes in and out of the fen can be important at times. The summer of 2003 had low precipitation and discharge measured at this site and in the surrounding region. Consequently, the water table dropped and subsidence of the peat surface occurred from July and into the winter of 2003-2004. In contrast precipitation and discharge in the fen region in the late spring and summer of 2004 was the highest on record, that brought the water table well above the peat surface. With extreme wetting and drying phases, the peat surface elevation changes were highly related to water table changes. Under more static water table conditions, factors other than water table elevation may influence peat thickness.

The lowered piezometric head in the winter of 2003 and 2004 may have been the result of freezing of the pore water. If additional water was transported to the freezing front from the water table, it was not measured. Freezing of water near the surface might cause the water pressure beneath the frost to decrease as this underlying layer becomes unsaturated. The abrupt rise in piezometric head during the spring of both years may also be due to the release of the lower pressure when the frost layer begins to dissipate.

During initial thaw in 2003 and 2004 the frost table was virtually impermeable, so that the piezometric head was unconnected to the perched water table. Surface water perched in the fen hollows and swales during and after snow-melt was gradually absorbed by the thawing peat. The frost in ridges affected the height of the water table for a short time in spring; in Figure 3.5-5 this is visible at a distance of 20 m from the south end of the Partially Treed site (at 0 m). The relatively impermeable frozen peat in the ridge created a temporary dam that held snow melt water. Additional observations of sustained water table differences inside and outside the polyethylene enclosure in both 2003 and 2004 supports the hypothesis of impermeable frost in the peat.

Accounting for the gradual freezing of peat over a range of temperature below zero, and/or of moisture redistribution may lead to different interpretations of frost or thaw depths (Goodrich, 1982). The two methods employed to gauge frost depth in this study didn't give the same results for the timing of thaw. The thermocouple data at depth in the peat suggested that the peat temperatures were slightly positive when frost probe surveys were still measuring substantial frost in the peat. While the frost probe readings were to the nearest 0.01 m and subject to additional error of as high as 0.01 m from the laser level survey method at distances greater than 20 m, the occurrence of hard frost at hundreds of points in the fen in the late spring was not a mistake. It is possible that the accuracy of the thermocouples was amiss, or else that the fiberglass rods to which they were affixed allowed conduction of heat to depth in the peat.

Thaw rates of the frost table measured with frost probe surveys were not significantly different between transects. However, swale sites in the fen centre transect were generally the quickest to thaw, likely due to the sensible heat of the snowmelt water. Most of the peat frost dissipated by the middle of June in 2003, and the beginning of June in 2004, with only intermittent frost observed under large hummocks in July. Both 2003 and 2004 were characterized by relatively dry fall conditions and little snow accumulation until January, sot that the frost penetrated to maximum depths of at least 0.4 to 0.5 m.

3.6.2 Water storage

Changes in water table, head, and soil moisture were not identical for the three sites monitored in the fen. The water table at the Edge site had dropped below the surface twice as far as the other sites in the fall of 2003. *C*hanges in water storage calculated for the spring and summers of 2003 and 2004 were also different for three sites in the fen. Accumulated loss of water from April to the end of October, 2003 ranged from 200 mm at the Partially Treed site to 400 mm at the Edge site. It would be useful to compare estimates of water content using storativity values with direct observations of water content.

A relationship between water storage and water table change was developed, that included peat compression. The storativity was assumed to be equal to 1.0 when the water table is at the peat surface, and decreases to approximately 0.13 at the base of the acrotelm (upper layer) of the peat. Integration of the storativity vs. water table depth plot allows the volume of water released with water table decline to be determined. This is related to changes of acrotelm thickness using the depth of the water table.

Measurements of precipitation minus evapotranspiration at the fen tower (between the Edge and Fen Centre sites) showed total losses of only 80 mm from May 1 to September 31, 2003. This was inconsistent with calculated negative change in storage based on water table depth and storage properties of the peat. Therefore water must have been lost through groundwater pathways. However, mean daily values of piezometric head and water table at the Edge and Centre fen sites usually indicated slight upward gradients consistent with losses by evapotranspiration. Fluctuations of the water table during the day showed the main losses occurred late in the afternoon, that shows the effect of evaporation. No over-pressuring was observed within the peat deposit in piezometer records. Lateral drainage through the peat is limited by water table gradients and peat hydraulic conductivity.

3.6.3 Specific storage and compressibility

The specific storage is the portion of total water storage lost or gained by volume change of the peat. It was as important as the specific yield in some studies (Schlotzhauer and Price, 1999) but in this study specific yield was more important. Surface adjustment implies the peatland is able to maintain higher water tables and water content in the dry years through subsidence. Lateral losses are impeded by low hydraulic conductivity. For the enclosed drainage test described in Chapter 2, the measured specific storage was 25% of total storage.

During the study period of 2003 and 2004, it was fortunate to have extreme drying and wetting trends that significantly influenced water table and peat surface elevations. The three sites in the open fen displayed the same general patterns of subsidence during prolonged dry periods and rebound during wet periods. Peat subsidence and rebound are highly correlated with changes in the water table and/or piezometric head. The seasonal vertical movement of the peat surface by as much as 0.15 m is an important water storage mechanism. Due to differences in peat depth and hydraulic properties, the seasonal subsidence and rebound of the peat surface was greatest in the centre of the fen and smallest at the Edge site.

The swelling of cutover peat from rising water levels was 5 times less than subsidence from declining water levels (Price and Schlotzhauer, 1999). In agreement with these results, a sub arctic fen also had greater subsidence than rebound for the same change in water table (Roulet, 1991). In this study, the magnitude of peat surface rebound for a unit piezometric head rise was less than would be expected if the peat was perfectly elastic in nature. During the wetting phase of 2004, the three sites in Sandhill Fen rebounded at different rates. The shallowest peat site on the fen edge didn't fully recover to its preliminary elevation in 2003. In contrast, the deep Fen Centre site recovered 90% of its original elevation.

Seasonal measurements of vertical strain were combined with estimates of change in effective stress to determine compressibility, that was as high as 2.5×10^{-5} Pa^{-1} in the upper peat. A large proportion (22%) of the peat subsidence occurred above the water table in the fall of 2003. These compressibility results are slightly higher than results from the study by Price (2003) in a drained bog peat, 7 years after abandonment, that found compressibility (α) of 3×10^{-6} Pa^{-1} at 1 m depth using a similar method.

As compressibility changes with the loading history of the deposit, and it was quantified during a very dry season in 2003, it might be of concern that the compressibility estimated in this study represented a virgin compression value. In that situation, compressibility would be too high, and the model would be predicting more extreme peat surface changes than would occur in future months. Other authors have attributed irreversible losses to the processes of secondary compression and peat oxidation (Kennedy and Price, 2004; Kennedy and Price, 2004). While this possibility cannot be ruled out, there is evidence to the contrary in the seasonal rebound of the peatland.

The Fen Centre site experienced almost complete rebound to previous elevations. Rebound lagged behind water table changes by a couple months at both Fen Centre and Partially Treed sites. The Edge site may have experienced irreversible compression in 2003 due to the extreme drawdown of the water table, or else the lag time for rebound is much greater.

3.6.4 The peat surface model

Modeling increases understanding of peatland processes and aims to predict future behavior. The potential accuracy of the model at three sites in the open fen was between 0.02 and 0.03 m, if defined by the $RMSE_u$ unsystematic error. At both the Fen Centre and Partially Treed sites, the model predicted the same elevation by September 2004 as that that was observed. The Edge site elevation by the end of the study didn't rebound as much as the model estimated it would. Given the simplicity of this monthly model, these results are quite reasonable.

As compressibility was measured at the Fen Centre site, its relationship with peat depth was most accurate there. As expected, use of the empirical equation defining acrotelm compaction yielded similar results as compressibility estimates at the Fen Centre site. Adjustment of compressibility could slightly improve the model performance at the sites where strain was not measured (Partially Treed and Edge sites).

Other sensitivity parameters that were adjusted were the storativity in the unsaturated peat layer, percentage of unfrozen water content in the frozen peat, and the depth of the peat between sites. Environmental changes such as loading from snow influence monthly peat surface movements in predictable ways. The model was sensitive to unsaturated peat density, that depended on the storativity. Increasing the peat storativity with water table depth caused less subsidence at the Fen Centre site, and reduced the agreement of predicted and observed monthly values.

Results of the modeling exercise that extended through the annual cycle were most erroneous during the spring thaw period. This suggests that some physical process is not being accounted for during the spring thaw, causing the average peat surface to be overestimated. Infiltration of snowmelt water through thawing peat near the surface may cause interstitial gases to become trapped. The timing of peat surface rebound in the model is dependent on the rise in piezometric head beneath the frozen peat. The observation of considerable lag in peat rebound on the seasonal scale may prevent a monthly peat thickness model from accurately capturing changes due to a quick rise in piezometric head.

The incorporation of frost expansion into the model is an improvement although it doesn't completely explain the expansion of Edge site peat in the winter of 2003-2004. In soils, there is always some water movement taking place as liquid or vapor, induced by temperature gradients (Farouki, 1981). Seasonally freezing soils may become oversaturated with ice because of moisture migration and subsequent freezing (Farouki, 1981). Falling piezometric levels in winter have been observed previously in hydrologic studies nearby (Price, 1983). Lowering of the pressure head in winter may indicate the migration of moisture in the saturated peat towards the freezing front above, or merely the freezing of water in place. Quinton and Hayashi (2004) have documented the increase of moisture content near the peat surface over the winter. This may be attributed to melt-water infiltration and refreezing during the winter and spring. The effect of freezing on pore pressure within the peat and its effects on peat surface movements have not yet been addressed in the peat hydrology literature.

In the wet years, partial rebound of the surface should lessen runoff over top the peat. As peat rebound in the fen centre is most efficient, surface runoff from this lower elevation zone will be diminished. As the water table declines into peat with higher specific retention and lower hydraulic conductivity, losses of moisture to evapotranspiration and lateral drainage should diminish. Transient interactions of the underlying substrate sand and the surrounding uplands with the peatland still require further investigation.

Major controls of peat thickness change at this site in western Canada are related to changes in water table and moisture content, and vertical frost expansion. While the monthly model was created to explain simple processes, it seems that the majority of peat surface movements could be explained by them. With quantitative observation of freeze-thaw and the possible redistribution of moisture upwards within the frozen peat, it may be possible to improve the structure of the model to account for additional processes. This model may perform well in other boreal fens with a similar type of peat.

In the long term, any effects of climate or land uses that influence water table elevations in peatlands will also largely control the elevation of the peat surface relative to that water table. The model is useful in predicting peat surface depth relative to water table elevation on the seasonal scale. Water table depth relative to the peat surface has important impacts on surface and subsurface hydrology, mass fluxes of carbon and moisture to the atmosphere, and survival of diverse species in a complex topography. The hydrology of Sandhill Fen will continue to be under the influence of seasonal and inter-annual climate.

4. Synthesis

The hydraulic properties of this seasonally frozen, minerotropic, patterned fen in Saskatchewan were characterized using a combination of laboratory and field methods. Porosity of the peat in ridges, swale and edge locations within the top 0.4 m was high compared to other studies, ranging from 92 to 97%. Bulk density of the upper peat, that may be an indicator of the degree of decomposition was relatively low compared to deeper layers; ranging from 50 to 150 kg/m^3. The water content of shallow peat was measured on a few occasions from peat cores extracted from frozen and thawed peat. The upper layers of peat are able to dry out considerably, as they did in the fall of 2003. Slug tests at various depths in Sandhill Fen showed a pattern of decreasing hydraulic conductivity with depth, ranging from 10^{-4} at 0.3 m depth to 10^{-6} at 2 to 3 m depth.

Drainage tests were completed in the laboratory on peat core extracted during a dry climatic period late in 2003. Results from these tests were variable, reflecting the different locations of the four peat cores, and the intrinsic heterogeneity of the deposit. Storativity measured for different layers of the cores was higher near the peat surface and decreased somewhat with depth. Using the numerical relationship between storativity and depth, the volume of water drained from the peat with successive water table decline was estimated. With further data this relationship may be improved.

Field drainage or filling tests conducted in a fully confined enclosure are a simple method of producing a bulk value of storativity on the scale of meters. In Sandhill Fen the seasonal frost table provided an impermeable barrier in the late spring of 2003. In northern peatlands characterized by permafrost, this method may be feasible. The method should be further tested for use in peat that is thawed so that it may be applied during the frost free season. At this site the hydraulic conductivity declines significantly with depth below the surface, so that the base of the enclosure will be installed in low hydraulic conductivity peat. The result from the confined and enclosed field test fell within the range of the laboratory drainage tests.

Pumping tests have never been used to characterize the transmissivity of peat deposits until recently. Tests were successfully completed in 0.4 m of thawed acrotelm peat above a virtually impermeable saturated frost layer, and then later in completely thawed peat at the same sites. Due to the significant decrease of hydraulic conductivity with depth, transmissivity results were highly dependent on water table depth below the surface. Distance-drawdown method transmissivity results were consistent with and without the presence of the confining layer below, with a slight decrease in the latter due to a lowered water table. Setting the drawdown in the pumping well at a shallow depth is recommended for future tests as this will avoid challenges with vertical heterogeneity. The duration of pumping tests performed at this fen site ranged from less than one hour to over 24 hours, but short duration tests are shown to achieve similar results. Pumping test results when the water table was 0.4 m below the surface gave similar results as slug tests at the same depth. An advantage with this method over conventional ones is that volumes of relatively undisturbed peat on the scale of cubic meters may be characterized.

The use of a surface loading test to produce information on the hydraulic diffusivity of the lower hydraulic conductivity layer of peat was successful. Through the use of highly accurate vibrating wire pressure transducers in piezometers closed to the atmosphere, it was possible to monitor the response of the piezometers to loading. The assumption that was applied in the calculations of vertical hydraulic conductivity: that the low hydraulic conductivity layer drained only upwards into shallower peat and downwards into the sandy deposit was not met in this experiment. A portion of the elevated piezometric head drained laterally away from the centre of the surface load. For future loading tests on peat to make use of the same theory and provide a more accurate result, the surface load should be spread out over a wide area with respect to the points of piezometric observation.

Hydrological observations made during this study include peat surface elevation, water table elevation, piezometric surface elevation, frost table elevation, peat temperature patterns with depth at several sites, and snow depth and snow density on a monthly basis. The dry climate of 2003, which was followed by high levels of precipitation in 2004, produced changes in the hydrology of Sandhill Fen in a relatively short period of time.

There were significant declines in water table and piezometric head elevation due to evapotranspiration demands in 2003, and this caused drying of the upper peat layer and prolonged subsidence over a period of months. Subsidence of the peatland was similar at all three study sites, although peat thicknesses were quite different, and this was verified by extensive peat surface elevation surveys along 100 m transects. It has been speculated that subsidence of highly compressible peat assists this system to conserve water. Additionally, the decline of the water table into peat with lower hydraulic conductivity should effectively reduce lateral groundwater flow. The influence of having a dry surface peat layer on evapotranspiration from the peatland needs further exploration.

With the above-normal levels of precipitation in the Sandhill Fen region in the spring of 2004, the water table quickly overtopped the 2003 seasonally compacted peat surface. Rebound of the peat was not equivalent to the amount of subsidence that had occurred the previous year. From the modeling exercise, it was predicted that once the water table rose above the surface there would be no further changes in effective stress on the peat. Observations during the wet season of 2004 showed that small amounts of surface rebound occurred after the initial rise in the water table, and that this process was slower. Rebound was greater and happened more quickly at the Fen Centre site with its greater peat thickness than at the adjacent study sites.

Peatlands such as Sandhill Fen are able to store large amounts of water. Temporal fluctuations in storage occur from dynamic processes of precipitation and evapotranspiration, microclimate variation, groundwater interactions of the peatland with surrounding uplands and the underlying mineral substrate, as well as slight changes in hydraulic properties caused by expansion or subsidence of the peat. Hydraulic properties are variable within the fen, and thus the scale at which storativity is measured may influence the results. The use of enclosed field methods to measure storativity at larger scales is under examination.

Estimation of water storage at a few sites in the fen was based mainly on water table changes over time. It is not certain how closely the estimates of unsaturated water storage volumes were to reality in the season of 2003 and 2004. Estimates of peat surface movement through the use of the monthly model were also dependent water storage changes, particularly in the frost-free season.

The model demonstrates reasonably well the patterns of peat surface movement that were measured at the three study sites in Sandhill Fen. The Fen Centre site continues to be influenced by changes in water storage and/or piezometric head even through the winter, because the frost layer penetrates only a fraction of the total peat thickness of over 4 m. In contrast, the Edge site with its thin layer of peat becomes almost completely frozen over its thickness, so that the influence of the frost is much more significant. The Edge site peat volume was observed to expand in the winter as the depth of frost increased. The Partially Treed site, displayed patterns of peat surface movement that were controlled both by frost and by water storage and piezometric head changes.

The model may be improved with better estimates of effective stress using water content measurements, as Kennedy and Price (2004) have done. This may help elucidate the influence of gas content during the snowmelt period, when the model results strayed from reality. Freezing and thaw processes in peatlands influence water storage over the winter and snow-melt runoff in the spring. There may be movement of moisture within semi-frozen peat during the winter, and this also requires further study. Alternatively, the model could be restructured to focus on effective stress change from water storage change, as calculated in Section 3.4.5, and avoid estimating density of the acrotelm peat completely. Further study could focus on simplifying the model in this manner.

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List of Appendices

Appendix A

Appendix A1. Specifications of pumping and observation wells at the Fen Centre site

Name	radial distance, m	top pipe to peat, m	total length, m	screen length, m	top screen depth, m	Area pipe (m3)
Well	0.000	0.300	1.218	1.200	0.000	0.00221
NW 0.1	0.100	1.231	1.790	0.200	0.359	0.00024
NW 0.2	0.200	1.234	1.790	0.200	0.356	0.00024
N1	1.030	0.371	0.801	0.284	0.146	0.00053
N2	2.030	0.419	0.805	0.291	0.095	0.00053
N3	2.990	0.387	0.800	0.289	0.124	0.00053
W1	0.990	0.343	0.705	0.285	0.077	0.00053
W2	2.100	0.554	1.002	0.296	0.152	0.00053
W3	2.980	0.569	0.861	0.186	0.106	0.00031
S1	0.992	0.598	0.970	0.300	0.000	0.00196
S2	2.000	0.553	0.970	0.300	0.000	0.00196
S3	3.050	0.727	2.860	0.500	0.150	0.00062
S5	5.000	0.685	2.860	0.500	0.150	0.00062

Appendix A2. Specifications of piezometers installed at the Fen Centre site

Name	radial distance, m	top pipe to peat, m	total length, m	screen length, m	top screen depth, m	Area pipe (m3)
NP .5/.5	0.51	0.488	0.992	0.095	0.409	0.00024
NP .5/1	1.045	0.486	0.982	0.095	0.401	0.00024
NP 1/1	1.05	0.477	1.483	0.095	0.911	0.00024
NP .5/2	2.04	0.44	0.985	0.095	0.45	0.00024
NP 1/2	2.058	0.344	1.49	0.095	1.051	0.00024
N-SS 2/1	1.198	1.054	2.9	0.085	1.9	0.00011
N-SS 3/1	1.198	1.256	4.18	0.085	2.88	0.00011
N-SS 2/2	2.15	1.054	2.9	0.085	1.9	0.00011
N-SS 3/2	2.15	1.302	4.18	0.085	2.88	0.00011
SP .5/.5	0.5	0.457	0.985	0.095	0.433	0.00024
SP .5/1	1.015	0.458	0.995	0.095	0.442	0.00024
SP 1/1	1.015	0.452	1.488	0.095	0.941	0.00024
SP .5/2	1.983	0.438	0.985	0.095	0.452	0.00024
SP 1/2 A	1.986	0.429	1.492	0.095	0.968	0.00024
S-SS 2/1	1.174	1.071	2.9	0.085	1.9	0.00011
S-SS 3/1	1.16	1.191	4.18	0.085	2.88	0.00011
S-SS 2/2	2.185	1.047	2.9	0.085	1.9	0.00011
Sss2.4/2	2.169	1.061	3.455	0.085	2.375	0.00011
SP 2/3	2.991	0.899	3.05	0.2	1.9	0.00062
GP 2.2/5	5	0.48	3.015	0.305	2.2	0.00108
WP 0.5/1	0.84	0.495	0.988	0.095	0.398	0.00024
WP 1/1	1.05	0.502	1.478	0.095	0.881	0.00024
SP 1/2 B	1.973	0.814	2.97	0.2	0.9	0.00062
SP 2/2	2.191	0.916	3.05	0.2	1.9	0.00062
SP 3/2	2.29	1.061	4.14	0.25	2.875	0.00062
SP 3/1	1.182	0.955	4.14	0.25	2.875	0.00062
SP 2/1	1.174	0.826	3.05	0.2	1.9	0.00062

Appendix B

Appendix B1. Pumping test No. 1, June 3 2003, at the Edge site

Static water level (m):			0.586			0.555			0.616			0.63			1.286
Well name:			**P1**			**P2**			**S15**			**S30**			**N100**
Q rate (m^3/s)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)
2.70E-05	20	0.02	0.610	35	0.01	0.564	85	0.034	0.65	100	0.016	0.646	165	0.004	1.29
2.70E-05	115	0.03	0.620	125	0.02	0.573	185	0.039	0.655	205	0.022	0.652	390	0.006	1.292
2.70E-05	220	0.04	0.623	235	0.02	0.576	270	0.044	0.66	295	0.025	0.655	705	0.010	1.296
2.70E-05	330	0.04	0.627	350	0.02	0.58	410	0.045	0.661	430	0.028	0.658	1025	0.012	1.298
2.70E-05	450	0.04	0.629	475	0.02	0.58	500	0.046	0.662	515	0.030	0.66	1436	0.013	1.299
2.70E-05	595	0.05	0.631	620	0.03	0.583	650	0.047	0.663	675	0.031	0.661	2220	0.015	1.301
2.70E-05	730	0.05	0.632	750	0.03	0.584	868	0.050	0.666	907	0.032	0.662	2910	0.016	1.302
2.70E-05	950	0.05	0.632	980	0.03	0.585	1050	0.052	0.668	1080	0.035	0.665	4500	0.018	1.304
2.70E-05	1110	0.05	0.633	1130	0.03	0.587	1180	0.053	0.669	1195	0.036	0.666	5150	0.020	1.306
2.70E-05	1220	0.05	0.633	1245	0.03	0.588	1280	0.052	0.668	1300	0.037	0.667			
2.70E-05	1345	0.05	0.635	1375	0.03	0.589	1600	0.054	0.67	1620	0.038	0.668			
2.70E-05	1390	0.05	0.635	1570	0.03	0.587	1880	0.056	0.672	1860	0.040	0.67			
2.70E-05	1735	0.050	0.636	1790	0.03	0.588	2140	0.057	0.673	2160	0.040	0.67			
2.70E-05	2065	0.05	0.637	2085	0.03	0.59	2805	0.058	0.674	2820	0.043	0.673			
2.70E-05	2702	0.05	0.638	2750	0.04	0.592	4393	0.060	0.676	4440	0.045	0.675			
2.70E-05	4225	0.05	0.640	4277	0.04	0.594	5021	0.060	0.676	5070	0.045	0.675			
2.70E-05	4920	0.06	0.641	4975	0.04	0.594									
	5418*	0.05	0.640	5440	0.04	0.592									
	5513	0.03	0.615	5540	0.02	0.58									
	5668	0.02	0.610	5640	0.02	0.575									
	5808	0.02	0.605	5745	0.02	0.572									
	5910	0.02	0.602	5970	0.01	0.568									
	6080	0.01	0.600	6360	0.01	0.567									
	6305	0.01	0.597	6660	0.01	0.565									
	6750	0.01	0.595	7155	0.01	0.564									
	7095	0.01	0.594	7960	0.01	0.561									
	7910	0.01	0.592	7970	0.01	0.56									

[1]Recovery of water levels measured in wells after pumping test is indicated by shaded portions of the table

Appendix B2. Pumping test No. 2, June 3 2003, at the Transect 2 site

Static water level (m):				0.561			0.52			0.575			0.625			1.22
Well name:				**P1**			**P2**			**N15**			**N30**			**S100**
Time (s)	Q rate (m^3/s)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)
600	9.1E-05	38	0.002	0.563	25	0	0.521	70	0.01	0.58	95	0.01	0.622	220	0	1.224
1020	9.1E-05	125	0.009	0.57	140	0.01	0.528	160	0.01	0.582	190	0.01	0.622	535	0.01	1.226
2520	8.3E-05	270	0.014	0.575	300	0.01	0.532	330	0.01	0.585	350	0.01	0.625	880	0.01	1.228
		410	0.015	0.576	425	0.01	0.532	455	0.01	0.586	480	0.01	0.626	1950	0.01	1.232
		588	0.016	0.577	630	0.01	0.534	668	0.01	0.588	750	0.01	0.629	2265	0.01	1.231
		780	0.016	0.577	825	0.02	0.535	920	0.01	0.589	940	0.01	0.629	2922	0.01	1.233
		1740	0.019	0.58	1816	0.02	0.536	1830	0.02	0.592	1860	0.02	0.632			
		2027	0.019	0.58	2070	0.02	0.536	2182	0.02	0.592	2220	0.02	0.632			
		2643	0.019	0.58	2722	0.02	0.536	2810	0.02	0.592	2865	0.02	0.633			
		3077 [1]	0.013	0.574	3110	0.01	0.532									
		3257	0.01	0.571	3330	0.01	0.528									
		3270	0.009	0.57	3460	0.01	0.527									
		3600	0.008	0.569	3640	0.01	0.527									
		3860	0.008	0.569	3820	0	0.523									
		4050	0.006	0.567	4080	0	0.523									
		4140	0.006	0.567												

[1] Recovery of water levels measured in wells after pumping test is indicated by shaded portions of the table

Appendix B3. Pumping test No. 3, June 10 2003, at the Transect 2 site

Static water level (m):				0.996			0.601			0.533			0.547	Static water level:		0.505		
Well name:				**N100**			**NP30**			**NP15**			**S15 (p1)**	**Well name:**		**S30 (p2)**		
Time (s)	Q rate (m^3/s)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Drawdown (m)
340	0.000428	130	0.019	1.015	152	0.043	0.644	170	0.057	0.59	223	0.053	0.6	243	0.042	0.547	64	0.010
420	0.000412	367	0.032	1.028	440	0.051	0.652	500	0.067	0.6	534	0.055	0.602	561	0.047	0.552	268	0.021
495	0.000412	735	0.039	1.035	760	0.054	0.655	790	0.070	0.603	840	0.062	0.609	870	0.052	0.557	590	0.030
580	0.000396	1050	0.043	1.039	1080	0.057	0.658	1110	0.072	0.605	1170	0.067	0.614	1200	0.054	0.559	900	0.034
660	0.000404	1410	0.043	1.039	1440	0.059	0.660	1470	0.074	0.607	1440	0.065	0.612	1560	0.055	0.56	1235	0.035
750	0.000389	1890	0.044	1.040	1960	0.061	0.662	1990	0.076	0.609	1650	0.066	0.613	2113	0.057	0.562	1590	0.037
840	0.000404	2400	0.048	1.044	2446	0.061	0.662	2490	0.078	0.611	2070	0.067	0.614	2610	0.059	0.564	2164	0.039
930	0.000396	2830	0.048	1.044	2860	0.063	0.664	2930	0.078	0.611	2580	0.068	0.615	3000	0.06	0.565	2640	0.039
1020	0.000404	3690	0.05	1.046	3750	0.064	0.665	3780	0.079	0.612	2970	0.070	0.617	3930	0.06	0.565	3050	0.040
1105	0.000369	4620	0.05	1.046	4680	0.065	0.666	4680	0.079	0.612	3900	0.070	0.617	4920	0.061	0.566	3960	0.042
1200	0.000396	7620	0.053	1.049	7680	0.069	0.670	7690	0.080	0.613	4920	0.070	0.617	7800	0.062	0.567	5040	0.043
1300	0.000375	8400	0.054	1.050	8445	0.069	0.670	8475	0.080	0.613	5025	0.070	0.617	8595	0.062	0.567	7830	0.045
1405	0.000382	10440	0.054	1.050	10460	0.069	0.670	10490	0.080	0.613	7770	0.072	0.619	10560	0.063	0.568	8640	0.045
1500	0.000396	11410	0.0545	1.051	11460	0.069	0.670	11480	0.080	0.613	8580	0.071	0.618	11560	0.063	0.568	10625	0.046
1620	0.000382										10530	0.071	0.618				11610	0.046
1824	0.000369										11520	0.070	0.617					
1920	0.000375																	
2040	0.000375																	

Appendix B4. Pumping test No. 4, July 16 2003, at the Transect 2 site

Time (s)	Q rate (m^3/s)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Drawdown (m)	Distance to water (m)
Static water level (m):				1.053			0.657			0.598			0.608			0.567	Static water level		1.266			1.034
Well name:				**N100**			**NP30**			**NP15**			**S15 (p1)**			**S30 (p2)**	**Well name:**		**S100**			**S300**
90	3.8E-04	307	0.019	1.072	186	0.035	0.692	110	0.039	0.637	137	0.039	0.647	230	0.031	0.598	269	0.015	1.281	1030	0.009	1.043
200	3.2E-04	460	0.022	1.075	428	0.042	0.699	390	0.049	0.647	495	0.046	0.654	540	0.034	0.601	570	0.019	1.285	1542	0.013	1.047
300	3.0E-04	900	0.027	1.08	870	0.049	0.706	840	0.054	0.652	940	0.049	0.657	970	0.038	0.605	1005	0.026	1.292	2454	0.014	1.048
420	2.9E-04	1360	0.03	1.083	1320	0.053	0.71	1290	0.055	0.653	1400	0.052	0.66	1440	0.043	0.61	1490	0.029	1.295	3270	0.015	1.049
540	2.8E-04	2310	0.034	1.087	2275	0.057	0.714	2250	0.057	0.655	2340	0.053	0.661	2390	0.045	0.612	2400	0.03	1.296	4950	0.018	1.052
660	2.8E-04	3090	0.039	1.092	3022	0.06	0.717	2990	0.059	0.657	3135	0.058	0.666	3165	0.05	0.617	3225	0.036	1.302	7200	0.023	1.057
780	2.7E-04	4740	0.044	1.097	4710	0.063	0.72	4680	0.063	0.661	4790	0.063	0.671	4860	0.054	0.621	4890	0.04	1.306	8250	0.025	1.059
900	2.7E-04	6920	0.045	1.098	6870	0.068	0.725	6860	0.065	0.663	6980	0.065	0.673	7020	0.055	0.622	7130	0.042	1.308	10440	0.027	1.061
1020	2.6E-04	7980	0.047	1.1	7950	0.069	0.726	7920	0.069	0.667	8070	0.066	0.674	8136	0.056	0.623	8180	0.044	1.31	10997	0.026	1.06
1140	2.6E-04	10200	0.048	1.101	10120	0.072	0.729	10080	0.069	0.667	10270	0.068	0.676	10300	0.057	0.624	10380	0.046	1.312	11331	0.022	1.056
1260	2.5E-04	10944 [1]	0.036	1.089	10911	0.049	0.706	11158	0.031	0.629	10840	0.039	0.647	10860	0.07	0.637	10968	0.036	1.302	11817	0.019	1.053
2580	2.2E-04	11253	0.029	1.082	11183	0.04	0.697	11564	0.024	0.622	11206	0.032	0.64	11230	0.03	0.597	11276	0.029	1.295	18644	0.013	1.047
2725	2.2E-04	11757	0.024	1.077	11601	0.035	0.692	18474	0.008	0.606	11700	0.024	0.632	11725	0.023	0.59	11784	0.025	1.291	61200	0	1.034
2860	2.2E-04	18582	0.007	1.06	18498	0.015	0.672	61200	0.001	0.599	18526	0.024	0.632	18555	0.007	0.574	18609	0.005	1.271			
3005	2.2E-04	61200	0.003	1.056	61200	0.004	0.661				61200	0.006	0.614	61200	0.003	0.57	61200	0.002	1.268			
3145	2.2E-04																					
3300	2.2E-04																					
3445	2.1E-04																					
3600	2.1E-04																					
4800	2.0E-04																					
4950	2.0E-04																					
5100	2.0E-04																					
7800	1.8E-04																					
7980	1.8E-04																					
8160	1.8E-04																					
8365	1.8E-04																					
8580	1.8E-04																					
10080	1.7E-04																					

[1] Recovery of water levels measured in wells after pumping test is indicated by shaded portions of the table

Appendix B5. Pumping test No. 5, July 31-August 1 2003 at the Fen Centre site

Static water level (m):				0.532			0.543			0.521			0.431	Static water level:		0.693		
Well name:				**N1**			**N2**			**N3**			**W1**	**Well name:**		**W2**		
Time (s)	Q rate (m^3/s)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)
900	8.38E-05	218	0.007	0.539				785	0.001	0.522	470	0.006	0.437	490	0.003	0.696	506	0.001
1500	0.000085	637	0.01	0.542	729	0.005	0.548	3251	0.01	0.531	1096	0.013	0.444	1178	0.007	0.7	1187	0.003
1500	8.11E-05	1376	0.017	0.549	1428	0.009	0.552	4763	0.011	0.532	3250	0.019	0.45	3350	0.01	0.703	3384	0.007
		2797	0.02	0.552	4740	0.013	0.556	7601	0.015	0.536	4980	0.02	0.451	7140	0.018	0.711	7260	0.015
2160	7.22E-05	4670	0.024	0.556	7590	0.023	0.566	10980	0.016	0.537	7110	0.027	0.458	7853	0.023	0.716	7878	0.017
2400	0.000075	4920	0.023	0.555	10920	0.024	0.567	17430	0.022	0.543	14340	0.031	0.462	11040	0.02	0.713	11092	0.013
2760	0.00007	5940	0.023	0.555	17400	0.031	0.574	22320	0.023	0.544	17520	0.034	0.465	17580	0.025	0.718	17640	0.024
3000	6.83E-05	6780	0.028	0.56	22260	0.031	0.574	26040	0.025	0.546	18720	0.034	0.465	18820	0.023	0.716	18840	0.019
3300	6.83E-05	7573	0.03	0.562	25980	0.033	0.576	32160	0.026	0.547	22380	0.038	0.469	22380	0.028	0.721	22380	0.027
3600	6.83E-05	10800	0.03	0.562	32040	0.033	0.576	48600	0.027	0.548	26220	0.037	0.468	26400	0.028	0.721	26460	0.028
4620	6.58E-05	14280	0.031	0.563	48300	0.04	0.583	76920	0.029	0.55	32160	0.037	0.468	32220	0.029	0.722	32280	0.027
4800	0.000065	17340	0.037	0.569	76860	0.042	0.585	94500	0.032	0.553	49560	0.041	0.472	49740	0.032	0.725	49740	0.029
5820	8.33E-05	22200	0.037	0.569	94380	0.042	0.585	420	0.03	0.551	76200	0.042	0.473	77160	0.037	0.73	77160	0.032
7320	7.08E-05	25920	0.039	0.571	414	0.034	0.577	863	0.03	0.551	94560	0.044	0.475	94500	0.039	0.732	94500	0.033
8100	6.83E-05	31920	0.041	0.573	856	0.031	0.574	1250	0.027	0.548	314	0.039	0.47	357	0.035	0.728	395	0.031
10080	0.000075	47980	0.046	0.578	1239	0.028	0.571	2714	0.027	0.548	891	0.035	0.466	957	0.033	0.726	972	0.03
11280	0.000075	76620	0.046	0.578	2565	0.026	0.569	5890	0.027	0.548	1298	0.032	0.463	1319	0.032	0.725	2807	0.028
12480	7.33E-05	90600	0.046	0.578	5820	0.028	0.571	26950	0.028	0.549	2746	0.031	0.462	2781	0.029	0.722	5980	0.028
16800	6.92E-05	94320	0.048	0.58	26950	0.024	0.567	95400	0.025	0.546	5920	0.031	0.462	5950	0.03	0.723	27010	0.028
21360	6.83E-05	125 [1,2]	0.046	0.578	95400	0.023	0.566	171000	0.026	0.547	27010	0.029	0.46	27010	0.028	0.721	95400	0.031
27600	6.67E-05	729	0.036	0.568	171000	0.022	0.565				95400	0.027	0.458	95400	0.029	0.722	171000	0.032
74100	0.000065	1227	0.03	0.562							171000	0.033	0.464	171000	0.032	0.725		
74280	6.33E-05	2428	0.031	0.563														
76980	0.00006	5770	0.028	0.56														
		27070	0.025	0.557														
		95400	0.029	0.561														
		171000	0.028	0.56														

[1]Recovery of water levels measured in wells after pumping test is indicated by shaded portions of the table

[2]Recovery time measured from pump shutoff not the beginning of the test

Appendix B Table 6. Pumping test No. 6, August 8 2003, at the Fen Centre site

Static water level (m):				0.54			0.551			0.53			0.439			0.704		
Well name:				**N1**			**N2**			**N3**			**W1**			**W2**		
Time (s)	Q rate (m^3/s)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)	Distance to water (m)	Time (s)	Draw down (m)
120	7.92E-05	180	0.012	0.552	210	0.002	0.553	330	0.003	0.533	240	0.013	0.452	270	0.004	0.708	300	0.003
840	7.50E-05	455	0.016	0.556	480	0.006	0.557	510	0.003	0.533	894	0.022	0.461	922	0.008	0.712	1480	0.006
1080	7.50E-05	756	0.022	0.562	780	0.009	0.56	810	0.004	0.534	1410	0.026	0.465	1443	0.011	0.715	2940	0.01
1560	7.50E-05	1225	0.022	0.562	1200	0.011	0.562	2410	0.008	0.538	2850	0.027	0.466	2920	0.015	0.719	4380	0.012
2220	7.17E-05	2360	0.025	0.565	2390	0.018	0.569	4260	0.013	0.543	4290	0.031	0.47	4370	0.017	0.721	8220	0.017
2760	7.17E-05	4200	0.03	0.57	4220	0.02	0.571	7740	0.016	0.546	8160	0.034	0.473	8220	0.021	0.725	11580	0.02
4200	6.50E-05	7620	0.033	0.573	7680	0.027	0.578	11340	0.021	0.551	11460	0.037	0.476	11520	0.024	0.728	12720	0.02
4800	6.50E-05	10980	0.033	0.573	11280	0.027	0.578	12600	0.022	0.552	12660	0.037	0.476	12720	0.024	0.728	403	0.017
7800	6.50E-05	12600	0.039	0.579	12600	0.028	0.579	269	0.022	0.552	374	0.027	0.466	374	0.021	0.725	941	0.016
11100	6.67E-05	115 [1,2]	0.038	0.578	230	0.026	0.577	869	0.02	0.55	1980	0.026	0.465	918	0.018	0.722	2250	0.016
12000	5.83E-05	838	0.024	0.564	854	0.021	0.572	2190	0.017	0.547	2220	0.024	0.463	2250	0.017	0.721	4740	0.012
12300	5.83E-05	2130	0.017	0.557	2160	0.016	0.567	4680	0.016	0.546	4740	0.021	0.46	4740	0.014	0.718	9960	0.012
		4680	0.017	0.557	4680	0.016	0.567	9840	0.015	0.545	9900	0.021	0.46	9900	0.014	0.718	14400	0.013
		7243	0.014	0.554	7243	0.012	0.563	14160	0.014	0.544	14280	0.019	0.458	14400	0.014	0.718		
		13740	0.013	0.553	13980	0.012	0.563											

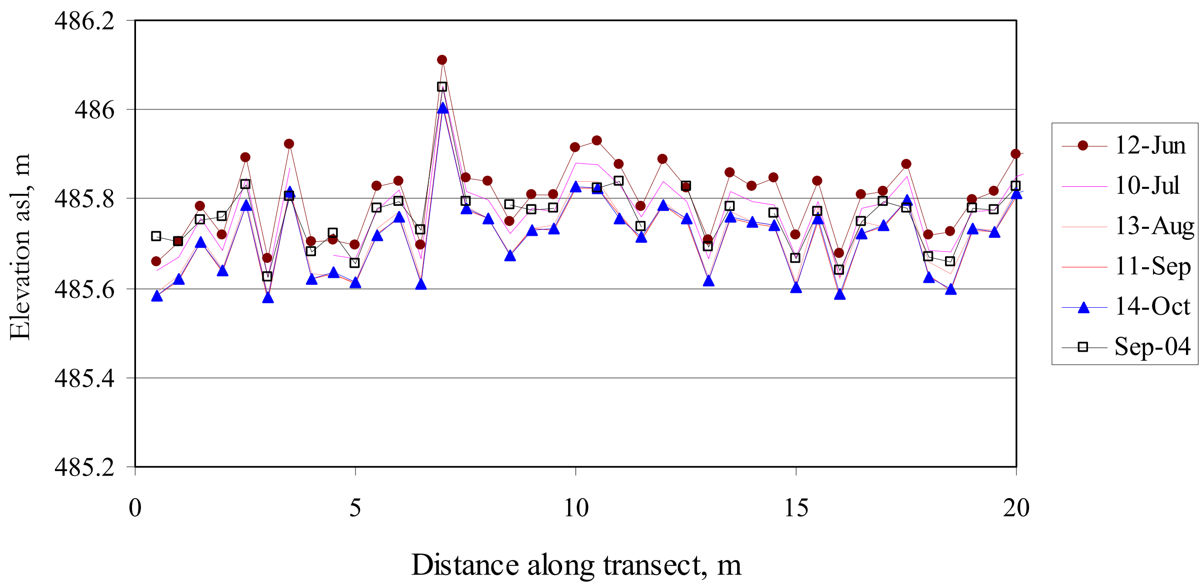
[1]Recovery of water levels measured in wells after pumping test is indicated by shaded portions of the table

[2]Recovery time measured from pump shutoff not the beginning of the test

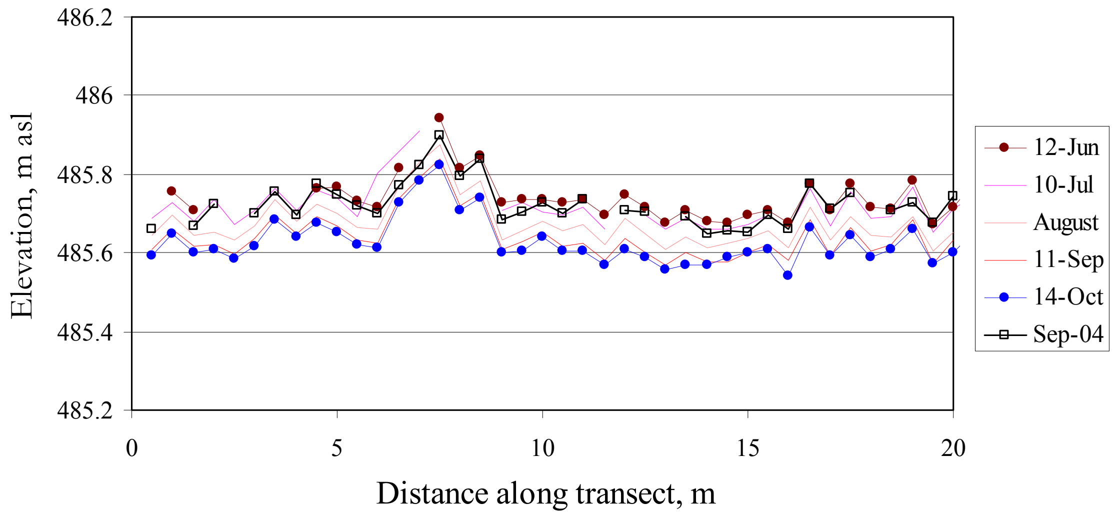
Appendix B7. Pumping test No. 7, August 13 2003, at the Edge site										
Static water level (m):				1.245			1.075			1.097
Well name:				**A**			**B**			**C 100**
Time (s)	Q rate (m^3/s)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Drawdown (m)	Distance to water (m)	Time (s)	Drawdown (m)	Distance to water (m)
190	1.4E-06	55	0.003	1.248	85	0.005	1.08	649	0.001	1.098
270	1.3E-06	112	0.007	1.252	140	0.008	1.083	910	0.003	1.1
350	1.3E-06	325	0.015	1.26	357	0.012	1.087	1165	0.003	1.1
440	1.1E-06	480	0.018	1.263	520	0.013	1.088	1425	0.004	1.101
525	1.2E-06	690	0.021	1.266	732	0.015	1.09	1783	0.006	1.103
600	9.3E-07	980	0.021	1.266	1001	0.015	1.09	2400	0.005	1.102
720	1.1E-06	1220	0.022	1.267	1250	0.016	1.091	4740	0.009	1.106
780	1.3E-06	1490	0.022	1.267	1530	0.017	1.092	6405	0.011	1.108
840	1.0E-06	1820	0.022	1.267	1848	0.017	1.092	8160	0.014	1.111
900	8.3E-07	2420	0.024	1.269	2450	0.019	1.094	10200	0.016	1.113
960	1.5E-06	4680	0.028	1.273	4715	0.021	1.096			
1020	1.0E-06	6330	0.033	1.278	6360	0.023	1.098			
1080	1.2E-06	8060	0.035	1.28	8100	0.025	1.1			
1140	1.2E-06	9240	0.033	1.278	9240	0.022	1.097			
1200	8.3E-07	10080	0.036	1.281	10140	0.026	1.101			
1260	1.3E-06									
1320	1.0E-06									
1380	1.2E-06									
1440	1.0E-06									
1920	1.1E-06									
1980	8.3E-07									
2340	9.2E-07									
2400	1.7E-06									
2880	9.4E-07									
3720	8.7E-07									
4530	1.0E-06									
5610	9.3E-07									
7000	7.9E-07									
7950	9.5E-07									
9143	8.4E-07									
10360	8.2E-07									
11910	6.6E-07									

Appendix C

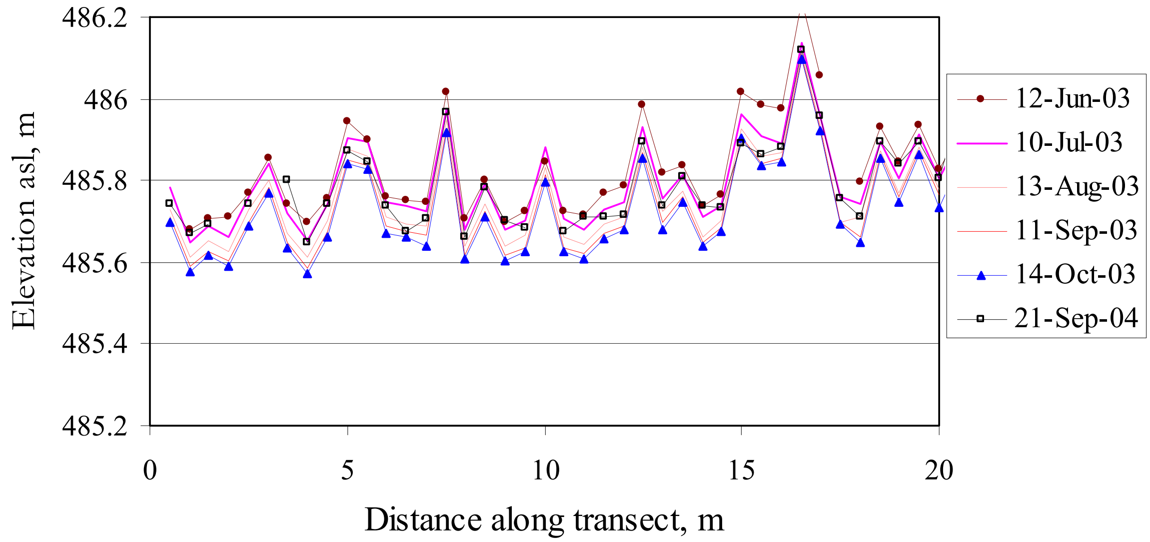
Appendix C1. Peat surface movements along the first 20 m of Transect 1 in the summer of 2003 and September 2004.



Appendix C2. Peat surface movements along the first 20 m of Transect 2 in the summer of 2003 and in September 2004.



Appendix C3. Peat surface movements along the first 20 m of Transect 3 in the summer of 2003 and in September 2004.



Appendix C4. Table of frost table and peat surface elevation survey results from April 2003 to September, 2004 for Transect 1

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table m	Peat Surface m	Frost Table m	Peat Surface m	Frost Table m	Peat Surface m	Frost Table m	Peat Surface m	Frost Table m	Peat Surface m	Frost Table m	Peat Surface m
0.5	485.708	485.708	485.688	485.688	485.578	485.648	485.45	485.68	485.418	485.668	485.298	485.658
1	485.733	485.733	485.721	485.731	485.588	485.718	485.465	485.71	485.431	485.706	485.343	485.703
1.5	485.808	485.808	485.793	485.813	485.608	485.808	485.487	485.797	485.46	485.79	485.373	485.783
2	485.733	485.733	485.728	485.748	485.628	485.738	485.5	485.73	485.468	485.718	485.378	485.718
2.5	485.843	485.903	485.823	485.903	485.618	485.908	485.5	485.9	485.468	485.898	485.388	485.893
3	485.718	485.718	485.703	485.703	485.633	485.693	485.51	485.68	485.478	485.668	485.388	485.668
3.5	485.823	485.933	485.818	485.938	485.633	485.933	485.53	485.93	485.498	485.923	485.413	485.923
4	485.738	485.738	485.718	485.728	485.653	485.723	485.605	485.725	485.498	485.713	485.403	485.703
4.5	485.723	485.723	485.703	485.703	485.648	485.708	485.53	485.72	485.498	485.713	485.418	485.708
5	485.668	485.668	485.655	485.655	485.601	485.701	485.58	485.7	485.478	485.693	485.398	485.698
5.5	485.808	485.828	485.798	485.828	485.676	485.826	485.54	485.825	485.518	485.818	485.448	485.828
6	485.778	485.868	485.763	485.873	485.658	485.888	485.55	485.88	485.523	485.863	485.438	485.838
6.5	485.768	485.768	485.765	485.765	485.695	485.735	485.555	485.715	485.528	485.708	485.448	485.698
7	485.928	486.118	485.928	486.128	485.673	486.123	485.56	486.12	485.518	486.108	485.438	486.108
7.5	485.833	485.873	485.833	485.883	485.718	485.888	485.675	485.875	485.595	485.92	485.458	485.848
8	485.818	485.868	485.793	485.873	485.678	485.868	485.59	485.86	485.558	485.848	485.468	485.838
8.5	485.768	485.778	485.763	485.783	485.628	485.778	485.528	485.768	485.495	485.765	485.408	485.748
9	485.813	485.823	485.805	485.825	485.666	485.826	485.625	485.815	485.613	485.813	485.408	485.808
9.5	485.798	485.833	485.783	485.833	485.668	485.828	485.535	485.82	485.508	485.808	485.428	485.808
10	485.808	485.928	485.778	485.838	485.603	485.933	485.57	485.93	485.5	485.92	485.413	485.913
10.5	485.783	485.943	485.778	485.948	485.668	485.948	485.58	485.94	485.525	485.925	485.448	485.928
11	485.823	485.913	485.823	485.903	485.753	485.913	485.57	485.9	485.533	485.893	485.448	485.878
11.5	485.808	485.808	485.798	485.798	485.643	485.803	485.62	485.8	485.528	485.798	485.433	485.783
12	485.828	485.898	485.753	485.903	485.675	485.905	485.57	485.89	485.538	485.878	485.448	485.888
12.5	485.848	485.848	485.833	485.843	485.683	485.843	485.59	485.84	485.558	485.828	485.463	485.823
13	485.748	485.758	485.723	485.723	485.645	485.735	485.54	485.725	485.498	485.718	485.418	485.708
13.5	485.778	485.888	485.803	485.883	485.692	485.872	485.55	485.87	485.512	485.862	485.418	485.858
14	485.738	485.838	485.733	485.843	485.618	485.848	485.545	485.845	485.508	485.843	485.408	485.828
14.5	485.838	485.838	485.778	485.838	485.748	485.848	485.6	485.84	485.568	485.838	485.468	485.848
15	485.728	485.728	485.718	485.758	485.668	485.748	485.564	485.734	485.518	485.718	485.418	485.718
15.5	485.688	485.838	485.683	485.843	485.638	485.848	485.535	485.845	485.498	485.848	485.388	485.838
16	485.703	485.703	485.688	485.748	485.638	485.698	485.51	485.69	485.473	485.673	485.388	485.678

	Appendix C4. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 1											
Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)
16.5	485.818	485.818	485.803	485.823	485.653	485.813	485.54	485.82	485.508	485.808	485.408	485.808
17	485.833	485.833	485.798	485.838	485.623	485.843	485.53	485.84	485.488	485.828	485.378	485.818
17.5	485.793	485.893	485.808	485.888	485.618	485.898	485.53	485.89	485.488	485.878	485.408	485.878
18	485.738	485.738	485.713	485.753	485.668	485.728	485.55	485.73	485.518	485.718	485.418	485.718
18.5	485.703	485.703	485.705	485.755	485.653	485.773	485.56	485.76	485.518	485.748	485.428	485.728
19	485.788	485.788	485.803	485.823	485.698	485.798	485.595	485.805	485.558	485.788	485.488	485.798
19.5	485.838	485.848	485.753	485.823	485.715	485.825	485.62	485.83	485.583	485.823	485.488	485.818
20	485.783	485.923	485.758	485.908	485.711	485.911	485.61	485.91	485.578	485.898	485.508	485.898
21	485.883	485.883	485.883	485.933	485.748	485.948	485.62	485.94	485.578	485.928	485.508	485.918
22	485.793	485.793	485.823	485.833	485.718	485.808	485.62	485.82	485.578	485.808	485.508	485.808
23	485.838	485.838	485.778	485.838	485.718	485.838	485.6	485.83	485.538	485.798	485.448	485.798
24	485.873	485.873	485.788	485.888	485.698	485.888	485.56	485.89	485.533	485.873	485.448	485.848
25	485.928	485.928	485.953	485.993	485.898	485.988	485.79	485.99	485.748	485.978	485.658	485.958
26	485.773	485.773	485.878	485.908	485.728	485.898	485.65	485.9	485.608	485.878	485.548	485.878
27	485.873	485.873	485.873	485.923	485.768	485.888	485.605	485.875	485.568	485.848	485.483	485.843
28	485.813	485.813	485.763	485.783	485.668	485.768	485.58	485.78	485.548	485.768	485.458	485.758
29	485.821	485.821	485.768	485.848	485.658	485.848	485.57	485.91	485.533	485.893	485.448	485.888
30	485.763	485.763	485.753	485.943	485.703	485.943	485.615	485.935	485.578	485.918	485.488	485.918
31	485.823	485.823	485.803	485.803	485.703	485.803	485.61	485.78	485.578	485.778	485.493	485.763
32	485.883	485.883	485.843	485.893	485.683	485.893	485.61	485.9	485.558	485.868	485.488	485.878
33	485.753	485.753	485.773	485.973	485.728	485.968	485.62	485.96	485.578	485.948	485.498	485.958
34	485.853	485.853	485.828	485.938	485.733	485.933	485.63	485.94	485.588	485.898	485.598	485.918
35	485.808	485.808	485.793	485.893	485.645	485.885	485.57	485.89	485.518	485.878	485.438	485.858
36	485.778	485.778	485.763	485.913	485.665	485.905	485.565	485.885	485.528	485.868	485.448	485.868
37	485.893	485.893	485.898	485.958	485.678	485.928	485.545	485.915	485.518	485.898	485.438	485.888
38	485.763	485.763	485.718	485.858	485.653	485.843	485.595	485.855	485.598	485.858	485.458	485.838
39	485.883	485.883	485.813	485.883	485.708	485.868	485.58	485.88	485.533	485.863	485.448	485.848
40	485.833	485.833	485.833	485.873	485.708	485.868	485.63	485.88	485.578	485.858	485.498	485.858
41	485.758	485.758	485.783	485.853	485.708	485.858	485.59	485.87	485.558	485.868	485.478	485.868
42	485.793	485.793	485.833	485.853	485.708	485.858	485.58	485.86	485.528	485.828	485.448	485.838
43	485.913	485.913	485.808	486.048	485.693	486.083	485.54	486.04	485.508	486.033	485.428	486.028

Appendix C4. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 1

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)
44	485.808	485.808	485.793	485.853	485.693	485.883	485.54	485.8	485.538	485.828	485.483	485.843
45	485.863	485.863	485.833	485.863	485.708	485.858	485.6	485.85	485.583	485.863	485.498	485.848
46	485.783	485.783	485.778	485.898	485.718	485.878	485.58	485.88	485.548	485.878	485.478	485.878
47	485.803	485.803	485.788	485.808	485.678	485.788	485.59	485.79	485.558	485.768	485.468	485.788
48	485.778	485.778	485.788	485.808	485.683	485.803	485.58	485.81	485.528	485.778	485.458	485.788
49	485.913	485.913	485.843	485.973	485.683	485.968	485.56	485.98	485.548	485.988	485.433	485.963
50	485.818	485.818	485.803	485.833	485.638	485.818	485.56	485.83	485.533	485.823	485.438	485.808
52	485.893	485.893	485.878	485.948	485.593	485.913	485.56	485.95	485.508	485.928	485.413	485.913
54	485.783	485.783	485.753	485.833	485.658	485.828	485.57	485.84	485.528	485.818	485.458	485.808
56	485.933	485.933	485.823	486.003	485.783	486.013	485.61	486	485.518	485.918	485.508	485.988
58	485.778	485.778	485.768	485.798	485.658	485.778	485.54	485.77	485.478	485.728	485.428	485.768
60	485.818	485.818	485.793	485.793	485.703	485.773	485.58	485.76	485.528	485.728	485.478	485.768
62	485.803	485.803	485.778	485.788	485.698	485.778	485.6	485.8	485.558	485.788	485.468	485.758
64	485.893	485.893	485.878	485.908	485.748	485.888	485.64	485.89	485.568	485.838	485.528	485.868
66	486.013	486.013	486.013	486.053	485.868	486.038	485.72	486.03	485.628	485.968	485.608	486.018
68	485.828	485.828	485.833	485.973	485.768	485.968	485.61	485.98	485.568	485.968	485.498	485.968
70	485.883	485.883	485.873	485.883	485.673	485.873	485.6	485.87	485.568	485.868	485.458	485.848
72	485.853	485.853	485.823	485.933	485.683	485.933	485.56	485.92	485.578	485.978	485.388	485.888
74	485.793	485.793	485.778	485.818	485.643	485.803	485.56	485.81	485.538	485.818	485.418	485.788
76	485.813	485.813	485.783	485.903	485.668	485.888	485.56	485.89	485.528	485.888	485.418	485.878
78	485.923	485.923	485.843	485.913	485.708	485.938	485.55	485.9	485.508	485.878	485.403	485.873
80	485.788	485.788	485.778	485.858	485.678	485.848	485.54	485.85	485.528	485.868	485.398	485.838
82	485.783	485.783	485.748	485.788	485.658	485.778	485.54	485.78	485.518	485.788	485.378	485.758
84	485.833	485.833	485.863	485.913	485.663	485.893	485.58	485.9	485.548	485.898	485.423	485.873
86	485.853	485.853	485.833	485.903	485.673	485.803	485.58	485.84	485.548	485.833	485.438	485.808
88	485.828	485.828	485.823	485.943	485.708	485.908	485.61	485.92	485.568	485.898	485.488	485.898
90	485.858	485.858	485.848	485.898	485.693	485.883	485.6	485.91	485.538	485.868	485.458	485.878
92	485.838	485.838	485.923	485.983	485.708	485.968	485.64	485.99	485.558	485.928	485.498	485.938
94	485.853	485.853	485.848	485.878	485.708	485.868	485.64	485.88	485.578	485.848	485.498	485.858
96	485.858	485.858	485.863	485.883	485.698	485.868	485.65	485.89	485.578	485.848	485.508	485.868
98	485.988	485.988	485.928	485.988	485.705	485.955	485.62	486.02	485.498	485.928	485.468	485.988
100	485.918	485.918	485.863	486.003	485.805	485.995	485.63	486	485.538	485.938		

Appendix C4. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 1

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
0.5		485.641	485.592	485.584	485.585		485.714
1		485.67	485.627	485.619	485.621	485.585	485.704
1.5		485.757	485.711	485.702	485.705		485.751
2		485.685	485.643	485.635	485.638	485.629	485.759
2.5		485.847	485.798	485.787	485.787		485.83
3		485.625	485.582	485.573	485.579	485.851	485.625
3.5		485.871	485.824	485.819	485.818		485.805
4			485.632	485.621	485.62	485.635	485.681
4.5		485.675	485.629	485.634	485.635		485.722
5	485.256	485.666	485.613	485.61	485.614	485.707	485.656
5.5	485.265	485.775	485.734	485.724	485.718		485.778
6	485.131	485.821	485.77	485.756	485.759	485.75	485.793
6.5		485.665	485.62	485.612	485.61		485.729
7		486.054	486.01	486.012	486.005	485.729	486.048
7.5	485.275	485.815	485.781	485.777	485.778		485.794
8	485.299	485.799	485.758	485.755	485.756	485.986	
8.5		485.723	485.679	485.673	485.674		485.786
9	485.229	485.779	485.734	485.733	485.731	485.807	485.777
9.5	485.23	485.77	485.741	485.731	485.734		485.778
10	485.24	485.88	485.839	485.825	485.826	485.874	
10.5		485.875	485.839	485.823	485.825		485.823
11		485.832	485.768	485.764	485.758	485.716	485.839
11.5	485.09	485.76	485.707	485.709	485.714		485.736
12	485.25	485.84	485.793	485.785	485.787	485.742	
12.5	485.265	485.795	485.752	485.747	485.755		485.826
13	485.235	485.665	485.623	485.617	485.618	485.793	485.693
13.5	485.215	485.815	485.771	485.758	485.761		485.784
14		485.795	485.749	485.744	485.747	485.808	
14.5		485.785	485.741	485.739	485.743		485.769
15	485.23	485.67	485.613	485.606	485.603	485.767	485.665
15.5	485.205	485.795	485.783	485.747	485.757		485.77
16		485.625	485.62	485.58	485.586	485.622	485.638

Appendix C4. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 1

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
16.5		485.78	485.748	485.724	485.723		485.748
17	485.1	485.79	485.737	485.739	485.742	485.7	485.793
17.5		485.85	485.802	485.797	485.799		485.78
18		485.685	485.66	485.627	485.626	485.683	485.671
18.5		485.68	485.633	485.596	485.6		485.658
19		485.77	485.735	485.73	485.733	485.641	485.778
19.5	485.326	485.776	485.73	485.728	485.728		485.774
20	485.34	485.85	485.82	485.805	485.814	485.902	485.828
21	485.355	485.885			485.843	485.879	
22	485.3	485.76			485.683	485.722	
23	485.27	485.74			485.685	485.676	
24	485.275	485.795			485.745	485.822	
25	485.465	485.895			485.857	485.845	
26	485.39	485.81			485.762	485.679	
27	485.33	485.82			485.793	485.847	
28		485.71			485.696	485.877	
29		485.835			485.765	485.892	
30	485.33	485.89			485.838	485.863	
31	485.34	485.75			485.673	485.895	
32	485.33	485.83			485.762	485.721	
33	485.32	485.92			485.858	485.721	
34	485.345	485.885			485.846	485.911	
35	485.28	485.82			485.77	485.763	
36	485.3	485.89			485.83	485.767	
37		485.855			485.822	485.862	
38		485.78			485.734	485.678	
39		485.84			485.8	485.87	
40		485.79			485.766	485.742	
41		485.807			485.77	485.879	
42		485.8			485.736	485.699	
43	485.28	486.01			485.937	485.717	

Appendix C4. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 1

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
44	485.3	485.8			485.788	485.747	
45	485.34	485.81			485.76	485.787	
46	485.33	485.85			485.803	485.744	
47	485.31	485.76			485.713	485.745	
48	485.3	485.75			485.714	485.667	
49		485.91			485.883	485.616	
50		485.76			485.71	485.65	
52		485.88			485.821	485.805	
54		485.79			485.766	485.857	
56	485.34	485.92			485.876	485.726	
58		485.73			485.679	485.662	
60		485.72			485.693	485.676	
62		485.735			485.653	485.672	
64	485.31	485.8			485.772	485.682	
66	485.41	485.96			485.917	485.88	
68	485.32	485.92			485.955	485.845	
70		485.87			485.817	485.704	
72		485.85			485.826	485.687	
74		485.78			485.713	485.802	
76		485.83			485.803	485.655	
78		485.835			485.79	485.747	
80		485.845			485.759	485.694	
82		485.75			485.694	485.702	
84		485.86			485.752	485.737	
86		485.8			485.752	485.682	
88		485.74			485.831	485.702	
90		485.74			485.782	485.715	
92	485.31	485.89			485.893	485.81	
94	485.34	485.86			485.754	485.807	
96	485.35	485.86			485.788	485.765	
98		485.86			485.863	485.649	
100		485.9				485.764	

Appendix C5. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 2

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)
0.5	485.69	485.69	485.652	485.662	485.522	485.722	485.402	485.732	485.377	485.727		
1	485.687	485.687	485.652	485.672	485.512	485.742	485.395	485.755	485.372	485.757	485.267	485.757
1.5	485.724	485.724	485.632	485.682	485.502	485.702	485.387	485.707	485.367	485.707	485.257	485.707
2	485.697	485.697	485.647	485.727	485.502	485.732	485.37	485.75	485.347	485.757		
2.5	485.707	485.707	485.612	485.652	485.472		485.347	485.677	485.327	485.667		
3	485.732	485.732	485.647	485.687	485.492	485.702	485.382	485.712	485.362	485.722		
3.5	485.722	485.742	485.642	485.732	485.5	485.76	485.382	485.772	485.357	485.767		
4	485.702	485.712	485.642	485.722	485.487	485.727	485.387	485.727	485.372	485.732		
4.5	485.732	485.752	485.687	485.747	485.524	485.754	485.432	485.752	485.422	485.762	485.312	485.762
5	485.712	485.712	485.672	485.752	485.532	485.762	485.462	485.772	485.447	485.767	485.357	485.767
5.5	485.692	485.692	485.667	485.717	485.55	485.73	485.482	485.732	485.457	485.717	485.382	485.732
6	485.712	485.712	485.677	485.717	485.557	485.722	485.512	485.732	485.497	485.727	485.397	485.717
6.5	485.787	485.827	485.782	485.822	485.692	485.842	485.504	485.834	485.477	485.837	485.367	485.817
7	485.867	485.887	485.772	485.902	485.597	485.917	485.457	485.887	485.442	485.892		
7.5	485.837	485.957	485.827	485.957	485.587	485.977	485.462	485.952	485.447	485.947	485.342	485.942
8	485.802	485.892	485.722	485.882	485.589	485.839	485.477	485.817	485.457	485.827	485.357	485.817
8.5	485.722	485.832	485.687	485.837	485.587	485.857	485.477	485.857	485.457	485.857	485.367	485.847
9	485.712	485.712	485.672	485.722	485.592	485.722	485.597	485.787	485.467	485.747	485.367	485.727
9.5	485.722	485.722	485.682	485.732	485.552	485.742	485.422	485.742	485.407	485.747	485.307	485.737
10	485.732	485.732	485.677	485.747	485.592	485.732	485.417	485.747	485.397	485.747	485.287	485.737
10.5	485.682	485.682	485.642	485.692	485.497	485.707	485.402	485.722	485.387	485.717	485.287	485.727
11	485.682	485.682	485.652	485.702	485.512	485.702	485.412	485.732	485.387	485.727	485.287	485.737
11.5	485.692	485.692	485.647	485.687	485.512	485.702	485.412	485.692	485.397	485.697	485.297	485.697
12	485.692	485.712	485.637	485.717	485.507	485.737	485.412	485.742	485.397	485.747	485.297	485.747
12.5	485.667	485.667	485.627	485.677	485.512	485.692	485.412	485.712	485.397	485.732	485.277	485.717
13	485.627	485.627	485.582	485.622	485.462	485.642	485.377	485.667	485.357	485.657	485.267	485.677
13.5	485.632	485.632	485.592	485.642	485.497	485.657	485.412	485.672	485.397	485.697	485.277	485.707
14	485.632	485.632	485.602	485.642	485.502	485.652	485.392	485.672	485.382	485.672	485.282	485.682
14.5	485.642	485.642	485.602	485.632	485.497	485.647	485.402	485.662	485.382	485.662	485.287	485.677
15	485.652	485.652	485.617	485.647	485.522	485.642	485.412	485.662	485.397	485.687	485.297	485.697
15.5	485.647	485.647	485.632	485.662	485.512	485.672	485.422	485.702	485.407	485.707	485.307	485.707
16	485.642	485.642	485.602	485.632	485.507	485.637	485.417	485.667	485.407	485.677	485.307	485.677

Appendix C5. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 2

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)
16.5	485.712	485.712	485.667	485.747	485.515	485.755	485.422	485.762	485.407	485.767	485.317	485.777
17	485.642	485.642	485.607	485.637	485.502	485.642	485.417	485.687	485.407	485.697	485.337	485.707
17.5	485.702	485.752	485.652	485.742	485.527	485.757	485.437	485.767	485.417	485.777	485.327	485.777
18	485.672	485.672	485.622	485.672	485.527	485.707	485.427	485.717	485.407	485.727	485.307	485.717
18.5	485.672	485.672	485.637	485.677	485.502	485.702	485.422	485.712	485.407	485.717	485.302	485.712
19	485.722	485.722	485.682	485.752	485.559	485.769	485.422	485.762	485.397	485.682	485.302	485.782
19.5	485.632	485.632	485.602	485.652	485.482	485.662	485.392	485.672	485.397	485.697	485.282	485.672
20	485.662	485.662	485.642	485.692	485.457	485.727	485.372	485.722	485.382	485.752	485.257	485.717
21	485.702	485.702	485.642	485.832	485.482	485.832	485.382	485.832	485.357	485.827	485.247	485.837
22	485.652	485.822	485.627	485.817	485.527	485.807	485.442	485.792	485.407	485.787		
23	485.832	485.852	485.652	485.842	485.547	485.867	485.452	485.852	485.427	485.847	485.342	485.852
24	485.672	485.672	485.642	485.832	485.542	485.842	485.462	485.852	485.427	485.847	485.332	485.842
25	485.657	485.657	485.627	485.667	485.542	485.702	485.452	485.702	485.427	485.697	485.327	485.707
26	485.702	485.702	485.667	485.717	485.527	485.737	485.452	485.742	485.437	485.737	485.327	485.737
27	485.802	485.812	485.827	485.887	485.582	485.912	485.457	485.917	485.437	485.927	485.307	485.917
28	485.842	485.872	485.682	485.862	485.532	485.842	485.452	485.862	485.427	485.867	485.337	485.877
29	485.682	485.682	485.617	485.777	485.527	485.797	485.442	485.802	485.427	485.807	485.327	485.797
30	485.682	485.682	485.632	485.672	485.527	485.687	485.462	485.702	485.447	485.727	485.337	485.717
31	485.702	485.702	485.652	485.722	485.532	485.712	485.482	485.732	485.457	485.737	485.367	485.737
32	485.752	485.822	485.712	485.762	485.592	485.762	485.492	485.782	485.487	485.797	485.387	485.777
33	485.692	485.692	485.657	485.687	485.602	485.702	485.522	485.702	485.507	485.707	485.402	485.692
34	485.812	485.842	485.807	485.847	485.687	485.857	485.562	485.842	485.537	485.837	485.467	485.817
35	485.712	485.712	485.687	485.937	485.627	485.967	485.542	485.962	485.532	485.972	485.447	485.947
36	485.702	485.702	485.682	485.732	485.602	485.752	485.502	485.762	485.477	485.757	485.407	485.747
37	485.852	485.882	485.712	485.862	485.672	485.902	485.477	485.917	485.457	485.917	485.347	485.907
38	485.702	485.702	485.672	485.712	485.582	485.742	485.477	485.727	485.447	485.732	485.347	485.727
39	485.692	485.692	485.662	485.702	485.557	485.717	485.462	485.742	485.447	485.747	485.337	485.737
40	485.692	485.692	485.632	485.692	485.547	485.717	485.447	485.732	485.437	485.757	485.317	485.737
41	485.692	485.692	485.642	485.682	485.552	485.692	485.472	485.712	485.437	485.697	485.357	485.707
42	485.702	485.702	485.687	485.737	485.632	485.762	485.502	485.762	485.477	485.767	485.377	485.757
43	485.742	485.742	485.717	485.737	485.602	485.762	485.477	485.737	485.487	485.777	485.347	485.717
44	485.762	485.762	485.702	485.742	485.592	485.762	485.492	485.762	485.487	485.767	485.377	485.747

Appendix C5. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 2

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03
Distance (m)	Frost Table	Peat Surface	Frost Table	Peat Surface	Frost Table	Peat Surface	Frost Table (m)	Peat Surface	Frost Table (m)	Peat Surface	Frost Table
45	485.782	485.782	485.692	485.742	485.582	485.782	485.492	485.782	485.477	485.797	485.367
46	485.772	485.772	485.702	485.742	485.567	485.747	485.477	485.767	485.457	485.767	485.347
47	485.722	485.722	485.707	485.767	485.572	485.742	485.492	485.762	485.447	485.747	485.367
48	485.732	485.732	485.707	485.737	485.577	485.757	485.512	485.752	485.457	485.727	485.387
49	485.762	485.762	485.732	485.762	485.652	485.782	485.532	485.772	485.497	485.747	485.427
50	485.832	485.832	485.822	485.832	485.727	485.827	485.582	485.812	485.497	485.767	485.447
52	485.792	485.822	485.717	485.747	485.582	485.762	485.452	485.782	485.487	485.827	485.357
54	485.622	485.622	485.612	485.662	485.522	485.662	485.442	485.712	485.437	485.717	485.317
56	485.672	485.672	485.642	485.682	485.527	485.697	485.442	485.762	485.437	485.777	485.327
58	485.702	485.702	485.572	485.632	485.512	485.662	485.442	485.712	485.437	485.707	485.307
60	485.702	485.702	485.642	485.682	485.562	485.702	485.452	485.722	485.437	485.737	
62	485.822	485.852	485.797	485.837	485.562	485.842	485.462	485.832	485.417	485.807	
64	485.712	485.712	485.692	485.722	485.572	485.712	485.472	485.722	485.417	485.697	485.347
66	485.752	485.752	485.692	485.752	485.542	485.772	485.432	485.782	485.407	485.787	485.307
68	485.712	485.712	485.702	485.752	485.542	485.702	485.462	485.772	485.417	485.757	485.327
70	485.722	485.722	485.712	485.742	485.552	485.702	485.512	485.742	485.447	485.707	485.377
72	485.882	485.882	485.882	485.952	485.652	485.912	485.562	485.922	485.517	485.907	485.407
74	485.822	485.822	485.752	485.762	485.642	485.772	485.502	485.772	485.477	485.777	485.372
76	485.817	485.817	485.732	485.762	485.577	485.757	485.422	485.762	485.457	485.817	485.327
78	485.762	485.762	485.697	485.737	485.552	485.732	485.452	485.752	485.427	485.767	485.307
80	485.682	485.682	485.692	485.692	485.562	485.742	485.452	485.742	485.467	485.757	485.327
82	485.767	485.767	485.807	485.877	485.627	485.897	485.492	485.892	485.487	485.917	485.337
84	485.682	485.682	485.677	485.707	485.552	485.742	485.492	485.762	485.457	485.757	485.327
86	485.832	485.832	485.802	485.872	485.632	485.842	485.522	485.852	485.447	485.797	485.367
88	485.812	485.812	485.752	485.782	485.582	485.772	485.502	485.792	485.467	485.777	485.377
90	485.732	485.732	485.717	485.737	485.602	485.722	485.512	485.752	485.437	485.707	485.377
92	485.732	485.732	485.722	485.732	485.652	485.742	485.522	485.742	485.437	485.687	485.397
94	485.792	485.802	485.852	485.902	485.652	485.792	485.552	485.842	485.477	485.787	485.427
96	485.922	485.952	485.772	485.952	485.632	485.932	485.612	486.012	485.457	485.887	485.407
98	485.762	485.762	485.742	485.772	485.642	485.752	485.582	485.862	485.457	485.757	485.357
100	485.812	485.812	485.752	485.782	485.652	485.822					

	Appendix C5. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 2						
Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
0.5		485.689	485.644	485.608	485.594		485.66
1		485.727	485.697	485.66	485.647	485.558	
1.5		485.682	485.643	485.615	485.599		485.67
2		485.734	485.652	485.62	485.61	485.594	485.723
2.5		485.673	485.631	485.596	485.583		
3		485.707	485.669	485.635	485.616	485.575	485.701
3.5		485.764	485.734	485.698	485.686		485.754
4		485.709	485.679	485.65	485.641	485.6	485.697
4.5		485.76	485.723	485.691	485.678		485.774
5		485.739	485.7	485.669	485.654	485.617	485.746
5.5		485.694	485.665	485.634	485.622		485.721
6		485.804	485.661	485.626	485.613	485.63	485.701
6.5		485.859	485.771	485.74	485.728		485.772
7		485.912	485.829	485.793	485.785	485.787	485.822
7.5			485.874	485.838	485.825		485.899
8		485.825	485.749	485.719	485.709	485.605	485.794
8.5			485.783	485.752	485.741		485.84
9		485.708	485.631	485.609	485.601	485.57	485.686
9.5		485.726	485.656	485.628	485.604		485.705
10		485.702	485.682	485.652	485.641	485.559	485.727
10.5		485.697	485.656	485.615	485.604		485.699
11		485.717	485.674	485.623	485.604	485.56	485.737
11.5		485.662	485.619	485.581	485.569		
12			485.688	485.637	485.61	485.542	485.707
12.5		485.697	485.648	485.599	485.59		485.704
13		485.662	485.61	485.569	485.557	485.505	
13.5		485.687	485.642	485.602	485.571		485.692
14		485.662	485.614	485.576	485.568	485.499	485.648
14.5		485.662	485.625	485.577	485.588		485.657
15		485.672	485.636	485.6	485.6	485.522	485.652
15.5		485.697	485.658	485.62	485.61		485.697
16		485.661	485.613	485.58	485.541	485.5	485.662

Appendix C5. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 2

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
16.5		485.762	485.715	485.683	485.666		485.777
17		485.668	485.631	485.593	485.593	485.524	485.712
17.5		485.754	485.694	485.664	485.643		485.752
18		485.689	485.645	485.605	485.59	485.562	
18.5		485.694	485.642	485.619	485.61		485.707
19		485.766	485.692	485.683	485.662	485.522	485.727
19.5		485.652	485.605	485.573	485.573		485.677
20		485.712	485.651	485.631	485.601	485.63	485.742
21		485.777			485.704	485.592	
22		485.792			485.677	485.582	
23		485.832			485.747	485.677	
24		485.822			485.726	485.565	
25		485.692			485.587	485.54	
26		485.722			485.631	485.585	
27		485.907			485.832	485.548	
28		485.852			485.793	485.7	
29		485.767			485.631	485.555	
30		485.692			485.588	485.559	
31		485.702			485.694	485.63	
32		485.757			485.654	485.59	
33		485.647			485.541	485.593	
34		485.779			485.705	485.64	
35		485.906			485.756	485.633	
36		485.69			485.611	485.63	
37		485.877			485.782	485.605	
38		485.702			485.624	485.56	
39		485.716			485.626	485.621	
40		485.722			485.631	485.562	
41		485.702			485.612	485.563	
42		485.752			485.688	485.62	
43		485.712			485.633	485.615	
44		485.732			485.675	485.64	

Appendix C5. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 2

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table	Peat Surface	Peat Surface	Peat Surface	Peat Surface	Peat Surface	Peat Surface
45		485.762			485.681	485.613	
46		485.736			485.641	485.585	
47		485.732			485.641	485.635	
48		485.712			485.603	485.605	
49		485.732			485.611	485.628	
50		485.776			485.686	485.708	
52		485.745			485.634	485.585	
54		485.706			485.669	485.565	
56		485.739			485.627	485.645	
58		485.682			485.659	485.54	
60		485.717			485.608	485.641	
62		485.802			485.715	485.67	
64		485.742			485.628	485.56	
66		485.767			485.668	485.595	
68		485.776			485.732	485.655	
70		485.726			485.679	485.792	
72		485.907			485.836	485.755	
74		485.762			485.683	485.687	
76		485.769			485.665	485.644	
78		485.767			485.666	485.625	
80		485.712			485.617	485.605	
82		485.854			485.789	485.61	
84		485.717			485.635	485.612	
86		485.83			485.721	485.688	
88		485.782			485.746	485.69	
90		485.722			485.656	485.682	
92		485.732			485.678	485.635	
94		485.822			485.731	485.67	
96		485.922			485.859	485.71	
98		485.752			485.681		
100		485.755			485.655	485.715	

Appendix C6. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 3

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)
0.5	485.71	485.735	485.781	485.811	485.651	485.821	485.516	485.816	485.446	485.806		
1	485.739	485.739	485.701	485.731	485.581	485.721	485.506	485.716	485.471	485.701	485.351	485.681
1.5	485.749	485.749	485.696	485.726	485.581	485.731	485.506	485.726	485.471	485.711	485.356	485.706
2	485.74	485.74	485.701	485.731	485.618	485.708	485.481	485.721	485.446	485.716	485.321	485.711
2.5	485.799	485.809	485.736	485.786	485.606	485.786	485.471	485.781	485.441	485.781	485.311	485.771
3	485.856	485.896	485.821	485.881	485.621	485.881	485.471	485.891	485.431	485.871	485.306	485.856
3.5	485.786	485.786	485.736	485.756	485.601	485.761	485.471	485.761	485.441	485.761	485.311	485.741
4	485.726	485.726	485.686	485.716	485.586	485.716	485.501	485.721	485.411	485.641	485.376	485.696
4.5	485.788	485.788	485.741	485.781	485.671	485.781	485.611	485.791	485.581	485.771	485.496	485.756
5	485.947	485.987	485.906	485.976	485.881	485.991	485.736	485.996	485.681	485.981	485.486	485.946
5.5	485.916	485.936	485.861	485.931	485.664	485.934	485.551	485.941	485.511	485.931	485.391	485.901
6	485.808	485.808	485.776	485.796	485.641	485.751	485.526	485.806	485.491	485.781	485.361	485.761
6.5	485.784	485.784	485.736	485.766	485.596	485.766	485.486	485.776	485.451	485.766	485.391	485.751
7	485.776	485.776	485.736	485.756	485.616	485.766	485.526	485.776	485.501	485.771	485.416	485.746
7.5	485.996	486.036	485.916	486.016	485.811	486.021	485.716	486.036	485.651	486.041	485.436	486.016
8	485.816	485.816	485.786	485.786	485.656	485.736	485.531	485.731	485.501	485.731	485.376	485.706
8.5	485.806	485.836	485.766	485.816	485.626	485.826	485.506	485.836	485.471	485.821	485.351	485.801
9	485.778	485.778	485.686	485.706	485.591	485.791	485.476	485.706	485.451	485.701	485.336	485.696
9.5	485.741	485.741	485.706	485.726	485.596	485.746	485.476	485.726	485.446	485.726	485.336	485.726
10	485.891	485.931	485.791	485.921	485.636	485.926	485.476	485.916	485.449	485.909	485.336	485.846
10.5	485.746	485.746	485.696	485.736	485.586	485.746	485.476	485.746	485.451	485.731	485.366	485.726
11	485.751	485.751	485.696	485.706	485.586	485.716	485.526	485.726	485.511	485.731	485.436	485.716
11.5	485.796	485.796	485.751	485.781	485.656	485.786	485.586	485.786	485.566	485.786	485.491	485.771
12	485.823	485.823	485.801	485.821	485.726	485.816	485.621	485.831	485.581	485.811	485.486	485.786
12.5	485.946	486.026	485.926	486.016	485.836	486.016	485.661	486.021	485.621	486.021	485.506	485.986
13	485.861	485.871	485.841	485.861	485.766	485.856	485.636	485.866	485.591	485.841	485.481	485.821
13.5	485.906	485.906	485.826	485.886	485.686	485.896	485.531	485.881	485.501	485.876	485.386	485.836
14	485.821	485.821	485.781	485.811	485.646	485.796	485.496	485.776	485.456	485.746	485.356	485.736
14.5	485.831	485.831	485.786	485.806	485.626	485.806	485.556	485.796	485.526	485.786	485.446	485.766
15	486.036	486.066	486.021	486.051	485.966	486.056	485.976	486.066	485.971	486.061	485.646	486.016
15.5	486.006	486.036	485.976	486.026	485.896	486.026	485.741	486.031	485.687	486.027	485.596	485.986
16	485.981	486.011	485.956	485.996	485.846	486.006	485.666	486.006	485.621	486.001	485.576	485.976

Appendix C6. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 3

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)
16.5	486.086	486.246	486.006	486.236	485.976	486.256	485.876	486.256	485.871	486.251	485.851	486.241
17	486.086	486.106	486.066	486.096	486.016	486.086	485.936	486.106	485.896	486.096	485.726	486.056
17.5	485.936	485.936	485.896	485.896	485.806	485.886	485.736	485.876	485.581	485.861		
18	485.926	485.926	485.876	485.876	485.776	485.876	485.766	485.866	485.746	485.846	485.496	485.796
18.5	485.996	486.006	485.986	486.006	485.826	485.996	485.826	485.996	485.811	485.991	485.551	485.931
19	485.906	485.906	485.876	485.886	485.786	485.886	485.751	485.941	485.666	485.876	485.516	485.846
19.5	485.996	486.006	485.966	485.996	485.876	485.996	485.756	486.006	485.596		485.506	485.936
20	485.896	485.906	485.876	485.886	485.816	485.896	485.616	485.886	485.581	485.871	485.446	485.826
21			486.026	486.076	485.946	486.056	485.911	486.041	485.516	486.036	485.396	485.996
22	485.851	485.881	485.836	485.876	485.686	485.876	485.546	485.866	485.511	485.861	485.396	485.846
23	485.826	485.826	485.751	485.751	485.636	485.756	485.501	485.761	485.471	485.821		
24	485.881	485.911	485.846	485.896	485.666	485.896	485.536	485.896	485.503	485.893		
25	485.821	485.821	485.746	485.756	485.636	485.746	485.496	485.766	485.471	485.771	485.356	485.756
26	485.906	485.936	485.896	485.916	485.896	485.926	485.496	485.926	485.461	485.911	485.336	485.906
27	485.796	485.796	485.726	485.736	485.616	485.776	485.501	485.761	485.461	485.741		
28	485.766	485.766	485.726	485.726	485.596	485.726	485.476		485.441	485.731		
29	485.751	485.751	485.696	485.696	485.606	485.716	485.486	485.886	485.451	485.731	485.346	485.656
30	485.741	485.741	485.696	485.706	485.576	485.716	485.476		485.451	485.731	485.326	485.696
31	485.851	485.891	485.836	485.886	485.636	485.876	485.616	485.886	485.601	485.871	485.351	485.851
32	485.776	485.776	485.731	485.741	485.586	485.736	485.501	485.761	485.471	485.751	485.336	485.726
33	485.836	485.836	485.806	485.806	485.676	485.816	485.536	485.816	485.506	485.806	485.376	
34	485.836	485.916	485.756	485.886	485.646	485.906	485.496	485.886	485.461	485.861	485.336	
35	485.836	485.836	485.766	485.796	485.626	485.816	485.486	485.816	485.456	485.816	485.326	
36	485.873	485.913	485.816	485.876	485.651	485.891	485.486	485.906	485.461	485.901	485.326	
37	485.826	485.826	485.706	485.726	485.596	485.736	485.466		485.431	485.731		
38	485.856	485.886	485.796	485.896	485.651	485.891	485.506	485.906	485.451	485.891	485.346	
39	485.826	485.826	485.786	485.866	485.606	485.846	485.496	485.846	485.461	485.851		
40	485.816	485.856	485.786	485.786	485.626	485.756	485.506	485.766	485.476	485.766	485.346	
41	485.791	485.791	485.751	485.761	485.636	485.786	485.511	485.771	485.481	485.771	485.366	
42	485.786	485.786	485.716	485.726	485.626	485.746	485.531		485.501		485.386	485.706
43	485.856	485.926	485.781	485.901	485.671	485.911	485.586	485.906	485.551	485.891	485.446	485.876
44	485.806	485.806	485.766	485.776	485.661	485.781	485.616	485.776	485.611	485.781	485.586	485.756

Appendix C6. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 3

Date	10-Apr-03		15-Apr-03		30-Apr-03		21-May-03		26-May-03		12-Jun-03	
Distance (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)	Frost Table (m)	Peat Surface (m)
45	486.006	486.016	485.956	485.956	485.886	485.986	485.671	485.991	485.631	485.781	485.476	485.956
46	485.886	485.926	485.856	485.906	485.666	485.906	485.536	485.916	485.496	485.896	485.366	485.886
47	485.866	485.896	485.866	485.916	485.686	485.936	485.516	485.926	485.471	485.921		
48	485.856	485.866	485.776	485.846	485.626	485.826	485.496	485.836	485.451	485.821		
49	485.876	485.926	485.846	485.896	485.686	485.896	485.536	485.906	485.551	485.921	485.536	485.906
50	485.851	485.851	485.736	485.766	485.596	485.766	485.486	485.776	485.461	485.771		
52	485.856	485.856	485.736	485.736	485.596	485.746	485.456	485.776	485.426	485.746		
54	485.846	485.846	485.736	485.746	485.606	485.706	485.506	485.786	485.481	485.731		
56	485.866	485.866	485.776	485.776	485.666	485.746	485.536	485.886	485.501	485.851		
58	485.871	485.881	485.816	485.826	485.706	485.836	485.586	485.846	485.501	485.791		
60	485.861	485.861	485.776	485.776	485.636	485.746	485.476	485.796	485.431	485.771	485.296	485.766
62	485.856	485.886	485.836	485.886	485.666	485.866	485.536	485.886	485.506	485.886		
64	485.891	485.891	485.751	485.761	485.696	485.846	485.546	485.796	485.501	485.771	485.396	485.766
66	485.866	485.866	485.826	485.876	485.696	485.856	485.611	485.871	485.591	485.851	485.576	485.846
68	485.866	485.866	485.836	485.856	485.706	485.836	485.561	485.861	485.531	485.831	485.426	485.826
70	485.966	485.996	485.916	485.976	485.746	485.976	485.626	485.976	485.581	485.961	485.446	485.936
72	485.886	485.886	485.846	485.846	485.696	485.776	485.606	485.836	485.571	485.811	485.451	485.791
74	485.896	485.896	485.836	485.856	485.696	485.866	485.556	485.876	485.521	485.861	485.396	485.826
76	485.966	486.066	485.906	486.056	485.766	486.046	485.646	486.066	485.631	486.031	485.496	485.936
78	485.906	485.906	485.796	485.806	485.701	485.811	485.606	485.816	485.571	485.801	485.466	485.786
80	485.896	485.896	485.836	485.866	485.726	485.876	485.616	485.896	485.571	485.871	485.456	485.856
82	485.936	485.946	485.851	485.921	485.746	485.916	485.586	485.926	485.531	485.911	485.416	485.906
84	485.896	485.896	485.846	485.866	485.656	485.756	485.526	485.856	485.511	485.891	485.386	485.846
86	485.866	485.866	485.846	485.856	485.726	485.876	485.586	485.846	485.561	485.851	485.436	485.836
88	485.926	485.946	485.896	485.946	485.736	485.936	485.606	485.946	485.571	485.941	485.436	485.916
90	485.841	485.841	485.786	485.786	485.726	485.826	485.636	485.856	485.591	485.841	485.486	485.826
92	486.056	486.076	485.866	485.966	485.836	486.026	485.636	486.016	485.581	486.001	485.476	485.976
94	485.956	485.976	485.946	485.986	485.746	485.966	485.586	485.936	485.561	485.931		
96	485.891	485.891	485.816	485.816	485.696	485.806	485.586	485.856	485.531	485.831		
98	485.906	485.926	485.836	485.916	485.726	485.946	485.586	485.936	485.531	485.921	485.446	485.926
100	485.911	485.941	485.836	485.886	485.706	485.926	485.596	485.956	485.551	485.951		

Appendix C6. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 3

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
0.5		485.782	485.728	485.709	485.699		485.742
1		485.649	485.614	485.589	485.575		485.672
1.5		485.687	485.652	485.627	485.616		485.692
2		485.661	485.627	485.602	485.592		
2.5		485.762	485.727	485.7	485.69		485.744
3		485.843	485.803	485.781	485.77		
3.5		485.718	485.669	485.647	485.636		485.802
4		485.655	485.613	485.587	485.573		485.65
4.5		485.741	485.703	485.677	485.664		485.742
5		485.905	485.875	485.85	485.841		485.874
5.5		485.893	485.857	485.839	485.829		485.845
6		485.748	485.709	485.688	485.67		485.738
6.5		485.736	485.694	485.674	485.663		485.676
7		485.723	485.687	485.668	485.641		485.705
7.5		485.977	485.948	485.925	485.916		485.966
8		485.682	485.641	485.616	485.609		485.664
8.5		485.792	485.743	485.723	485.71		485.781
9		485.681	485.64	485.615	485.602		485.703
9.5		485.702	485.666	485.635	485.626		485.686
10		485.88	485.834	485.813	485.797		
10.5		485.705	485.663	485.637	485.626		485.676
11		485.68	485.646	485.621	485.61		485.711
11.5		485.729	485.694	485.671	485.657		485.711
12		485.746	485.71	485.69	485.68		485.714
12.5		485.931	485.882	485.867	485.855		485.896
13		485.757	485.724	485.699	485.682		485.74
13.5		485.815	485.775	485.759	485.749		485.812
14		485.711	485.662	485.65	485.639		485.739
14.5		485.738	485.703	485.684	485.677		485.733
15		485.961	485.925	485.908	485.902		485.889
15.5		485.908	485.858	485.842	485.839		485.865
16		485.891	485.866	485.855	485.845		485.882

Appendix C6. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 3

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
16.5		486.139	486.109	486.103	486.097		486.121
17		485.958	485.935	485.927	485.922		485.956
17.5		485.76	485.7	485.699	485.692		485.756
18		485.744	485.713	485.661	485.649		485.713
18.5		485.896	485.873	485.863	485.854		485.893
19		485.806	485.769	485.759	485.749		485.843
19.5		485.911	485.882	485.871	485.863		485.896
20		485.805	485.779	485.767	485.732		485.807
21		485.99			485.951		
22		485.825			485.757		
23		485.726			485.668		
24		485.886			485.84		
25		485.739			485.687		
26		485.913			485.852		
27		485.736			485.677		
28		485.716			485.655		
29		485.692			485.655		
30		485.706			485.637		
31		485.866			485.792		
32		485.736			485.688		
33		485.786			485.723		
34		485.851			485.778		
35		485.781			485.719		
36		485.886			485.826		
37		485.736			485.656		
38		485.886			485.852		
39		485.846			485.783		
40		485.766			485.709		
41		485.751			485.68		
42		485.686			485.622		
43		485.796			485.75		
44		485.746			485.693		

Appendix C6. Frost table and peat surface elevation from April 2003, to September 2004, for Transect 3

Date	10-Jul-03		13-Aug-03	11-Sep-03	14-Oct-03	19-Feb-04	21-Sep-04
Distance (m)	Frost Table (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)	Peat Surface (m)
45		485.926			485.901		
46		485.901			485.805		
47		485.806			485.82		
48		485.911			485.741		
49		485.911			485.844		
50		485.756			485.686		
52		485.721			485.65		
54		485.731			485.657		
56		485.876			485.786		
58		485.821			485.754		
60		485.906			485.83		
62		485.886			485.81		
64		485.766			485.705		
66		485.826			485.789		
68		485.786			485.718		
70		485.906			485.864		
72		485.791			485.74		
74		485.806			485.72		
76		485.866					
78		485.776			485.719		
80		485.826			485.776		
82		485.891			485.83		
84		485.841			485.675		
86		485.846			485.752		
88		485.921			485.86		
90		485.776			485.735		
92					485.94		
94					485.872		
96					485.798		
98					485.81		
100					485.863		

Appendix D

Appendix D Bog shoe surface elevation and manual water level measurements made from 2002 to 2004 at the three main study sites in Sandhill Fen: Fen Centre, Edge, and Partially Treed

Date	Peat elevation at the bog shoes (m)			Surface water table measurements (m)			Piezometric elevation of benchmark-piezometers (m)		
	Centre	Edge	Treed	Centre	Edge	Treed	Centre	Edge	Treed
6-Nov-02	485.720						485.621		
14-Nov-02	485.724						485.621	485.497	485.529
26-Nov-02	485.720						485.603	485.427	485.510
23-Dec-02	485.704						485.532	485.323	485.457
17-Jan-03	485.694	485.617					485.473	485.236	485.409
18-Feb-03	485.686	485.616					485.356	485.140	485.305
13-Mar-03	485.680	485.622					485.281	485.079	485.227
18-Mar-03	485.679	485.615					485.263	485.066	485.207
24-Mar-03	485.674	485.626					485.257	485.083	485.199
10-Apr-03	485.674	485.607	485.734	485.757			485.249	485.119	485.174
15-Apr-03	485.671	485.612	485.731		485.744	485.752	485.240	485.166	485.193
24-Apr-03	485.671	485.610	485.728				485.312	485.274	485.252
30-Apr-03	485.684	485.610	485.724	485.712			485.388	485.337	485.307
8-May-03	485.695	485.602	485.722	485.704			485.460	485.528	485.520
21-May-03	485.693	485.590	485.714		485.667	485.706	485.529	485.509	485.591
26-May-03	485.689	485.579	485.699				485.542	485.521	485.601
30-May-03	485.691	485.574					485.557	485.547	485.616
3-Jun-03	485.690	485.569	485.696		485.643		485.592	485.566	485.644
10-Jun-03	485.695	485.567	485.700	485.638	485.608	485.696	485.634	485.596	485.681
12-Jun-03	485.693	485.562	485.698		485.631	485.686	485.622	485.600	485.686
17-Jun-03	485.689	485.555	485.694	485.615		485.686	485.625	485.591	485.671
20-Jun-03	485.685	485.550	485.690				485.601	485.575	
24-Jun-03	485.686	485.551	485.692				485.628	485.587	
4-Jul-03	485.687	485.548	485.692	485.629		485.682	485.628	485.567	485.662
8-Jul-03	485.685	485.544	485.688	485.624		485.661	485.617	485.554	485.656
10-Jul-03		485.542	485.685	485.614	485.527		485.617	485.538	
16-Jul-03	485.674	485.533	485.677		485.518		485.597	485.490	
17-Jul-03	485.673	485.533	485.675				485.586	485.479	
24-Jul-03	485.663	485.523	485.664				485.547	485.403	
29-Jul-03	485.662	485.522	485.662				485.533	485.382	
31-Jul-03	485.658	485.520		485.512		485.551	485.527	485.368	485.546
1-Aug-03	485.656				485.303		485.529	485.356	
3-Aug-03	485.651	485.517					485.508	485.335	
7-Aug-03	485.652	485.517	485.654	485.514		485.548	485.509	485.329	485.537
13-Aug-03	485.643	485.507	485.643				485.477	485.281	
4-Sep-03	485.611	485.496	485.648				485.327	485.089	
11-Sep-03	485.609	485.495	485.642	485.308			485.301	485.054	
21-Sep-03	485.604	485.494	485.639				485.291	485.060	
1-Oct-03	485.597	485.493	485.636				485.265	485.044	
4-Oct-03	485.596	485.492	485.634	485.258		485.287	485.254	485.040	485.283
14-Oct-03	485.591	485.492	485.632	485.227	485.045	485.276	485.224	485.025	485.259
17-Oct-03	485.590	485.495			485.031		485.216	485.026	
23-Oct-03		485.489	485.630	485.212	485.001	485.266	485.202	485.032	485.251
26-Oct-03	485.586	485.492	485.628	485.322		485.426	485.210	485.033	485.406

Appendix D Bog shoe surface elevation and manual water level measurements made from 2002 to 2004 at the three main study sites in Sandhill Fen: Fen Centre, Edge, and Partially Treed

Bog shoe surface elevation, manual water level measurements made from 2002 to 2004 at the three main study sites in Sandhill Fen: Edge, Fen Centre, and Partially Treed									
Date	Peat elevation at the bog shoes (m)			Surface water table measurements (m)			Piezometric elevation of benchmark-piezometers (m)		
	Centre	Edge	Treed	Centre	Edge	Treed	Centre	Edge	Treed
13-Nov-03	485.585	485.494	485.634	485.257		485.341	485.192	485.043	485.226
2-Dec-03	485.576	485.498	485.630	485.247		485.336	485.112	484.948	485.166
10-Jan-04	485.556	485.508	485.629				484.992	484.873	485.056
20-Jan-04	485.552	485.509	485.629						
19-Feb-04	485.545	485.515	485.629				484.962	484.848	485.026
16-Mar-04	485.538	485.517	485.625				484.962	484.848	485.011
24-Mar-04	485.537	485.517	485.625				484.982	484.853	485.036
15-Apr-04	485.553	485.519	485.629	485.622	485.643	485.636	485.222	485.003	485.046
20-Apr-04	485.555	485.519	485.634	485.637	485.648	485.656	485.252	485.063	485.206
28-Apr-04	485.594	485.522		485.652	485.653	485.636	485.402	485.173	485.306
13-May-04	485.640	485.521	485.656	485.612	485.613	485.636	485.572	485.393	485.491
27-May-04	485.646	485.517	485.666	485.587	485.588	485.631	485.597	485.503	485.601
31-May-04	485.653	485.521	485.673						
9-Jun-04	485.670	485.529	485.680	485.732	485.713	485.741	485.727	485.618	485.731
30-Jun-04	485.681	485.534	485.684	485.732	485.708	485.736	485.747	485.728	485.746
7-Jul-04	485.680	485.534	485.684	485.727	485.713	485.726	485.727	485.723	485.731
29-Jul-04	485.688	485.537	485.686	485.732	485.713	485.726	485.742	485.723	485.741
11-Aug-04	485.690	485.540	485.689	485.792	485.808	485.876	485.802	485.768	485.871
18-Aug	485.694	485.545	485.693						
26-Aug-04	485.691	485.548	485.696	485.867	485.878	485.951	485.867	485.868	485.951
8-Sep-04	485.694	485.548	485.698						
16-Sep-04	485.696	485.548	485.699						
21-Sep-04	485.696	485.547	485.700	485.947	485.955	485.960	485.954	485.961	
27-Sep-04	485.697	485.547	485.702	485.937	485.908	485.955	485.952	485.935	485.963