THE INS AND OUTS OF BURNS BOG: A WATER BALANCE STUDY

by

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ABSTRACT

This study assesses the influence of forest encroachment on the water balance of Burns Bog in Delta, British Columbia by determining the differences in the evapotranspiration and interception losses between a forested and non-forested (open) bog site. Throughfall in the forested bog site was 88% of the precipitation. During the growing season (June 15 – September 15, 2009), average evaporation in the open bog site, was 0.9 mm/day. The average evapotranspiration from the forested bog site was 1.1 mm/day; average transpiration was 0.4 mm/day while the average evaporation rate was 0.7 mm/day. Water storage was greater in the open bog site, with higher water levels and soil moisture. Deep drainage accounted for up to 10% of the water balance at both sites. A water balance model that requires few input variables was successfully created and calibrated and can be used to simulate water levels in Burns Bog.

Keywords: Water Balance, Peat, Sphagnum, Raised Bog, Forested Bog

Subject Terms: Raised Bog Water Management, Water Balance, Peat Hydrology, Burns Bog

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1.0 INTRODUCTION

1.1 Background

Approximately 2% of the Earth's land surface is covered by peatlands (Clymo, 1984). Peatlands consist of partially decomposed plant and animal matter that is poorly aerated because high water levels result in low decomposition rates and the accumulation of organic matter (Hebda et al., 2000). The accumulation of peat causes increasingly acidic and nutrient-deficient conditions due to the ability of organic matter to adsorb cations in exchange for hydrogen ions (Rydin and Jeglum, 2006). These acidic and nutrient-deficient areas support a distinctive flora.

Peatlands can be differentiated through water chemistry, hydraulic head distribution, as well as temperature (Adema et al., 2005). Ombrotrophic peatlands, also known as bogs, receive water only from precipitation. Minerotrophic peatlands, known as fens, receive water from both groundwater and precipitation (Holden et al, 2002). Bogs, being largely isolated from groundwater, are low in nutrients and ions relative to other types of peatlands because rainwater is low in both nutrients and ions. Distinct flora can therefore be found in bog environments (Ingram, 1967). Moore (1987) notes that there is a tendency for peatlands to develop into bogs because of the way peatlands grow through the accumulation of peat below living moss. Clymo's (1984) bog growth model describes that bogs are formed when plant mass is added at the surface at a rate greater than the decomposition of dead plants below the surface. As peat accumulates, the surface rises and the influence of groundwater diminishes (Hebda et al., 2000). Over time, the surface layers become isolated from groundwater and become increasingly ombrotrophic.

Peatlands are found mostly between 45 and 64^{o}N where photosynthetically active radiation and temperature, as well as moisture availability, are most favourable (Price et al., 2003). The southern boundary of raised bogs in North America is determined more by the precipitation during the summer months than by the annual precipitation (Rydin and Jegulm, 2006). Conditions for the development of peatlands are particularly prevalent in northern areas of Canada, where many peatlands lie above permafrost (Tarnocai et al., 2000). However, peatlands also occur in temperate regions, e.g. there are also peatlands in the Fraser Valley of British Columbia and in Washington and Oregon, USA. As the Fraser River Delta prograded towards the ocean, several bogs developed on the floodplain in areas beyond the limit of tides (Hutchinson et al., 1998). Beginning as freshwater marshes, these areas were transformed through ecological succession into raised bogs (Hebda, 1977, Hutchinson et al., 1998). These thick peat mats are covered by a variety of vegetation, and are a habitat for species that frequently can only be found in these areas.

1.2 Conceptual Models of Raised Bog Development

There are two influential models that describe the form and development of bogs: the Bog Growth Model (Clymo, 1984, Belyea, 2006) and the Groundwater Mound Hypothesis (Ingram, 1982, Belyea 2006). Ingram (1978) introduced a two-layered conceptual model of bogs, in which each layer is distinct in structure and hydraulic characteristics. A bog has an active upper layer, and a less active lower layer.

The upper layer, called the acrotelm, consists of living moss on its surface with decaying moss situated directly below. This layer is usually no more than the top 40 cm of the peat profile (Hebda et al., 2000). The acrotelm is annually drained and flooded as the water table falls and rises. Hydrologically, this layer is distinct from the lower layer in that the acrotelm has a higher hydraulic conductivity, as well as a high porosity, high specific yield, and high infiltration capacity (Price and Ketcheson, 2009). This means most of the lateral flow occurs in this layer (Holden and Burt, 2003). Because of these characteristics, the acrotelm plays an extremely important role in the functioning of a healthy bog environment. The lower layer, called the catotelm, consists of decayed and humified peat and is normally permanently saturated. This layer has a much lower hydraulic conductivity. As new plant material accumulates on the surface of the acrotelm, the catotelm increases in thickness as it incorporates decaying material from the base of the acrotelm.

As bog plants die and decay, the density of the peat increases due to the collapse of pore spaces in the dead plant material. This increase in density leads to a decrease in hydraulic conductivity (Clymo, 1984; Price et al., 2003). The anaerobic conditions created by constant saturation decrease the rate of decomposition of plant matter (Clymo, 1984). Clymo's, (1984) bog growth model states that because new plant matter accumulates at the surface of the bog during successive years, and the slow drainage of the catotelm due to the low hydraulic conductivity of the decayed peat, both the water level and the surface of the bog are raised over time. This leads to the increased height of the water mount as the bog grows.

In undisturbed bogs, the water table fluctuates in a narrow range within the acrotelm (Hokka et al., 2008), with the catotelm remaining saturated. The boundary between the acrotelm and the catotelm can therefore be defined as the mean depth of the water table during the late summer months when it is at its lowest (Belyea, 2006), meaning that the acrotelm corresponds to the water table fluctuation zone (Price et al., 2003). Ingram (1987) describes the importance of a high water mound for the health of a bog due to both the susceptible nature of the surface vegetation to dry conditions (Clymo, 1984), as well as the irreversible changes that occur to the structure of the peat with dewatering.

1.3 Effects of Drainage

The depth to the water table controls the stability of the bog (Holden and Burt, 2002). Draining a bog (e.g. through ditching) results in a lowering of the water table. As a result, more of the peat becomes susceptible to decomposition by aerobic microorganisms (Clymo, 1984). This ultimately destabilizes the bog through changes in the amount of stored water, the structure of the peat, vegetation composition, and a decrease in the rate of new peat formation (Hebda et al., 2000). Subsidence also occurs from drainage; in some peatlands, shrinkage in the peat above the water table can be greater than 50 cm (Eggelsmann et al., 1993). This can result in a drastic change in the thickness of the acrotelm, as it is typically 40 cm or less in depth (Hebda et al., 2000).

After disturbance, the re-establishment of *Sphagnum* becomes increasingly difficult due to the large fluctuations in water levels caused by a degrading acrotelm (Price et al., 2003). *Sphagnum* relies on the high water level created by the undecomposed moss below it. In a drained bog, *Sphagnum* is unable to generate the capillary pressure to draw water from depth (Price et al. 2003). *Sphagnum* relies on passive water transport through the capillary action created by its close network of branchlets, making it vulnerable to changes in soil moisture. Up to 90% of water content is held within the pore spaces, and 99% of the water moved upwards is between the branchlets (Thompson and Waddington, 2008). Shoot density and contact between branches is an important aspect in the health of *Sphagnum*, as it regulates the amount of water available to the plant.

The lowered water table allows for aeration of the peat and the growth of vascular plants that can access water within deeper parts of the peat profile (Price et al., 2003). Although there may be trees in undisturbed areas of bogs, these are typically sparse and severely stunted. Compared to the larger trees along the perimeter of a bog, these trees do not significantly contribute to evapotranspiration (Hokka et al., 2008).

An increase in the density and size of trees causes an increase in interception, thereby decreasing the total amount of rainfall reaching the surface to replenish peat moisture. Trees may also cause a significant decrease in water storage through transpiration because their roots can access water far below that which is accessible to mosses (Hokka et al. 2008). This creates significant water stress on the *Sphagnum*. Models of drained peatlands showed that *Sphagnum* has difficulty re-establishing itself near vascular plants due to water stress. A rapidly falling water table during dry periods driven by vascular plants results in water stress in *Sphagnum* mosses that would typically occur later in the dry season had the vascular plants not been in close proximity (Schouwenaars and Gosen, 2007). However, the evapotranspiration from *Sphagnum* decreases due to the presence of trees and shrubs, as a result of shading, and the associated decrease in wind turbulence.

Drainage also has a profound impact on the morphology of bogs. The reduced water storage caused by drainage affects the ability of the bog to sustain its elevated profile by severely reducing the rate at which peat accumulation occurs (Clymo, 1984; Price et al., 2003). Further, if peat is kept dry for too long, the resulting changes in its structure can be irreversible (Rycroft et al., 1975a, Holden and Burt, 2003), leading to permanent changes in its hydraulic characteristics. The hydraulic conductivity of peat is affected by soil aeration because of de-watering voids in the peat (Ingram, 1967). Overland flow still occurs as saturation excess overland flow, but slow drainage from deep peat layers is greater than in undisturbed peatlands due to increases in macropore flow, pipe density, and pipe flow (Holden and Burt, 2002; Holden et al., 2004; Daniels et al, 2008). The quick drainage that occurs in altered peatlands is also due to the efficiency of the ditches, as water that would otherwise move through the peat matrix and pipes drains at a much greater rate through the ditches.

1.4 Water Balance

Given the close relationship between bog hydrology and ecology, analysis of the water balance is an important tool in determining the health of the bog. Such an analysis can also be applied to restoration. For example, restoration efforts could focus on the effects of tree encroachment and the subsequent discussion of the effectiveness ofthe removal of the trees to create a positive water balance. It is important to develop a water balance for the prediction of the hydrological effects that occur from human activities in bogs (Rydin and Jeglum, 2006).

The water balance approach has been successfully used to describe the hydrology of a few bogs (Hemond, 1980; Van Seters and Price, 2001; Kellner and Halldin, 2002; Dietrich et al., 2007). The basic equation is:

$$\Delta S = P_n - E - T - D - Q$$

Equation 1: Water Balance Equation

where ΔS is the change in storage, P_n is the net precipitation, E is the evaporation, T is the transpiration, D is deep drainage, and Q is discharge from the bog. Although the relative contribution of each component is dependent on the season, some of these components play a more significant role than others in the peatland water budget (Dietrich et al., 2007). Evaporation and transpiration dominate the outputs of undistrubed bogs relative to discharge and deep drainage (Hemond, 1980; Van Seters and Price, 2001), since highly humified peats have a low hydraulic conductivity.

1.4.1 Change in Water Storage (ΔS)

The total amount of water stored in a bog depends on the volume of water in the acrotelm and the catotelm, as well as in the ditches. Changes in the amount of water stored in a natural bog is dependent on changes in both peat moisture content and water table elevation, as annual, seasonal, and diurnal fluctuations in the water table elevation are common in bogs. Changes in water storage also result from changes in the elevation of the bog. Typically, the water table is at or above the peat surface in winter (when accumulated precipitation is greater than evapotranspiration). The water table will drop below the surface in the summer months. In undisturbed bogs, the lowest average point of water table drop coincides with the acrotelm-catotelm boundary (Holden and Burt, 2003). There are also fluctuations in water table in response to rainfall events and daily fluctuations in the water table due to evaporation at the surface of the bog, with the water level elevation decreasing during the day, and recovering during the evening (Schwartzel et al., 2006).

Water storage in bogs can also change over seasons as the peat surface expands and contracts. Changes in the surface elevation, also known as “mire breathing”, can result in a substantial increase in water storage within the peat through increased elevation and changes in moisture content (Kellner and Halldin, 2002; Veldkamp and Westein, 1993). Veldkamp and Westein (1993) studied the water balance of Raheenmore Bog in Ireland, and found that the bog could swell up to 7 cm in height, resulting in an additional storage of almost 70 mm of water. The surface of Burns Bog has been shown to change by up to 18 cm due to mire breathing (S. Howie, Corporation of Delta, personal communication, 2009).

1.4.2 Net Precipitation (P_n)

Net precipitation is the amount of precipitation that reaches the ground after losses from canopy interception. In this study, the canopy refers only to the tree canopy of the forest stand. Interception due to shrubs is considered separate from the tree canopy.

Interception losses (the component of precipitation that falls on the surfaces of vegetation and is evaporated) can be significantly different in bogs than in nearby forests. The tree density in the forested areas of bogs is very much lower, and the trees are stunted due to (periodic) stress from high water table levels, acidic conditions, and low nutrient availability. Thus it is expected that throughfall losses are lower in bogs than in nearby forests. Despite their lower tree density relative to surrounding forests, tree density and stand volume play a significant role in the hydrology of bogs (Sarkkola et al., 2010). With increased tree density, interception plays a greater role in decreasing the amount of precipititation reaching the surface of the bog, and the total amount of water leaving through transpiration is increased (Sarkkola et al., 2010). Higher tree densities also result in more shading.

1.4.3 Evaporation and Transpiration (*E+T*)

Evapotranspiration moves water from the ground (including the surface of vegetation and open water) to the atmosphere. It is one of the most significant variables in the water balance of a bog, as several studies have shown that it accounts for a large portion of the water leaving the bog. It is affected by many factors, such as humidity, wind speed, air temperature, and net radiation.

Evaporation rates in undisturbed bogs are sometimes controlled by the upward capillary flow driven by *Sphagnum*, but at other times, are controlled mostly by atmospheric demands (Schwartzel**,** 2006). Evaporation from *Sphagnum* is very sensitive to water table depth (Ingram 1982; Schouwenaars and Gosen, 2007)**.** The structure of *Sphagnum* moss requires the water table to be close to the surface, as it does not have roots like vascular plants. Instead, *Sphagnum* depend on matric forces generated by the small pores in the dense network of stems and leaves. These small pores allow water to be passively drawn towards the surface where the moss is growing (Schouwenaars et al, 2007). Due to the lack of vascular roots in *Sphagnum* moss and its inability to actively draw water from great depth, it is sensitive to fluctuations in the water table. This is most notable in the summer months when precipitation may be exceeded by evapotranspiration, resulting in a lowering of the water table that can be beyond the ability of *Sphagnum* moss to draw water upwards (Schouwenaars and Gosen., 2007). The rate of evaporation changes as water stress increases during the dry months (Schouwenaars and Gosen., 2007), prompting colour changes in desiccating moss, resulting in changes in albedo (Nichelson and Brown, 1980). Evaporation rates in areas with *Sphagnum* moss can sometimes be higher than open water evaporation (Campbell and Willamson 1997, Drexler et al., 2004), possibly due to the wicking action of the mosses (Drexler et al., 2004).

Trees, unlike Spaghnum moss, can continue to transpire after the bog water table has been lowered because of their root system. In undisturbed bog areas, trees are shallow rooted, severely stunted and contribute negligibly to the lowering of the water table. This is not the case for the larger trees in forested bog areas. However, in comparison to surrounding forests, trees in the forested bog areas still transpire less due to water stress, lack of nutrients, and the low pH in the bog environment.

1.4.4 Deep Drainage (*D*)

Deep drainage is the vertical movement of water through the base of the bog. The hydraulic head difference between peat and the underlying materials controls the direction of water movement. The movement of water through the underlying materials is typically very slow due to the low hydraulic conductivity of both the basal peat and underlying material. Deep drainage in Burns Bog for example, has been estimated to be 0.1 mm per day or 3,000 m^3 per day, across the entire area of the bog (Helbert and Balfour, 2000).

1.4.5 Discharge (*Q*)

The hydraulic conductivity of peat plays a significant role in water storage and the amount carried away as discharge (Rycroft et al., 1975). Runoff generation in peatlands occurs predominantly in the top 10 cm of the peat, where overland flow develops as saturation overland flow (Holden and Burt, 2003) rather than infiltration-excess overland flow (Holden et al., 2004). Matrix throughflow is usually not a significant contributor to discharge due to the low hydraulic conductivity of the peat. The acrotelm-catotelm model posits that the majority of lateral flow occurs within the acrotelm (Holden and Burt, 2003) where the hydraulic conductivity is highest.

The hydraulic conductivity decreases with increasing humification (Rycroft et al., 1975) and depth, leading to an exponential increase in runoff as the water table rises to the surface (Ingram, 1983; Helbert and Balfour, 2000). This was also experimentally found through laboratory tests on peat blocks, which showed that the majority of runoff occurred near the surface, and runoff decreased with depth (Holden and Burt, 2002) due to the exponential decrease in hydraulic conductivity with depth (Holden and Burt, 2003).

1.5 Research Objective and Research Questions

The health of an ombrotrophic bog is dependent on a positive water balance. Specifically, in bogs near the southern climatic limit on the west coast of North America, such as Burns Bog (Hebda et al., 2000), it is the amount of water that the bog receives in the moisture deficit season and the length of this season that is most important (Damman, 1979). Climate change in the form of decreasing precipitation and higher summer temperatures, leading to higher evapotranspiration rates, has led to an increased presence of vascular plants such as shrubs and black spruce in peatlands in south central Alaska (Acreman et al., 2009; Berg et al. 2009). Due to human activity in Burns Bog (drainage and peat harvesting), relatively large trees have established themselves along the perimeter of the bog. The impacts that these trees have on the water balance of the bog are unclear. It is thus currently also unclear if logging these trees would have a significant positive effect on the health of the bog.

The objective of this project was to compare the water balance of a forested site and an open bog site in Burns Bog and to develop a better understanding of the effects of forest encroachment on the water balance of raised bogs. This study will contribute to a better understanding of the current state of Burns Bog and contribute to the understanding of raised bog hydrology in general.

The specific questions that this research addresses are:

1. What is the water balance for a forested bog site and how different is this from the water balance of an open bog site in Burns Bog?

2. How much precipitation is lost to interception in the forested area of Burns Bog?

3. How much more evapotranspiration is there from the forested site compared to the open bog site?

4. Does the forest affect soil moisture changes in the acrotelm during the summer season?

5. What is the spatial distribution in rainfall across Burns Bog?

1.6 Study Site

This research took place in Burns Bog, located about 20 km southeast of Vancouver, British Columbia, Canada. The 3000ha bog lies in the flat lowlands of the southern Fraser River delta (Figure 1). The sedimentary basin in which the Fraser River deposited its load is bounded by the Coast Mountains to the north and the Cascade Mountains to the east. Large portions of the eastern Fraser River delta were areas of bog growth prior to human settlement (Figure 1).

1.6.1 Geologic History and Development of Burns Bog

About 10,000 years ago, the Cordilleran ice sheet had retreated from the eastern portions of the Fraser Valley, leaving large basins that would be filled with fluvial and lacustrine sediments (Hebda et al., 2000). Melt waters from the snout of the retreating glaciers carried large amounts of sediments to the Fraser River floodplain (Clague, 1983) and to a proto-delta near New Westminster, which rapidly prograded westwards.

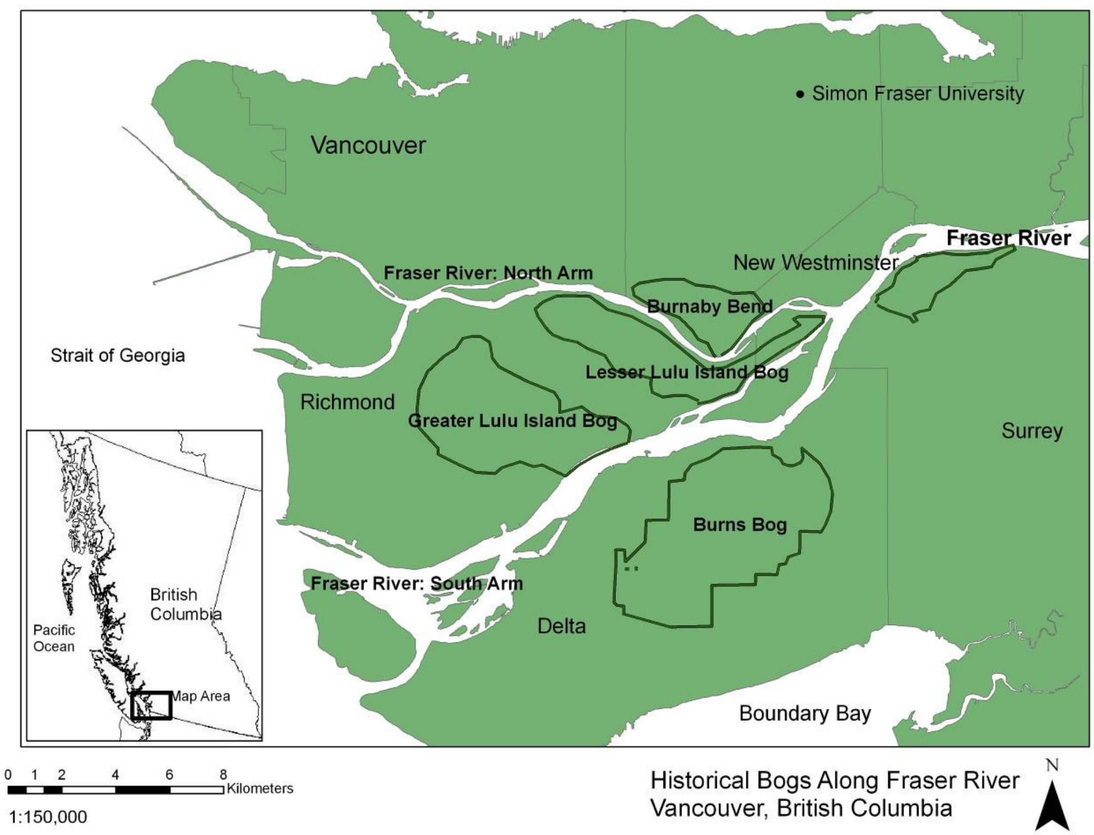

Figure 1: Map of the study site (Burns Bog) and the location of other (historic) bogs in the Fraser delta.

A subsequent rise in relative sea level caused the flood plain and delta surface to aggrade. The rise in sea level continued until approximately 5,000 years ago. When it stabilized near present datum, the delta front prograded south-westward past the Burns Bog and Boundary Bay areas into the Strait of Georgia, joining Point Roberts to the mainland. Since this time, the Fraser River has not emptied into the eastern Boundary Bay area (Clague, 1983), and the area changed from a sand deposition environment to silt and finally an organic sediment deposition area.

About 5,000 years ago, the intertidal zone at Burns Bog was colonized by aquatic vegetation (Hebda, 1977). The area developed into a sedge swamp area that was prone to flooding. With poor drainage and sufficient precipitation, the conditions allowed for the development of wetlands. As the elevation of the area increased due to the accumulation of sedge peat, and its distance from the delta mouth increased, the area developed into a shrub and heathland area. Shrub vegetation took over the sedge and grass species. Once this occurred, woody peat accumulation began, allowing for the appearance of *Sphagnum*. When *Sphagnum* was established, other species were deprived of nutrients due to the moss's high cation exchange capacity, leading to the development of *Sphagnum* peat and the present day bog (Hebda et al., 2000).

1.6.2 Local Geology

A 300 to 800 m thick layer of unconsolidated sands, silts, and clays underlies Burns Bog (Clague et al. 1983). This layer can be separated into two units; a lower unit comprised of well-sorted sand (Monahan et al. 1993) and an upper unit comprised of silt and clayey silt (Hebda et. al., 2000). The peat lies above these two units. It has been estimated that the peat was 4 to 5 m thick at the centre of the bog prior to peat mining, but is currently 2 to 3 m thick on average with the western areas being thicker (Hebda, 2000). The peat at the study sites is approximately 5 m thick.

1.6.3 Site Climate

Mean annual precipitation varies between 1000 and 1200 mm across Burns Bog. The average annual temperature is 9.6^{o}C. The average summer temperature is approximately 16.8^{o}C. The average winter temperature is approximately 2.5^{o}C (Hebda et al., 2000), similar to that measured at Vancouver Airport (Table 1)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Daily Average Temp (^{o}C)	3.3	4.8	6.6	9.2	12.5	15.2	17.5	17.6	14.6	10.1	6	3.5
Precipitation (mm)	153.6	123.1	114.3	84	67.9	54.8	39.6	39.1	53.5	112.6	181	175.7
Days with Precipitation:												
> 0.2 mm	18.5	16.3	17	13.9	13	11.2	6.9	6.8	8.6	14.3	19.7	19.8
> 5 mm	10.1	8.3	7.6	6	4.7	3.3	2.5	2.6	3.7	7	10.8	10.7

Table 1: Climate data for the Vancouver area measured at the Vancouver International Airport. (49^{o} 11’ 42’’ N, 123^{o} 10’ 55’’ W) (Environment Canada, 2010)

1.6.4 Study Sites

Two sites were selected within the south-western corner of Burns Bog (Figure 2). The study plots are located approximately 500 m north of the Vancouver Landfill at 49°6'25.99"N, 123°1'20.23"W (Figure 2). The forested site was selected in an area that is representative of the forested areas along the outer perimeter of the bog. Predominantly lodgepole pine and the occasional western hemlock and birch trees grow in these forested areas. Dense shrub growth, principally salal and bog bilberry, also occurs in these areas (Figure 3). *Sphagnum* moss is difficult to find, as conditions do not favour moss proliferation.

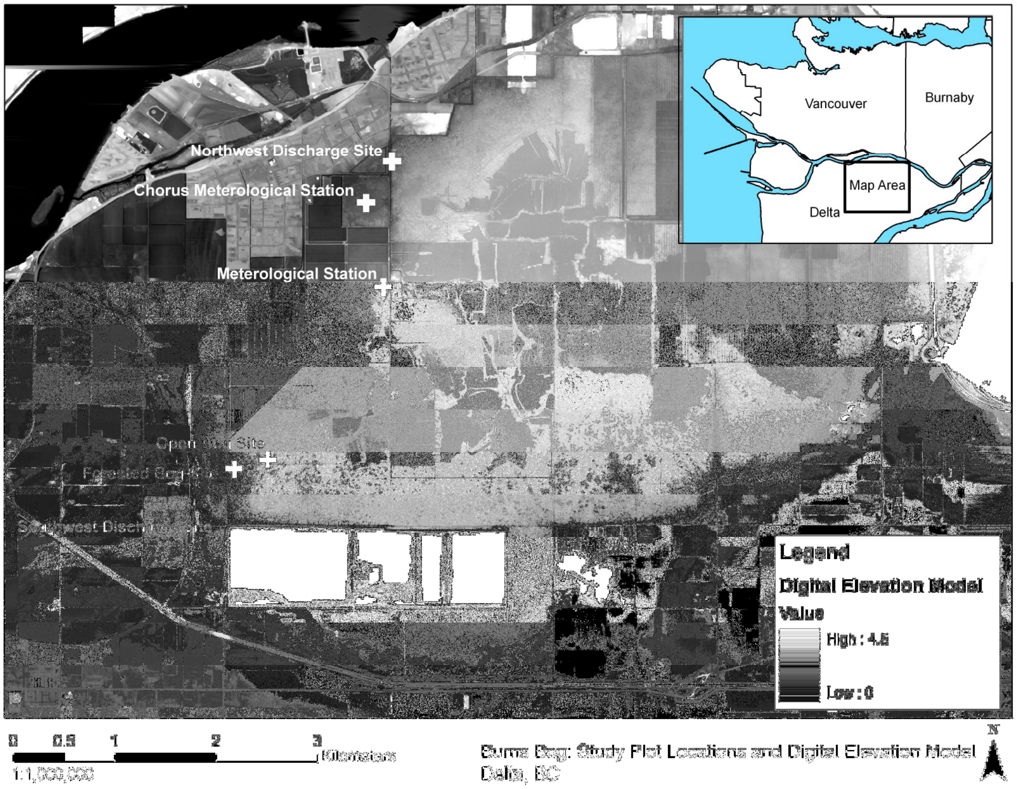

Figure 2: Location of the open bog plot, forested bog plot, and the meteorological stations. The shading represents the surface elevation (m) of the bog and the surrounding areas. Areas of peat mining in the north-east of the bog and the landfill in the south-western portion of the bog are clear. The DEM data was obtained from a August lidar survey. Data courtesy of the Corporation of Delta.

Figure 3: Forested bog site characterized by dense shrub growth and relatively large trees

An open bog site, representative of the undisturbed interior areas of Burns Bog, was selected approximately 200 m east of the forested site. This open bog site has an abundance of *Sphagnum* and lichens. Trees are severely stunted and are generally less than 1.5 m tall and are sparsely distributed (Figure 4). The shrubs that are common in the forested site are not found in this area.

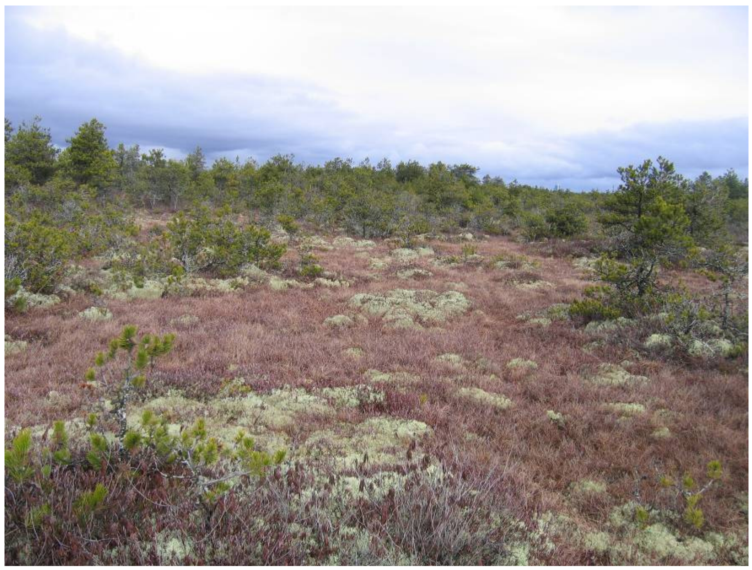

Figure 4: Open bog site featuring hummocks of *Sphagnum* moss and stunted trees approximately 1 to 1.5 m in height

2.0 METHODOLOGY

All variables in the water balance equation (Equation 1) were measured or estimated at both the forested and open bog sites. The methodology of this project was passive in nature because of the protected status of Burns Bog. Due to the sensitive nature of the vegetation in the bog, movement in the plots was restricted to the trails in order to minimize the damage to the vegetation. In the open bog site, a trail had to be created to access all measurement points. In the forested site, existing animal trails were used. As such, all instrumentation was placed within reaching distance from the trails.

Daily precipitation data was obtained from the Environment Canada Burns Bog meteorological station (WMO ID 71892) (Figure 2). Hourly measurements of relative humidity, temperature, and radiation data were obtained from the meteorological station at the Chorus Transmission Site, approximately 3 km from the study sites, operated by Levelton Associates (Figure 2).

2.1 Field Measurements of the Water Balance Components

2.1.1 Changes in Storage: Water Table

A piezometer nest was installed in both study plots to measure the water table depth and its response to rainfall events and prolonged dry periods. The nests consisted five piezometers made of 3.25 cm diameter PVC piping that was anchored in the unconsolidated silts below the peat using rebar. The PVC pipe was slotted and covered with a nylon mesh along the bottom 10 cm of the pipe. Capacitance water level data loggers (Odyssey, Christchurch, New Zealand) were housed within each PVC pipe. The loggers recorded the water level at 15-minute intervals. Each piezometer was categorized nominally as 0.5, 1.0, 1.5, 3.0, and 5.0 m, but after installation, their true depth from the surface varied as the surface elevation of the bog changed (Table 2).

	Actual Depth Below Surface (m) on June 26, 2009	
Piezometer Name	**Forested Bog Site**	**Open Bog Site**
0.5 m	0.52	0.61
1.0 m	0.93	1.08
1.5 m	1.43	1.55
3.0 m	2.85	3.04
5.0 m	4.58	4.91

Table 2: Nominal Piezometer name/depth and the actual depth of the piezometer on June 26, 2009.

2.1.2 Changes in Storage: Surface Elevation

The relative changes in surface elevation of the Bog were determined by measuring the distance between the top of the 5 m piezometer and the surface of the bog. These measurements were made approximately once per week during the summer months (May through September) of 2009 and then monthly during the non-summer period (October through April) of 2009 and 2010.

2.1.3 Changes in Storage: Soil Moisture

Surface soil moisture measurements were made with a 30 cm time domain reflectometry soil moisture sensor (ESI Environmental Sensors, Sidney, BC, Canada). Soil moisture measurements were taken twice per week throughout the summer months and weekly in the fall and winter of 2009.

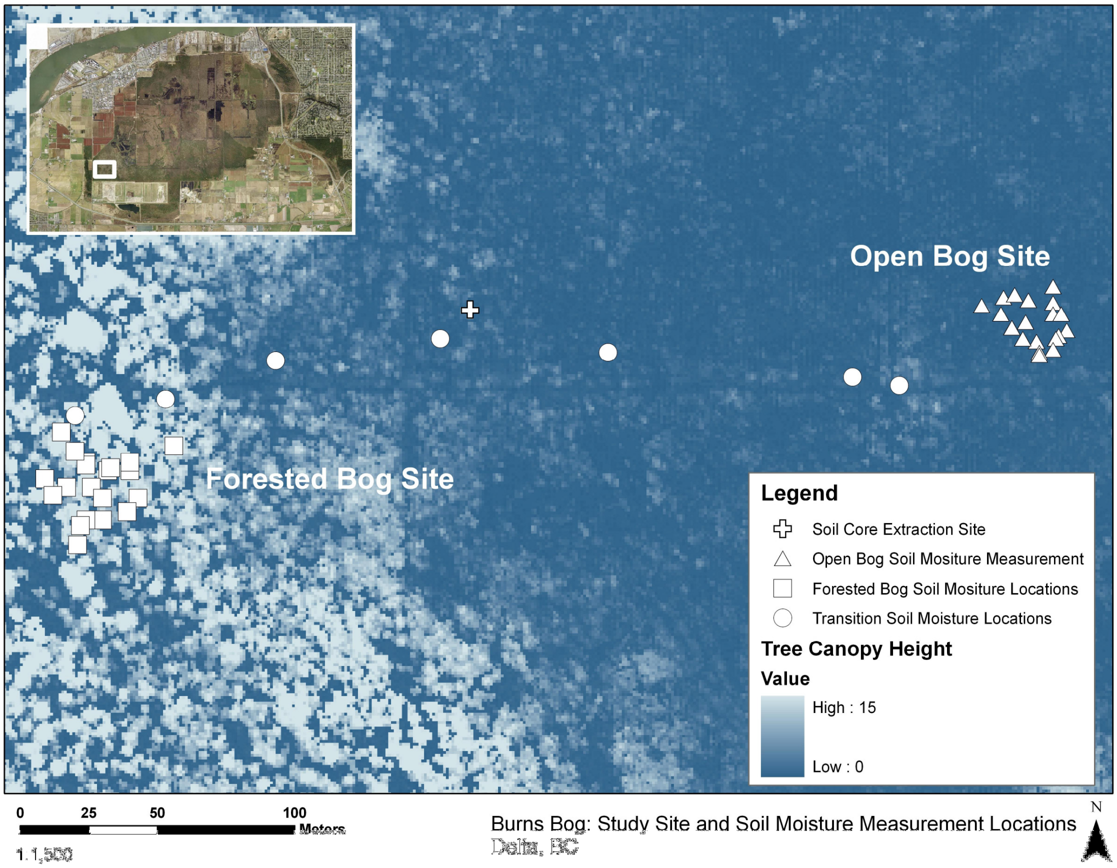

Figure 5: Location of the soil moisture measurement points in both the open bog and forested bog plots. Seven soil moisture measurements points were located along a trail connecting the two sites. The coloured background represents the tree canopy height (m), obtained from lidar data. Data courtesy of the Corporation of Delta.

Twenty soil moisture measurement locations were randomly selected in both the forested and open bog plots (Figure 5). The soil moisture points were classified into hummocks and hollows, to determine if there was a significant difference in soil moisture between them. Seven additional soil moisture points were located along a transect between the open and forested bog sites to measure the changes in soil moisture across the landscape transition from a forested bog to open bog.

A 650 cm^3 peat core was taken near the forested bog site (Figure 5) using a cylindrical peat sampler constructed of sheet metal (0.15 m diameter and 0.5 m high). The core from the bog was 0.36 cm in height. It was transported to the laboratory at

Simon Fraser University for calibration of the soil moisture probe on March 13, 2010. The core was weighed and the soil moisture was measured every two days until no measurable changes in weight occurred within 2 days. The core was then oven dried at 60^{o}C for 2 days and weighed to determine the mass of the dry peat.

2.1.4 Precipitation

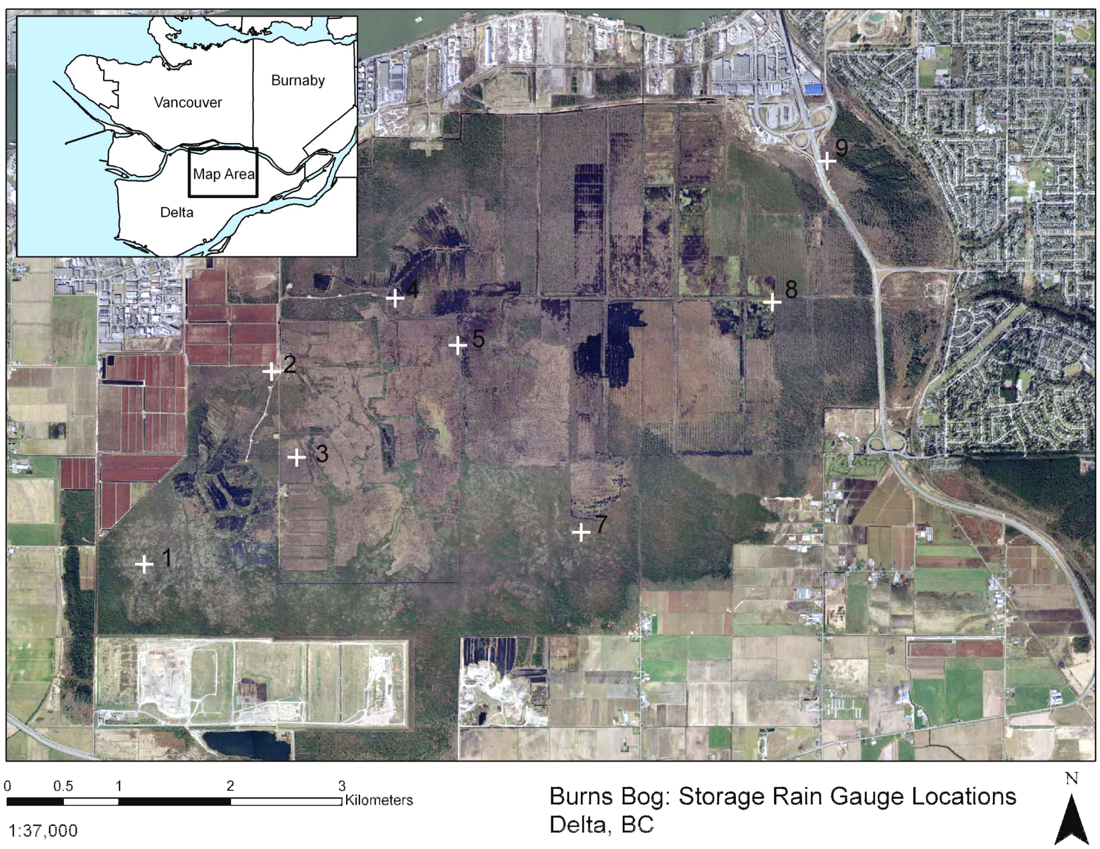

Figure 6: Location of the storage rain gauges across Burns Bog

Previous research using precipitation data from climate stations in Delta, Richmond, Surrey and New Westminster suggested that there is an increase in average precipitation from the south-western to the north-eastern border of Burns Bog (Helbert and Balfour, 2000). In order to determine the spatial variability in precipitation across

Burns Bog at a much higher spatial resolution than Helbert and Balfour (2000), precipitation was measured across the Bog using 9 non-recording storage rain gauges (Figure 6). The rain gauges consisted of a 20 cm diameter funnel and a 10 L bottle, and were measured and emptied approximately every two months between April 2009 and April 2010. The 10 L bottles were replaced with 17 L buckets with lids in December 2009. After each measurement, the funnel was levelled using a bubble-level.

2.1.5 Throughfall

In the forested plot, 7 throughfall gauges consisting of two 60 cm long and 8 cm diameter troughs leading to a 17 L bucket were used to quantify the amount of precipitation reaching the bog surface. One throughfall gauge was located in the open plot as it was assumed that due to lack of canopy cover, the spatial variation in throughfall at the open bog site would be small. Data were collected between April 23, 2009 and April 26, 2010 at 2 to 4-day intervals duringthe summer (dependent on storms) and 1 to 2-week intervals duringthe fall and winter months.

Shrubs provide a dense cover of vegetation relative to the forestcanopy. In some areas, shrub vegetation is dense enough to make movement through the area difficult. Fifteen wedge-type rain gauges were installed in the forested site on October 1, 2009, with an additional 8 gauges installed below the shrub vegetation on January 23, 2010 (Figure 7). Shrub throughfall measurements were made every 1 to 2 weeks, from October 1, 2009 to April 26, 2010. One standard wedge rain gauge was installed in the open bog site near the trough gauge for comparison between the two throughfall measurements.

The interception loss was calculated as the difference between average throughfall measured in the forested plot and the open plot.

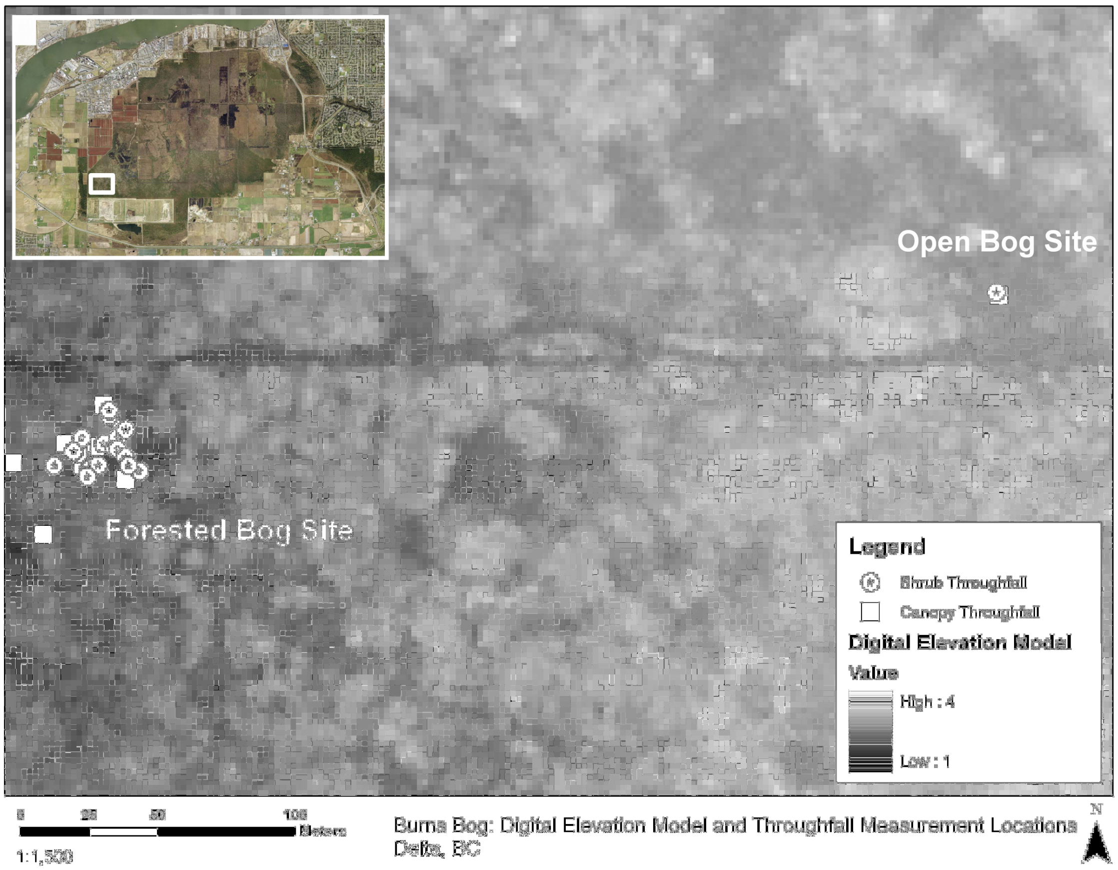

Figure 7: Location of throughfall rain gauges (canopy throughfall) and standard wedge rain gauges (shrub throughfall), with the lidar derived DEM data (m) in the background. DEM data courtesy of the Corporation of Delta.

2.1.6 Evaporation

Evaporation rates were determined using six lysimeters; three in the forested site and three in the open site. At each site, two lysimeters were installed in a hollow, and one in a hummock (Figure 8).

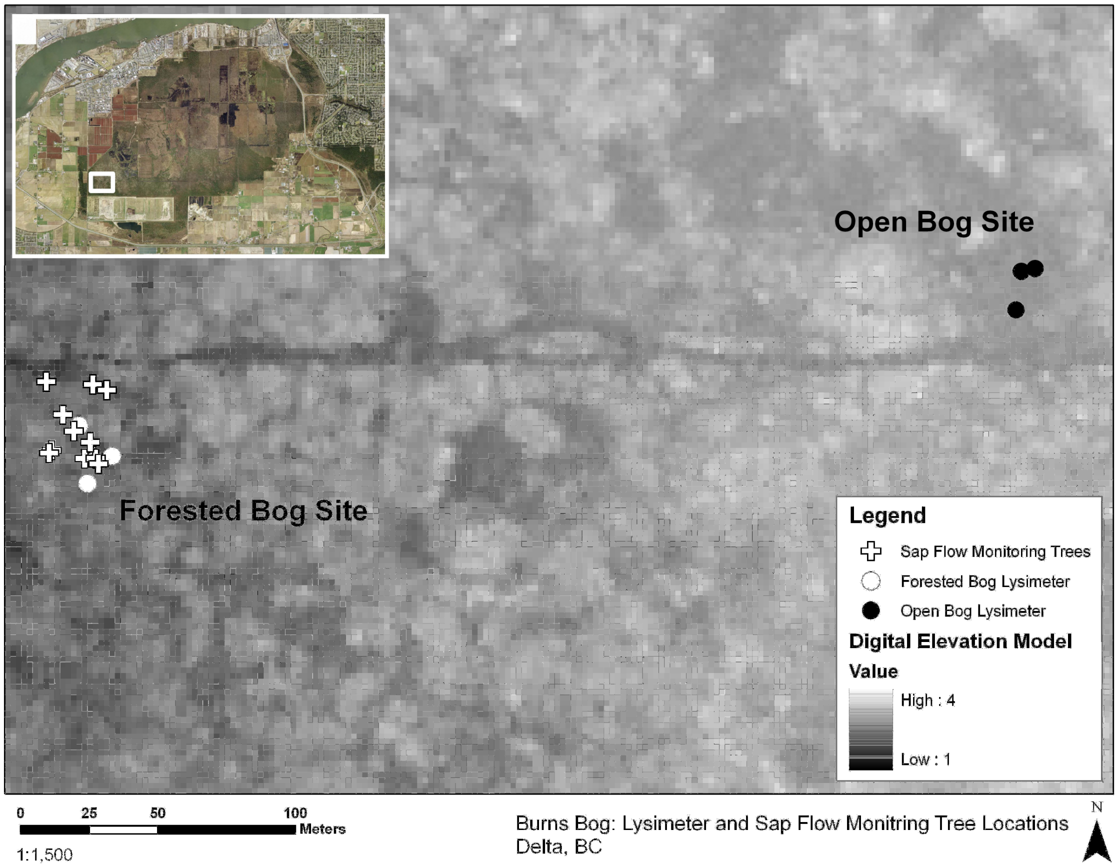

Figure 8: Location of evaporation lysimeters and trees with sap flow sensors, with the lidar derived DEM data (m) in the background. DEM data courtesy of the Corporation of Delta.

Each lysimeter consisted of two 17 L buckets. A peat monolith was collected close to the study site, using the technique described by Strack and Price (2009). The monolith was encased by a bottomless bucket, which sat within a second bucket lined with gravel and a metal mesh (Figure 9). A flexible tube connected to the bottom of the gravel-lined bucket allowed water to be drained after large rainfall events. A clamp installed on the tube prevented water from draining out of the bottom of the lysimeter in between measurements. The apparatus was placed into holes dug at the sites, so that the top of the peat in the lysimeter was flush with the surrounding surface (Figure 10).

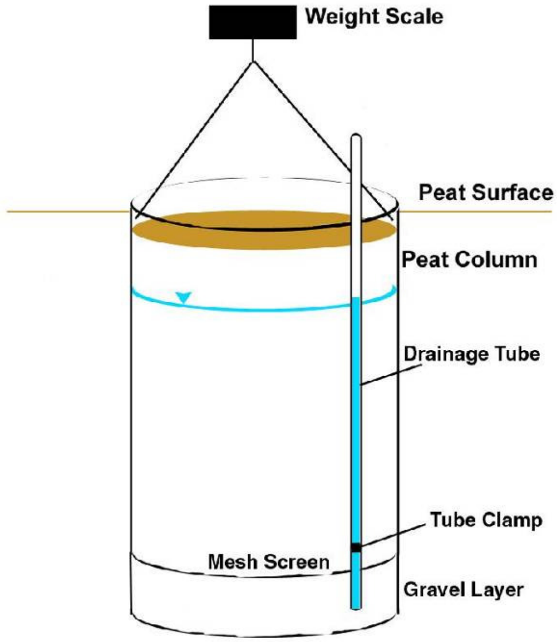

Figure 9: Overview of the lysimeter

Figure 10: An open bog lysimeter in the ground

Figure 11: An open bog lysimeter taken out of the ground for weighing

The lysimeters were weighed weekly by hanging them on a hanging scale (Electro-Sampson Digital Hanging Scale, 0.02 kg precision). The difference in weight between measurements was attributed to the amount of water lost to evaporation and the amount gained due to precipitation (measured with the rain gauges). This assumes that differences in weight due to peat oxidation and *Sphagnum* growth were negligible. Differences in the water loss between lysimeters installed on hummocks and hollows were examined to determine the impacts of microtopography on evaporation.

A comparison between the measured evaporation from the lysimeters and the potential evapotranspiration measured by the evaporation pan located at the meteorological station could not be done because the resolution of the data from the evaporation pan was too low (1 mm). Instead, a comparison was made with the estimated potential evapotranspiration calculated by the Kucerova et al. (2010) method:

$$PET = \frac{0.013\left(\frac{R_g}{0.041868}+50\right)T_a}{T_a+15}$$

Equation 2: Calculation of the daily potential evaporation (mm/day) following Kucerova et al. (2010)

where R_g is the daily sum of radiation (MJ/m^2/day), and T_a is the mean daily air temperature (^{o}C). This method was developed by Kucerova et al. (2010) after the method of Turc (1961) and was shown to represent potential evapotranspiration in a wooded peat bog in the Czech Republic well.

2.1.7 Transpiration

Transpiration in the forested site was measured with constant heat sapflow sensors (Granier, 1987) during the summer of 2009. This method was chosen because it is relatively inexpensive, simple to use, and was successful in other transpiration studies (e.g. Clearwater et al., 1999). Six sapflow sensors (4 in pine and 2 in hemlock trees) were installed on May 25, 2009, and another 6 (all in pine trees) were installed on June 22, 2009 (Figure 8). The sensors, 15 mm long for the pine trees, and 20 mm long for the hemlock trees, consisted of 2 thermocouples installed into the sapwood approximately 10 cm apart. Since trees in open bog areas are sparse and stunted, transpiration in the open bog plot was assumed to be negligible.

Given the small size of the pine trees in the bog, a shortened probe length was used because Clearwater et al. (1999) reported underestimations of the flux when the probe was too long and came in contact with inactive xylem. The upper probe was heated to create a temperature difference between the two probes, which was measured as a voltage difference. A control box consisting of a solar panel, voltage regulator, and batteries linked the probes to the power supply, . The data logger (CR10X, Campbell Scientific, Edmonton, Canada) measured the voltage difference between the two probes every 30 seconds and recorded the average temperature difference every 15 minutes. The temperature difference between the probes allowed for the calculation of K, a dimensionless variable (Granier, 1987):

$$K = \frac{\left(\Delta T_{\max} - \Delta T\right)}{\Delta T}$$

Equation 3: Granier's dimensionless K equation

where $\Delta T_{\max}$ is the maximum difference in temperature (measured at predawn when transpiration is assumed to be zero), and ΔT is the difference in temperature at any other time during the day. The velocity, v (m/s), of the water through the sapwood was calculated from this parameter as described by Granier (1987):

$$v = 0.119K^{1.231}$$

Equation 4: Sap flow velocity equation from Granier (1987)

This velocity was multiplied by the sapwood area of the tree to determine the transpiration rate for the instrumented trees. To determine the total volume of water leaving the study site through transpiration, the average transpiration rate per unit sapwood area was multiplied by the total sapwood area of the forested site.

The number of trees and diameter at breast height (DBH) of each species of tree in a 40x40 m sampling area were measured in order to determine the total sapwood area of the site. Thirty-seven trees, 12 of which were trees with sapflow sensors, were cored to determine the relation between sapwood depth and DBH. Twenty-four of the cores were treated with 40% perchloric acid to determine the sapwood depth as described in Kutcha and Sachs (1962). The sapwood depth was used to calculate the sapwood area for each cored tree by subtracting the heartwood area (based on the diameter of the tree minus the sapwood depth) from the total basal area of each tree. The relation between sapwood area and DBH was used to estimate the total sapwood area of the forested site. It was necessary to sample 6 trees outside of the 40x40 m plot to create a more accurate relation between DBH and sapwood depth for the hemlock trees due to the low number of hemlock trees in the plot.

2.1.8 Deep Drainage

The water flux into the silt underneath the bog was calculated using the Darcy equation (Equation 5):

$$q = K\frac{dh}{dz}$$

Equation 5: Darcy equation used to estimate deep drainage

where q is the estimated vertical flux (m/s), K is the hydraulic conductivity (m/s), $\frac{dh}{dz}$ is the hydraulic gradient (m/m), as the ratio of the difference in water level in the 3.0 and 5.0 m piezometers (*dh*), and distance between the 2 piezometers (*z*).

In order to determine the hydraulic conductivity of the peat, bail tests were conducted in the piezometers in both plots on January 23, 2010 and February 20, 2010. Water was removed from each piezometer using a peristaltic pump and the resulting changes in water level were recorded by the capacitance water level recorders. The hydraulic conductivity of the peat at the depth of the piezometer was calculated by using the Hvorslev (1951) equation (Equation 6)

$$K = \frac{r^2 \ln(L/R)}{2LT_0}$$

Equation 6: Equation used to calculate the hydraulic conductivity from the bail test

where K is the hydraulic conductivity (m/s), r is the radius of the casing (m), L is the length of the screen (m), R is the radius of the piezometer (m), and T_o is the time required for the water level in the piezometer to recover to 37% of the original water level (s).

2.1.9 Discharge

Discharge was measured in two ditches: one draining the north-western portion of the Bog, and one draining the south-western portion (Figure 2). Capacitance water level recorders (Odessey, Christchurch, New Zealand) were used to measure the water level in the ditches every 15 minutes. Although the weir was a 90 degree V-notch weir, standard equations used to estimate discharge could not be used because the water level below the weir was not muchlower than above the weir, which may have affected the flow of water out of the weir. Discharge was measured with a current velocity meter (Swoffer Instruments, Inc., Seattle, USA) above the 90 degree v-notch weir on several days in the fall of 2009 and winter of 2010. A stage-discharge relation was created and used to calculate the discharge through both the north-western and south-western draining ditches. The discharge measurements do not give the total discharge from the bog because there are many ditches draining the bog, but it does provide useful information on how runoff responded to rainfall events in both timing and relative magnitude. Results and discussion

Field measurements started in March 2009. A break in all measurements, except groundwater level and sapflow measurements, occurred from July 22 to September 12, 2009 due to the closure of Burns Bog because of extreme fire hazard conditions. Measurements resumed as planned when the bog was reopened and continued until April 26, 2010.

2.2 Changes in Storage: Water Table Responses

The piezometers installed in the open and forested bog sites provided continuous measurements of water table fluctuations during the May 2009 to September 2010 period (Figure 12). The minimum and maximum depth to water table were 0.36 m and 0.73 m for the forested site and 0.13 m and 0.32 m for the open site respectively. Throughout the observation period, water levels were always significantly deeper in the forested bog site than in the open bog site. Kellner and Halldin (2002) studied Stormossen bog, a smal (2 km^2) bog in central Sweden that has similar characteristics as Burns Bog (i.e. human interactions through ditching in outlying areas, and the occurrence of undisturbed open areas in the interior of the bog) and reported similar differences in for the depth to water table in forested and open bog areas.

The 0.5 m-piezometer in the forested bog site dried out by mid June, indicating the water table fell more than 0.4 m below the surface of the bog (the 0.5 m piezometer protruded 0.12 m above the surface of the bog in summer). The lowering of the water table in Burns Bog in the summer of 2009 was greater than the groundwater level changes of up to 0.3 m in the Stormossen Bog (Keller and Halldin, 2002). Although the Stormossen Bog is disturbed along its perimeter, this disturbance is much lower than the disturbance found in Burns Bog. However, findings by Price et al. (2003), suggested that disturbed bogs can show water table fluctuations up to 67% greater than undisturbed bogs agree with measurements made in Burns Bog. Kellner and Halldin (2002) reported that drainage ditches affected the water storage of the bog within 80 m of the ditch during dry periods, but water table fluctuations were relatively uniform in the open bog area. The results from this study do not show a significant influence from the nearby ditch (80 m away), however this may be due to several plywood ditch-blockages installed along the length of the ditch draining towards the landfill. Ditch blocking, part of the ongoing restoration efforts in Burns Bog, resulted in water table increases over a two-year period beginning in 2001 (Howie et al., 2009).

Interception and transpiration by trees have been shown to have an effect on the water level (Sarkkola et al., 2010) and would contribute to the increased depth to the water table in the forested site compared to the open bog site. Further, Sarkkola et al. (2010) found that tree stand density played a more significant role in determining the depth to water table from the surface of a ditched forested bog in dry summers compared to wet summers, with the water table remaining 30 to 40 cm below the surface during wet summers, and presumably deeper during dry summers. Results from this study show that the water level in Burns Bog dropped significantly lower than in the peatlands studied by Sarkkola et al. (2010).

Alternatively, the difference in the water level in the open site and the forested site could be due to the difference in the location of the two sites. Previous studies have shown that the water level is closest to the surface in the centre of a bog and deepest at the edge of a bog (Ingram, 1987). Because the open site was located further from the edge of the bog, it is expected to have a water table that is closer to the surface.

The 0.5 m piezometer in the forested bog site remained dry until a series of rain events in early October 2009 (Figure 12). Water table elevations in Burns Bog recovered to pre-summer levels in mid-October. By November 2009, the open bog site was flooded, with water ponding on the surface of the Bog. Flooding remained until April 2010. Kellner and Halldin (2002), Howie et al. (2009), and Liator et al. (2007) measured similar cyclic changes in ground water level, observing increasing water table depth throughout the summer months and a recovery in September and October.

The water levels gradually decreased during the summer months, with interruptions due to storm events that resulted in small, but rapid rises in water levels in the 1.0 m piezometer in the forested bog site, and the 0.5 m and 1.0 m piezometer in the open bog site. The water level began to drop immediately after the end of the storm, and returned to pre-storm elevations within 4 days. The quick responses measured in Burns Bog are similar to the responses reported by Liator et al. (2007). In the Israeli peatland, the quick response was due to the effectiveness of macropores, which could explain the same response observed in Burns Bog, as during the summer months, desiccation cracks were observed at the peat surface, and roots were found during the peat core extraction process.

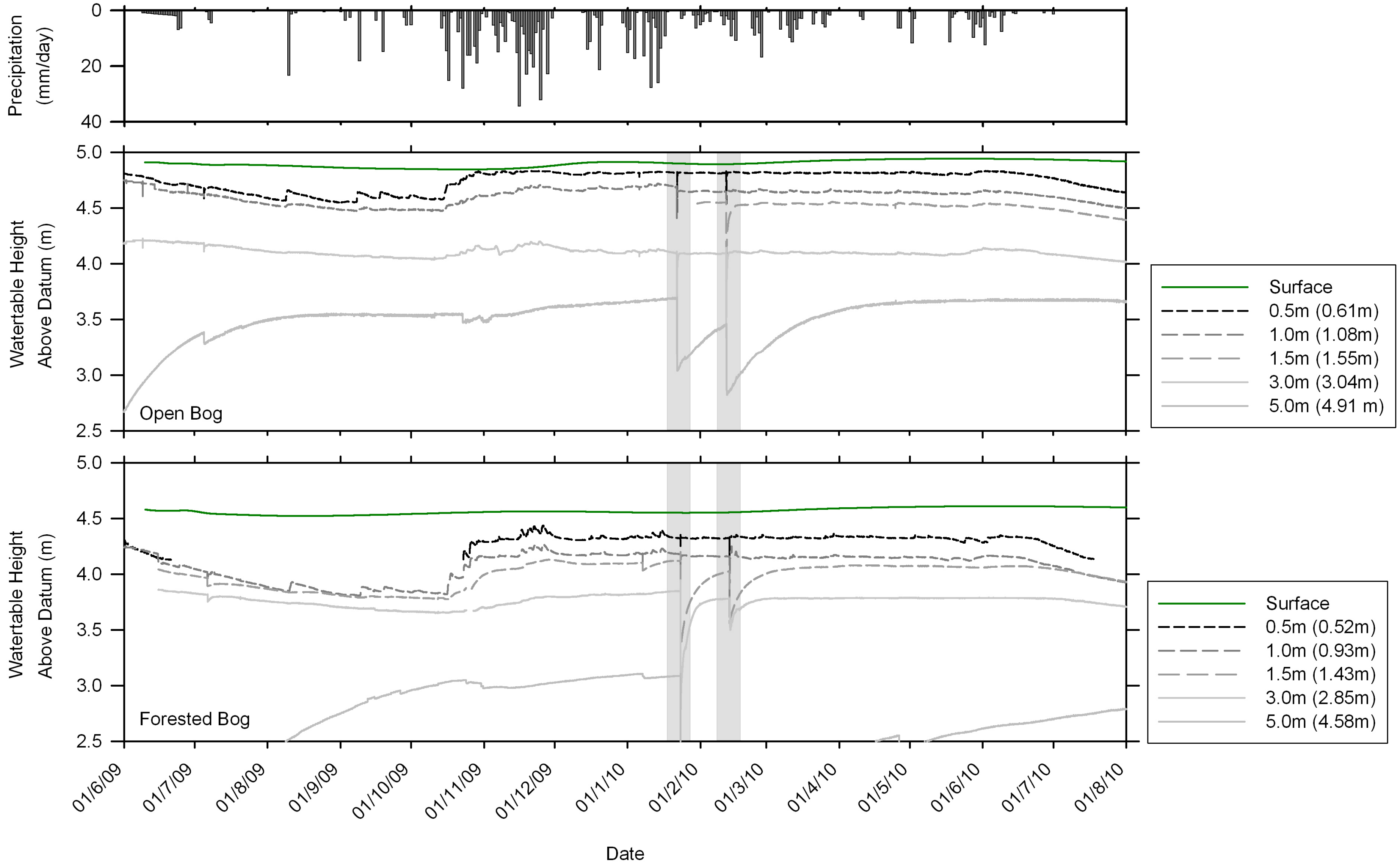

Figure 12: Hydraulic head measured in the forested and open bog sites from June 2009 to August 2010. Shaded areas show times of piezometer pumping. Note that the piezometeres installed in the silt (5.0 m in the open and forested bog) have very long recovery times. The value in parentheses in the legend shows the depth of the piezometer from the surface on June 26, 2009 (see also Table 6).

2.3 Changes in Storage: Surface Elevation Changes

The elevation of the surface fluctuated by 7 cm in the open site and 5 cm in the forested site throughout 2009 and 2010, confirming the presence of mire breathing in Burns Bog as suggested by Howie et al. (2090). The surface elevation had a similar pattern to the water table, with the elevation of the surface gradually decreasing throughout the summer (Figure 12). The lowest surface elevation in Burns Bog coincided with the lowest soil moisture and lowest water table in the summer and was recorded at the end of the growing season in late September 2009. The maximum elevation was measured in March 2010 at both the forested and open sites. Surface elevation responded quickly to precipitation in November and December 2009, with the increase in elevation becoming more gradual into the winter months (Figure 12). However, the relation between the surface elevation and water level was also characterized by hysteresis (Figure 13). The water level decreased throughout the summer, but the surface elevation did not respond as quickly as the water level to increased precipitation in the fall.

The observed changes in surface elevation were similar to the values reported by Howie et al. (2009) for Burns Bog in 2007. Fluctuations in elevation of 5 to 7 cm are also consistent with values reported by Mawby (1995) for raised bogs in northern England that have also been altered by human activity. Also, the decrease in volume of 11% in the core removed from Burns Bog agrees with values reported by Price et al. (2003).

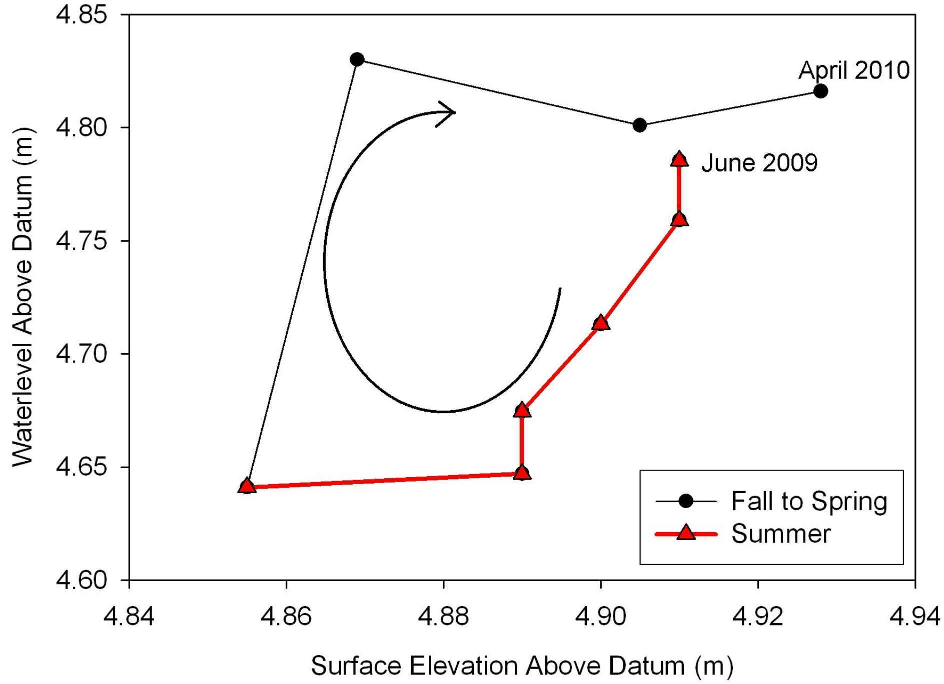

Figure 13: Hysteretic relationship between the surface elevation and the water level elevation in the open bog. The water level decreased quicker than the surface elevation in the summer, and increased quicker than the surface elevation in the fall. The data shown spans the June 2009 to April 2010 period.

2.4 Changes in Storage: Soil Moisture

The soil core was used to calibrate the soil moisture sensor. This calibration (Figure 14) was applied to all soil moisture measurements. Saturated moisture contents in the peat core agreed with values for other *Sphagnum* bogs (89% to 92 %; Price et al., 2008).

Soil moisture was lower in the forested bog site than in the open bog site at all times, with hummocks having a lower soil moisture contents than the hollows in both sites (Figure 15).

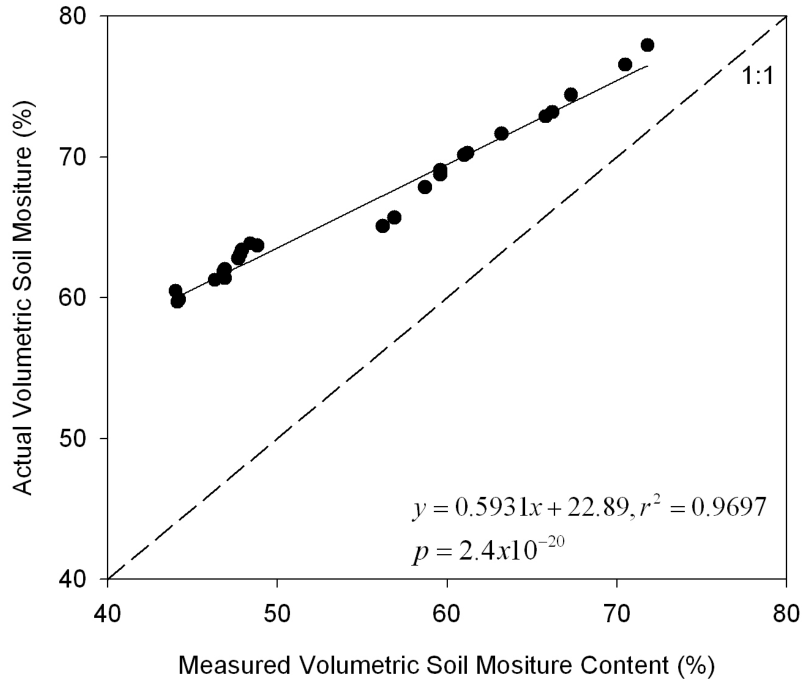

Figure 14: Calibration results for the soil moisture probe. Measurements were taken in the peat core

Soil moisture decreased throughout the summer months with the lowest average soil moisture measured in mid-July prior to the closure of the bog due to the extreme fire hazard. Soil moisture did not significantly increase from this seasonal low until mid-October. By November, the open bog site was inundated, with only the hummocks protruding above the water. In the forested bog site, soil moisture also increased to a relatively constant maximum in November (Figure 15). No part of the forested bog site was submerged.

Soil moisture was highly variable across both sites, with variability being higher in the forested hollows relative to the open bog hollows. However, the hummocks in the open bog showed greater variability than the hummocks in the forested bog site. During the fall and winter months, the variability in soil moisture in the open bog site was lower than in the summer months, as the majority of the hollow soil moisture points were under water (Figure 15). The opposite was found in the forested bog site, with the hummocks displaying low variability in soil moisture during the summer season as they dried out and remained in a dry state until the fall, when wetting of the hummocks occurred.

2.5 Distribution of Precipitation Across Burns Bog

The distributed rain gauges showed a gradient of increasing precipitation from the south-west to the north-east of the bog (Figure 17), confirming the results of an earlier study based on data from meteorological stations at Vancouver International Airport, Boundary Bay and Surrey (Hebda et al. 2000). Total precipitation between March 31, 2009 and March 24, 2010 was 1278 mm, which was greater than the mean annual precipitation measured by Helbert and Balfour (2000) of 1100 mm and the long-term average of 1200 mm measured at Vancouver International Airport in Richmond.

Annual precipitation was measured at only three locations across the bog because the other gauges experienced failure from high winds that detached the funnel from the storage container and others were lost due to theft of equipment. From March 2009 to March of 2010, the northeast corner of the Bog received 1514 mm of precipitation, approximately 357 mm more than the southwest corner (Table 3). This gradient was generally observed throughout the year (Figure 17), with the northeast corner receiving on average 20% more precipitation during each measurement period (Table 3, Figure 17, and Appendix I). Contour lines were drawn by hand when a gradient was readily evident. Kriging in ArcGIS was used to determine the contour lines during the periods of May 14 to June 23, 2009 and December 12, 2009 to January 31, 2010.

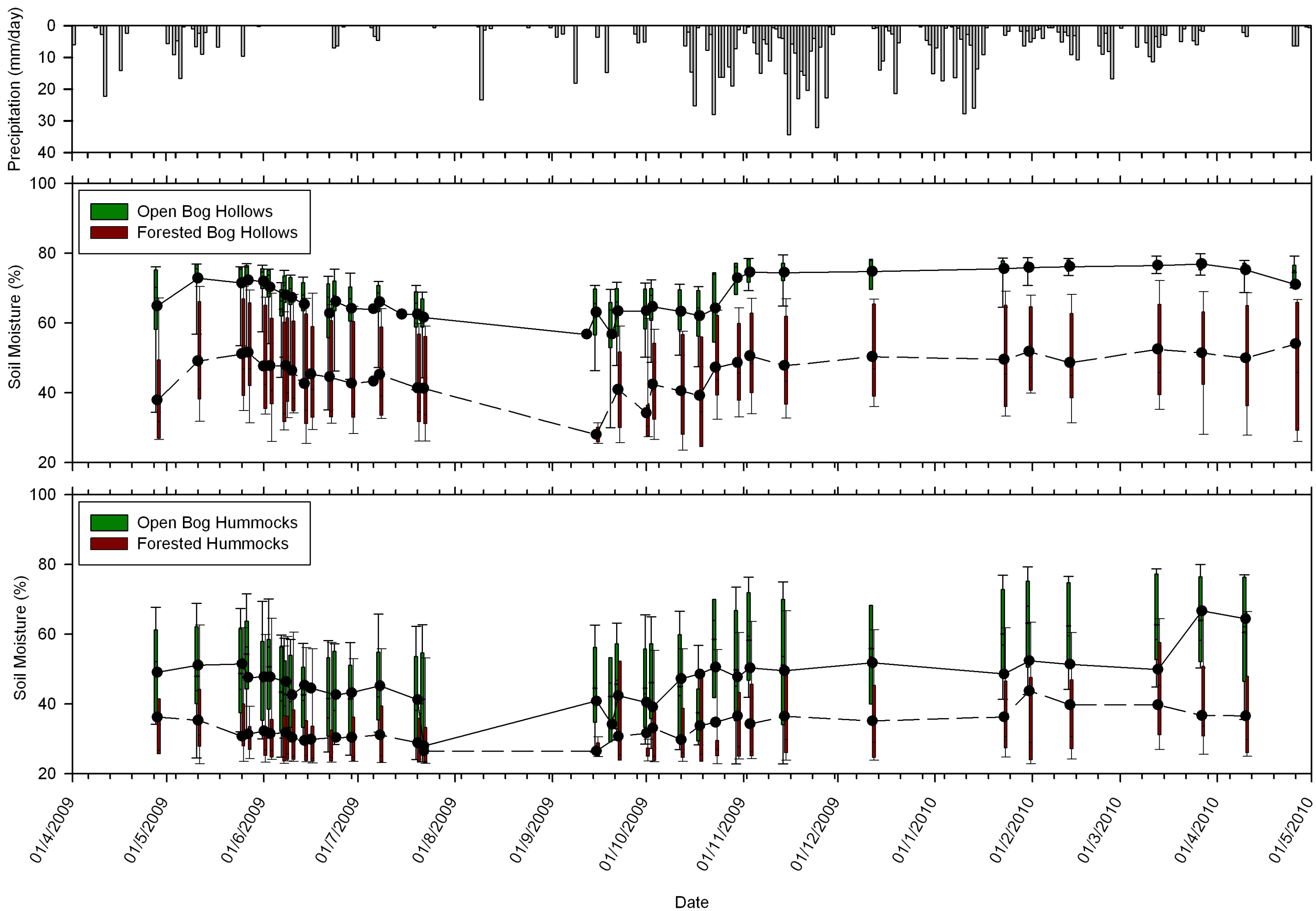

Figure 15: Time series of measured soil moisture in the hollows and hummocks of the forested and open bog sites. Data gaps were due to bog closure in summer and freezing conditions in winter. Box plots represents the 25th and 75th percentile of the soil moisture measurements, the whiskers the 5th and 95th percentile, while the solid circles representing the average measured soil moisture for that day.

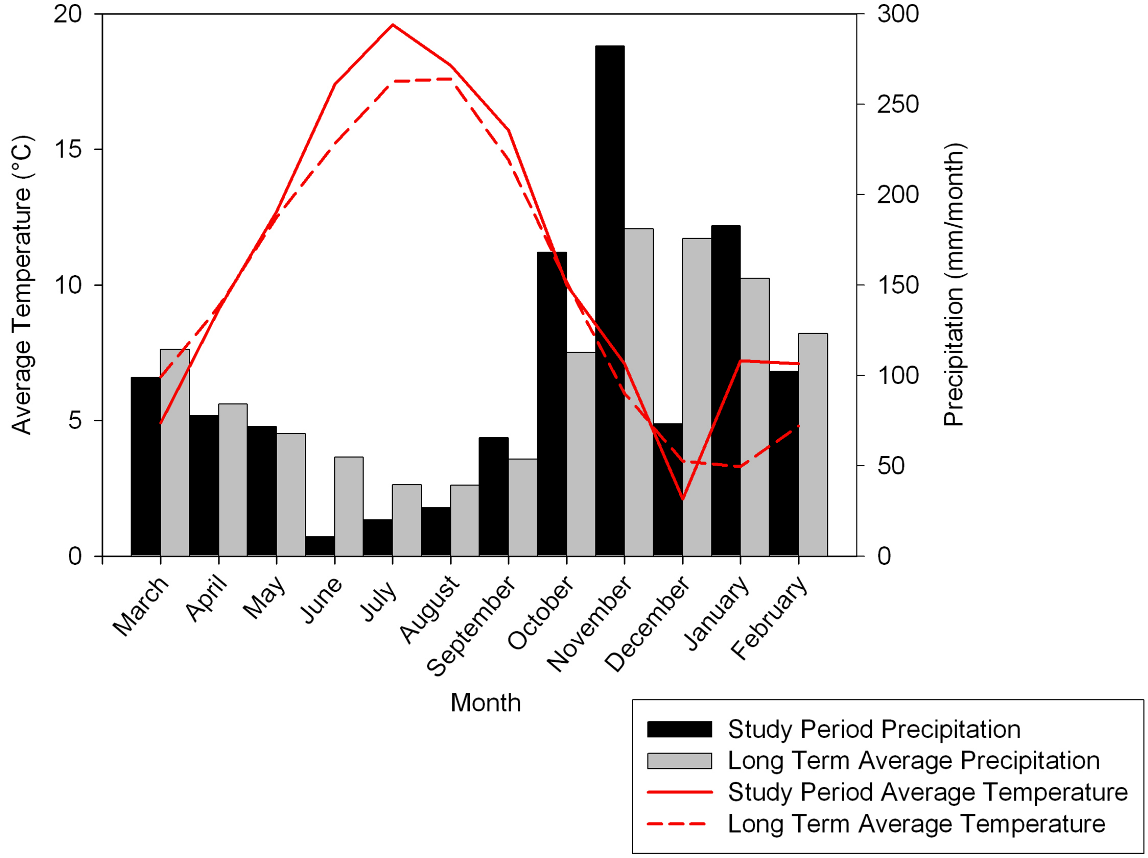

Figure 16: Long term average precipitation and temperature compared to the March 2009-2010 study period precipitation and average temperature at Vancouver International Airport (49° 11'42.0 N, 123°10'55.0 W). Data: Environment Canada (WMO ID 71892)

The gauge closest to the surrey uplands consistently received the most precipitation but gauges 4 and 6 would sometimes receive higher than expected amounts of precipitation based on to their position along the gradient. Despite the study period being a wetter year, the precipitation gradient found by Helbert and Balfour (2000) was evident for each measurement interval.

Gauge	UTM Coordinates (Zone 10U)		3/31 to 5/14	5/14 to 6/23	6/14 to 11/3	11/11 to 12/12	12/12 to 1/31	1/31 to 3/24	Total(mm)
1-SW	498683	5439727	124	32	265	108	389	239	1156 ± 22
2	499823	5441465	123	29	-	195	432	316	-
3	500047	5440696	122	35	-	266	368	156	-
4	500934	5442121	120	35	268	201	390	152	1164 ± 22
5	501266	5437749	120	31	-	197	301	217	-
6	501492	5441707	-	36	284	232	462	170	-
7	502605	5440025	122	31	268	-	410	339	-
8	504315	5442083	-	32	290	297	-	-	-
9-NE	504806	5443351	131	34	290	282	441	336	1513 ± 22
Average			123	33	278	222	399	241	1278 ± 22

Table 3: Total precipitation (mm) measured from March 2009 to March 2010. Gauge numbers are arranged by location. Gauge 1 is located in the southwest corner, gauge 9 in the northeast corner of Burns Bog (see Figure 6)

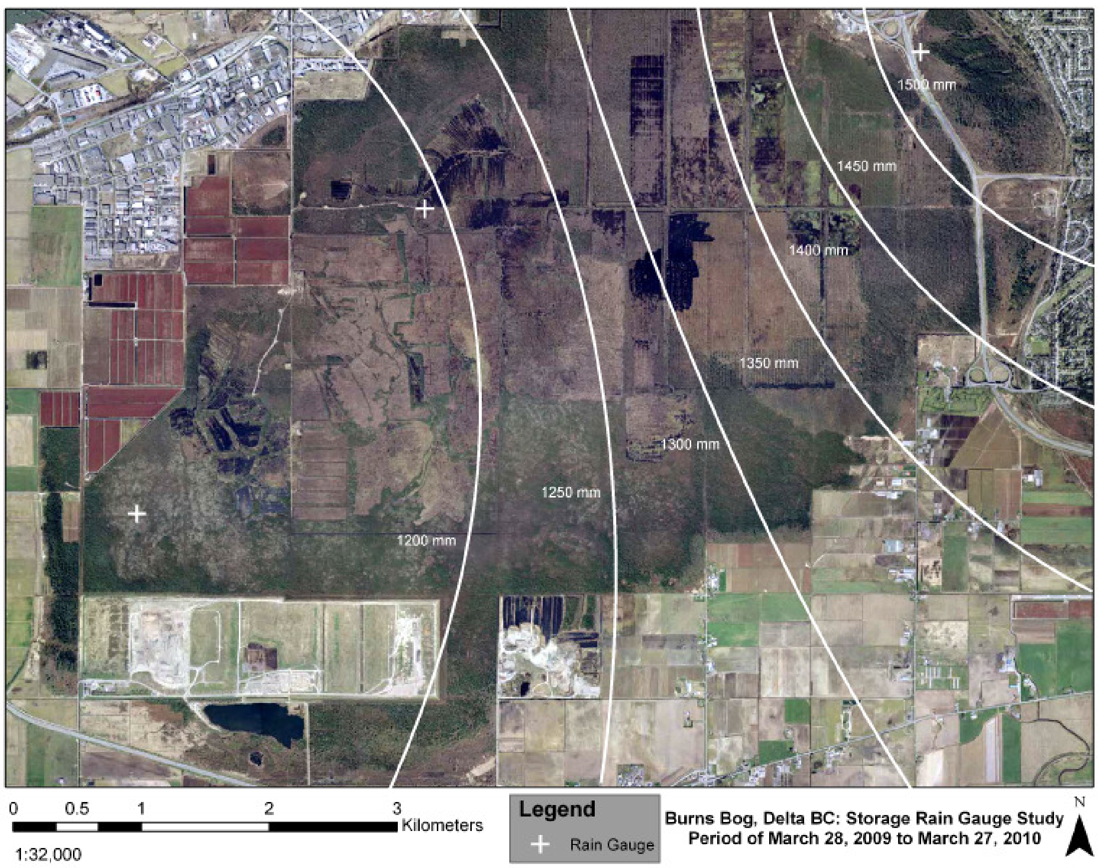

Figure 17: Precipitation contours for the March 28, 2009 to March 27, 2010 period showing the highest precipitation in the northeast corner of Burns Bog, with decreasing amounts towards the southwest. Contour lines were drawn by hand. For maps of the individual precipitation measurement periods, see Appendix 1.

2.6 Canopy and Shrub Interception

The forested bog received, on average, 88% of the precipitation reaching the surface of the open bog due to interception losses from the tree canopy during the April 28, 2009 to April 26, 2010 period (Figure 18). This is more than the 76% of total rainfall reaching the surface of a forested site in a bog in Sweden (Paivanen, 1966, as quoted in Farrick and Price, 2009) and only slightly more than the 85% measured by Chin (2009) in a mature Hemlock-Western Red cedar forest near Maple Ridge, BC. The reduced interception loss in the bog compared to forests in coastal BC can be attributed to the differences in tree density and canopy density, as well as leaf area index. Van Seters (1999, as cited in Van Seters and Price, 2001) found that the tree canopy intercepted 32% of precipitation in a peatland in Quebec, much more than in this study.

Interception loss was highly variable, with the seven gauges showing an average interception loss between 4 and 44% (Figure 18a and b). Larger rain events produced larger variability between gauges, but the coefficient of variation of throughfall did not increase appreciably (Figure 19).

The amount of throughfall below the shrubs in Burns Bog was even more variable than below the forest canopy. Some gauges measured throughfall to be only 45% of open precipitation, while other gauges measured 265% for the same event (Figure 18c). The canopy storage of the shrub layer was greater than the forest canopy storage: 3.4 mm compared to 1.3 mm (determined by the intercept of regression line of the relation between precipitation and throughfall). Farrick and Price (2009) found that peatlands in Quebec, Canada received many low intensity events (<3 mm). They report that the shrub canopy interception storage was around 2 mm, and tree canopy interception was approximately 3 mm, such that much of the precipitation in small intensity events did not

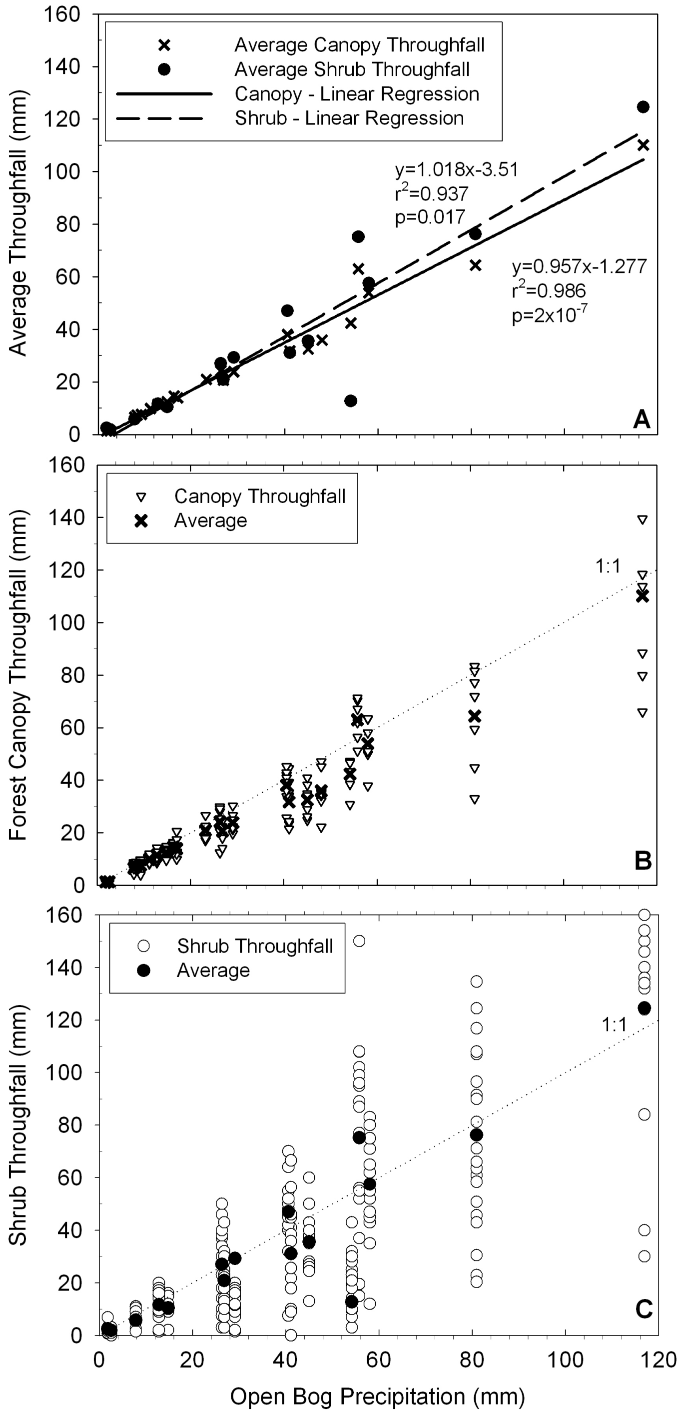

Figure 18: Throughfall as a function of precipitation (precipitation was measured with the trough gauge in the open bog site).

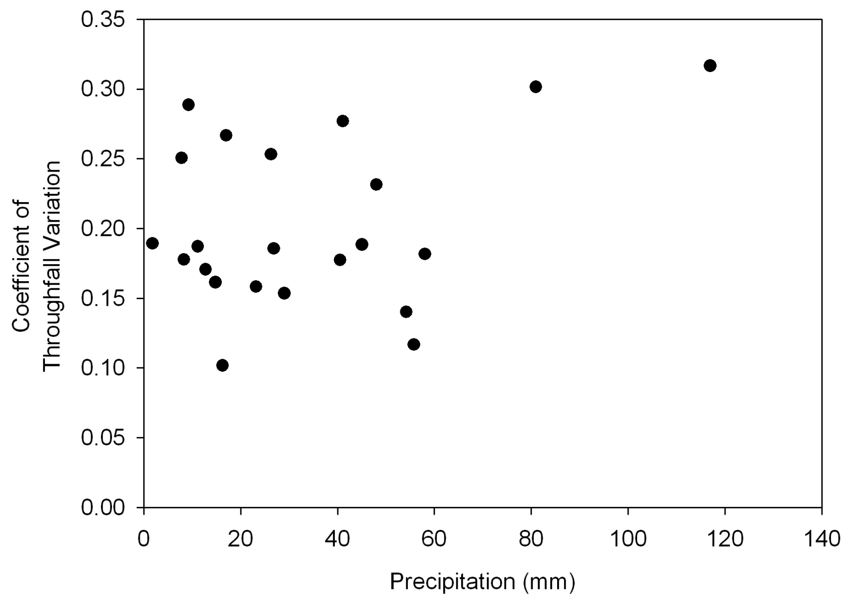

Figure 19: Coefficient of variation of throughfall as a function of measured precipitation.

reach the surface of the bog. Farrick and Price (2009) concluded that larger storms are important for maintaining the water content in the peat because they found that in their study, 100% interception occurred at low intensity, short duration precipitation events. During high intensity, short duration precipitation events up to 16 mm/hr, interception was 10% of the precipitation. Many precipitation events in Burns Bog are also smaller than 5 mm/day (Table 1) such that interception loss is high.

It is important to note that the 2009 summer was a very dry summer followed by an unusually wet autumn (Figure 16). The results from the summer period of this study may only be representative of dry summers.

2.7 Evaporation and Transpiration

There are very few studies on transpiration from pine trees in raised bogs, as most studies estimate evaporation and transpiration together using equations such as the Thornwaithe equation or combined approaches such as Priestley and Taylor approach

(Van Seters and Price, 2001), or measure the evapotranspiration with the eddy covariance method. In this project evaporation from the bog surface was measured separately from transpiration of trees.

2.7.1 Tree Survey

Pine was the dominant species, accounting for 95% of the trees in the 40x40 m forested plot. The remaining 5% of the trees were hemlock. The tree density was 844 stems/ha. The oldest tree sampled was 55 years old and 78% of the trees in the forested site were between 35 and 55 years old (Figure 20)

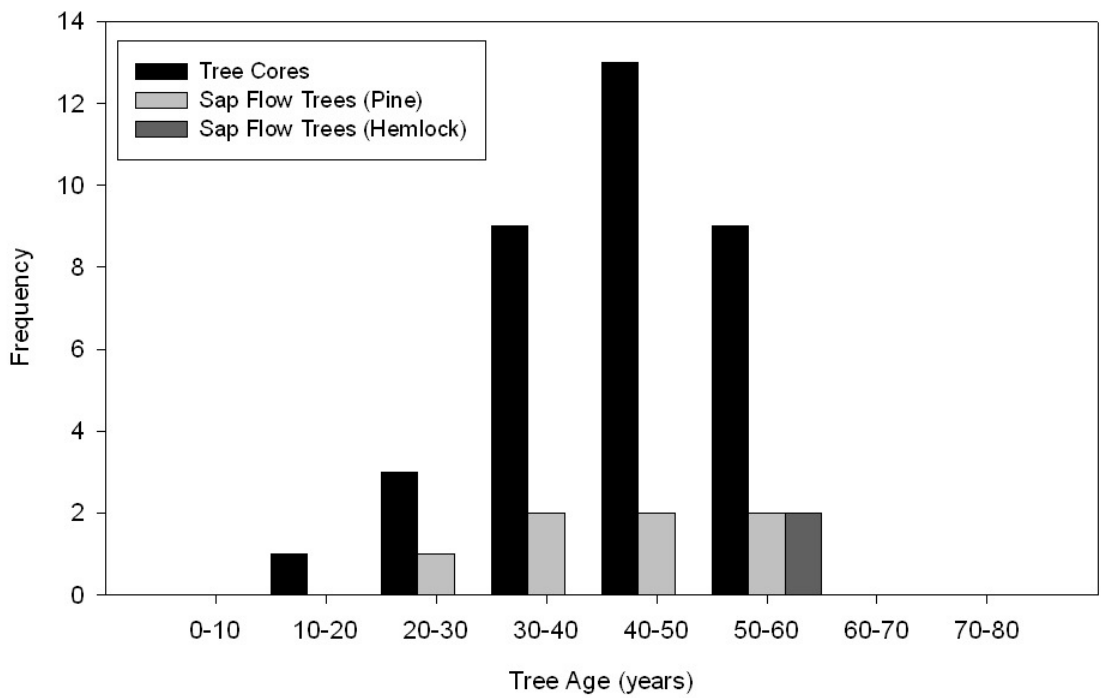

Figure 20: Age distribution of 34 trees in the sample plot, and age distribution of trees sampled for sap-flow measurements.

The circumference-sapwood area relations were significantly different for the two species (Figure 21). Based on these relations and the tree survey, the total sapwood area in the 40x40 m forested plot was estimated to be 3.4 m^2 (21.3 m^2/ha).

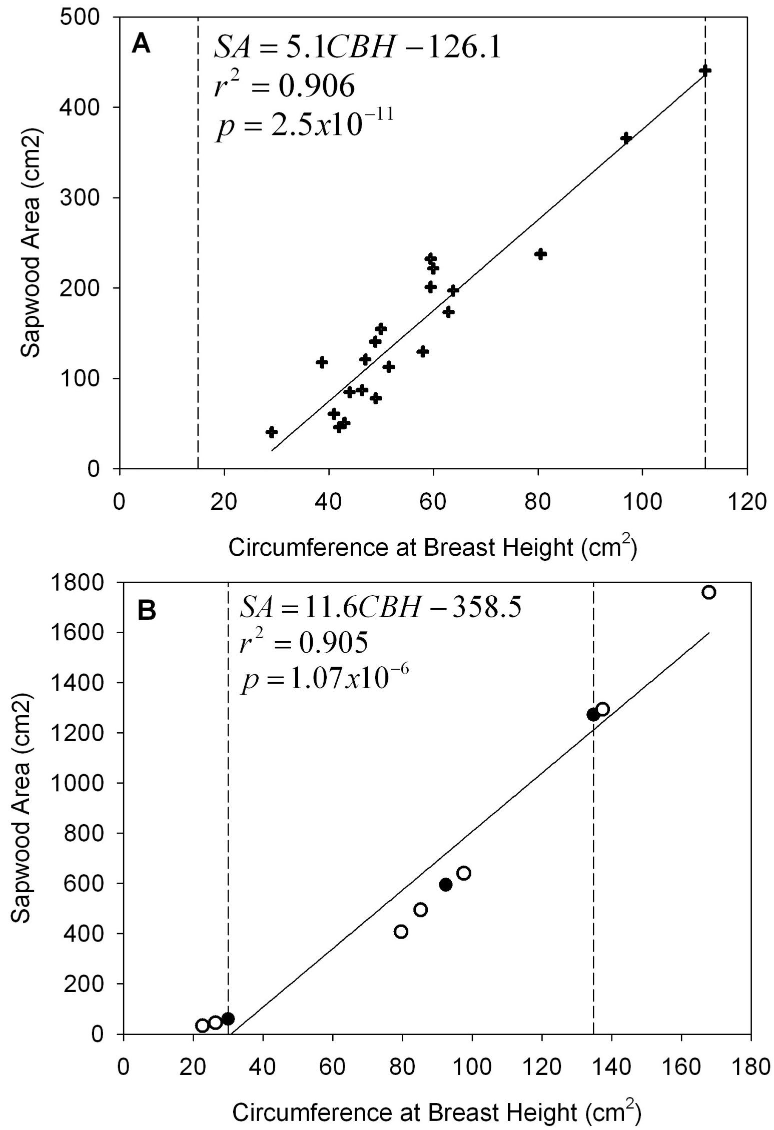

Figure 21: Relation between sapwood area (SA) and tree circumference at breast height (CBH) for the pine trees (a) and the hemlock trees (b) in the forested bog site. Dotted lines show the smallest and largest measured circumference of hemlock trees in the forested bog site. Open circles in (b) are hemlock trees from outside the sample plot.

The results of the tree survey are in agreement with the generalization that tree growth in bogs is generally poor (Kucerova et al., 2010) as the trees in the bog are smaller in diameter and are much shorter than the trees found in non-bog areas.

The distribution of diameter at breast height (DBH) in the forested bog site is skewed towards smaller diameters (Figure 22) and does not follow the same shape as the distribution of tree ages (Figure 20). This is in agreement with the findings of Sarkkola et al. (2003) on the changes in tree stand characteristics with water-level drawdown. Sarkkola et al. (2003) concluded that the skewness in the distribution of diameters at breast height is attributed to the presence of better growing conditions created by a lowered water table, which triggered colonization. This could explain the age and size of the tree stand in the forested bog, since agricultural activity was established prior to 1900 in the south and southwestern boundaries of the bog. Extensive peat mining began approximately 70 years ago when the perimeter of the bog was located further west than the current boundary (Hebda et al., 2000). The lowered water level may have allowed for the growth of new trees towards the centre of the bog. Although new trees could establish themselves, growing conditions still remained relatively poor, thus resulting in relatively smaller and shorter trees in the bog compared to the surrounding forests.

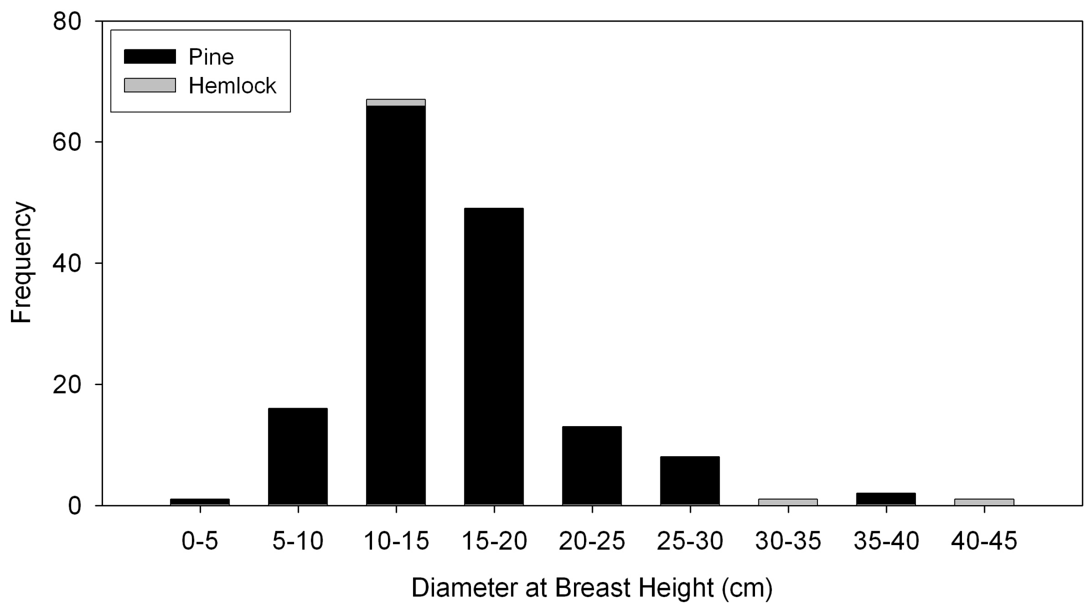

Figure 22: Distribution of diameters at breast height of the trees in the forested bog site.

2.7.2 Evaporation

Measured evaporation was higher in the hollows than the hummocks in the open bog site and higher in the hummocks than the hollows in the forested bog site. These results for the open bog agree with Farrick and Price (2009), who found higher evapotranspiration from hollows than from hummocks. Evaporation measured from open bog hollows was higher than from the forested bog hollows (114.8 mm and 54.4 mm respectively for the June 15 to September 15 2009 period, Figure 26a). However, evaporation was greater from forested bog hummocks relative to open bog hummocks (63.2 mm and 84.9 mm respectively for the June 15 to September 20 2009 period) (Figure 26b).

Evaporation from the open hollow and the forested hummocks exceeded the potential evapotranspiration from June 29 to July 6, 2009 (Table 4). Evaporation from the forested hummocks and hollows also exceeded potential evaporation from July 20-22, 2009.

Evaporation in the open site did not show a statistically significant ($p=0.05$) relation to net radiation, temperature, relative humidity, or vapour pressure deficit (Figure 23 and Figure 24). However, evaporation from the forested site showed a relationship to net radiation ($p=0.008$), temperature ($p=0.02$), relative humidity ($p=0.006$), and vapour pressure deficit ($p=0.02$). Strack and Price (2009) reported that evaporation from a peat monolith was closely linked to vapour pressure deficit through pronounced reductions in moisture content with decreasing relative humidity. There was no relation between the depth to the water surface or soil moisture and the evaporation rates from the open bog site or the forested bog site either (Figure 25). Farrick and Price (2009) showed that evaporation decreased with increasing water table depth. Several studies have shown that evaporation decreases with a lowering water table, because of a decline in the upward flow of water through capillary action (Schouwenaars, 1993; Romanov, 1968, as cited in Farrick and Price, 2009). However this relation was not apparent for the data from Burns Bog. Through modelling the energy balance of the Mer Bleue Bog, Canada, Admiral and Lafleur (2007) found that rather than evaporation being severely limited when the water table is very deep, transpiration from shrubs continued but at a reduced rate.

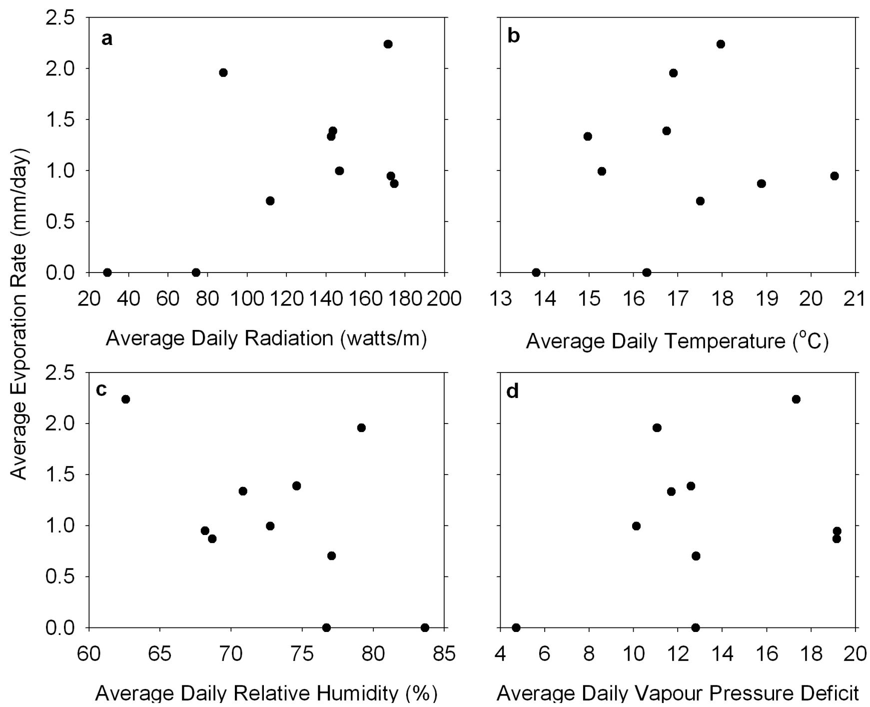

Figure 23: Open bog evaporation rates as a function of average net radiation (a), average daily temperature (b), average daily relative humidity (c), and average daily vapour pressure deficit (d)

Calculated daily average potential evapotranspiration rates (Equation 2) in Burns Bog were generally higher than the measured evaporation rates, agreeing with the conclusions of Schouwenaars (2007) that the upward movement of water might be limited when pore water pressures become low (<-10 cm in Fochteloerveen bog, Netherlands).

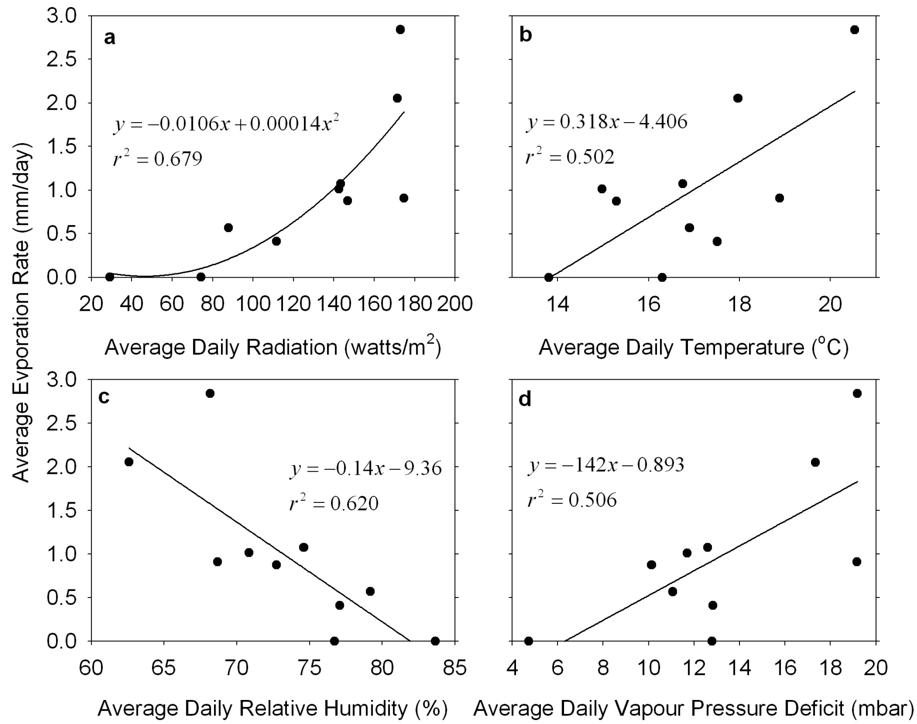

Figure 24: Forested bog evaporation rates as a function of average net radiation (a), average daily temperature (b), average daily relative humidity (c), and average daily vapour pressure deficit (d)

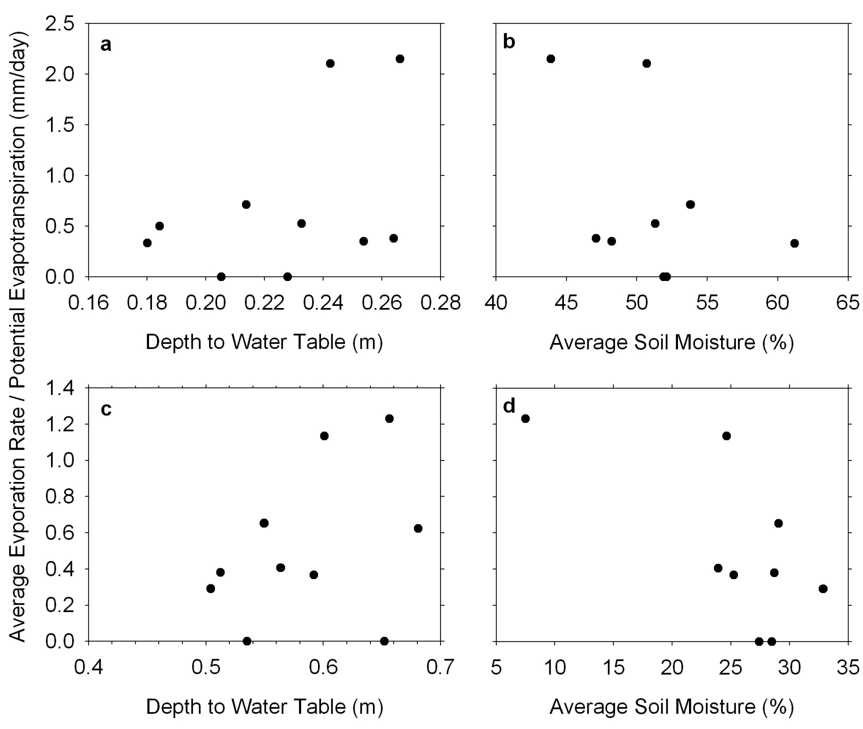

Figure 25: Evaporation divided by potential evapotranspiration rates as a function of depth to water surface and average soil moisture in the open bog (a and c) and forested bog (b and d)

Campbell and Williamson (1997) concluded that due to low plant nutrient status in bog environments or limited water uptake by particular bog species, evaporation from peatlands may be less than the potential evapotranspiration calculated from meteorological variables.

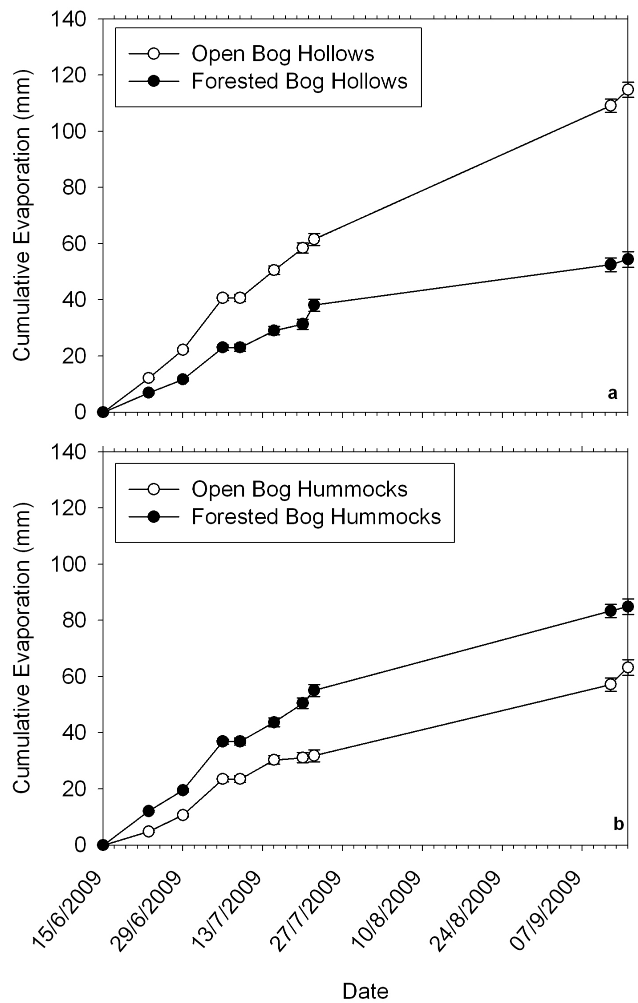

Figure 26: Cumulative average evaporation from the hollows (a) and hummocks (b) during the growing season (June – mid-September) of 2009.

	Number of Days	PET (mm/day)	Hollows (mm/day) open	Hollows (mm/day) forested	Hummocks (mm/day) open	Hummocks (mm/day) forested
June 15 - June 23	8	2.3	1.5	0.6	0.5	1.1
June 23 - June 29	6	0.9	1.7	0.8	1.0	1.2
June 29 - July 6	7	1.6	2.6	1.6	1.8	2.5
July 6 - July 9	3	2.5	0.0	0.0	0.0	0.0
July 9 - July 15	6	1.6	1.6	1.0	1.1	1.1
July 15 - July 20	5	2.3	1.6	0.5	0.2	1.4
July 20 - July 22	2	3.8	1.5	3.4	0.4	2.3
July 22 - Sept 15	52	0.5	0.9	0.3	0.5	0.5
Sept 15 - Sept 20	3	0.5	1.9	0.6	2.0	0.5
Total (mm)	92 days	89mm	115mm	54mm	63mm	85mm

Table 4: Measured average daily evaporation (mm/day) and average daily potential evapotranspiration (mm/day) calculated using the Equation 2.

2.7.3 Transpiration

Only nine of the 12 sapflow sensors functioned correctly throughout the 5-month monitoring period. These sensors showed a distinct diurnal signal with the lowest temperature differences during the day and the highest temperature differences at dawn (Figure 27). The other 3 sensors displayed very noisy data and showed an inverted signal and were therefore not used in the analyses.

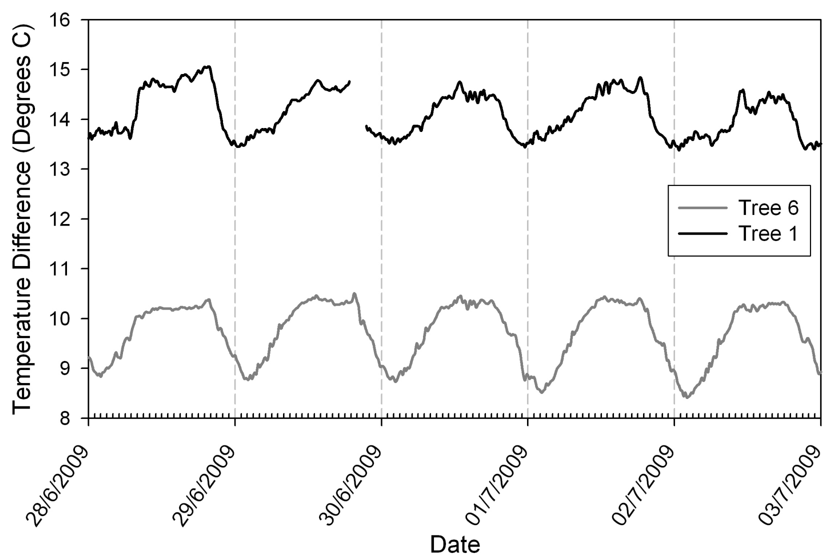

Figure 27: A clear diurnal signal in temperature differences was detected in both Pine (e.g. Tree 1) and hemlock (e.g. Tree 6) trees. The figure shows temperature differences measured between midnight June 28 and midnight July 3, 2009

Spikes in the temperature difference, which persisted for 30 to 60 minutes at approximately an hour after sunrise were detected in several of the sensors. These spikes in temperature can be explained by changes in the temperature gradient created by the sensors. This may have been generated from the sun heating the sensors, temperature changes of the xylem water from the root to above ground stem, heat storage in the stem or heat conductance differences between day and night (Kostner et al., 1998). These short spikes were removed from the data before calculation of the transpiration rates.

Transpiration rates calculated from the sap flow measurements generally decreased throughout the summer, from a maximum of 0.7 mm/day in May to a minimum of 0.2 mm/day in early September. On average, approximately 0.44 mm/day of water was transpired from the forested bog site between May 22 and September 22, 2009, with pine trees contributing the majority of the transpiration flux (Figure 28). Hemlock trees contributed relatively little to total transpiration due to the limited number of hemlock trees (2 trees) in the forested site. However, the hemlock trees are larger and transpired up to 60 L/day, while the pine trees transpired, on average, 6 to 7 L/day.

Similar to other studies (Granier, 1987; Sarkkola et al., 2010; Lundblad and Lindroth, 2002) no correlation was found between water level depth below the surface and the transpiration rate or soil moisture (hummocks and hollows) and the transpiration rate (Figure 30). Daily transpiration rates increased with increasing radiation and air temperature, and decreased with increasing relative humidity (Figure 30), agreeing with findings from Kucerova et al. (2010), Lundblad and Lindroth (2002), and Tang et al. (2009). Kucerova et al. (2010) reported that correlation between canopy transpiration and radiation was significant only when the vapour pressure deficit (VPD) was below a threshold value of 0.4 kPa (approximately 4 mbar), and that transpiration remained almost constant when VPD values were higher, regardless of increases in global radiation. This was explained by stomatal closure and decreased stomatal conductance for VPD values above the threshold and was also found in this study (Figure 30g). Lundblad and Lindroth (2002) also found strong relations between evapotranspiration and radiation, but a weak dependence on vapour pressure deficit. They found that the potential evapotranspiration from a forest stand on peat soils (not a bog) was generally higher than actual transpiration that there was a good correlation between potential and actual evapotranspiration. Results from this study showed a statistically significant relationship between potential evapotranspiration and observed transpiration ($p=0.02$) (Figure 31).

Hokka et al. (2008) showed that transpiration was related to air temperature, vapour pressure deficit, and net radiation in a drained peatland in central Finland. In this study, only vapour pressure deficit and net radiation were observed to have a statistically significant relationship with transpiration (Figure 30e and Figure 30f). Similar to the results of this study, Tang et al. (2006) found that sap flux and canopy transpiration were mainly controlled by vapour pressure deficit (Figure 30g) and photosynthetically (Figure 30e) active radiation. Vapour pressure deficit was related to transpiration by an exponential relationship with saturation at high deficits, and a linear relationship with photosynthetically active radiation (Figure 30g).

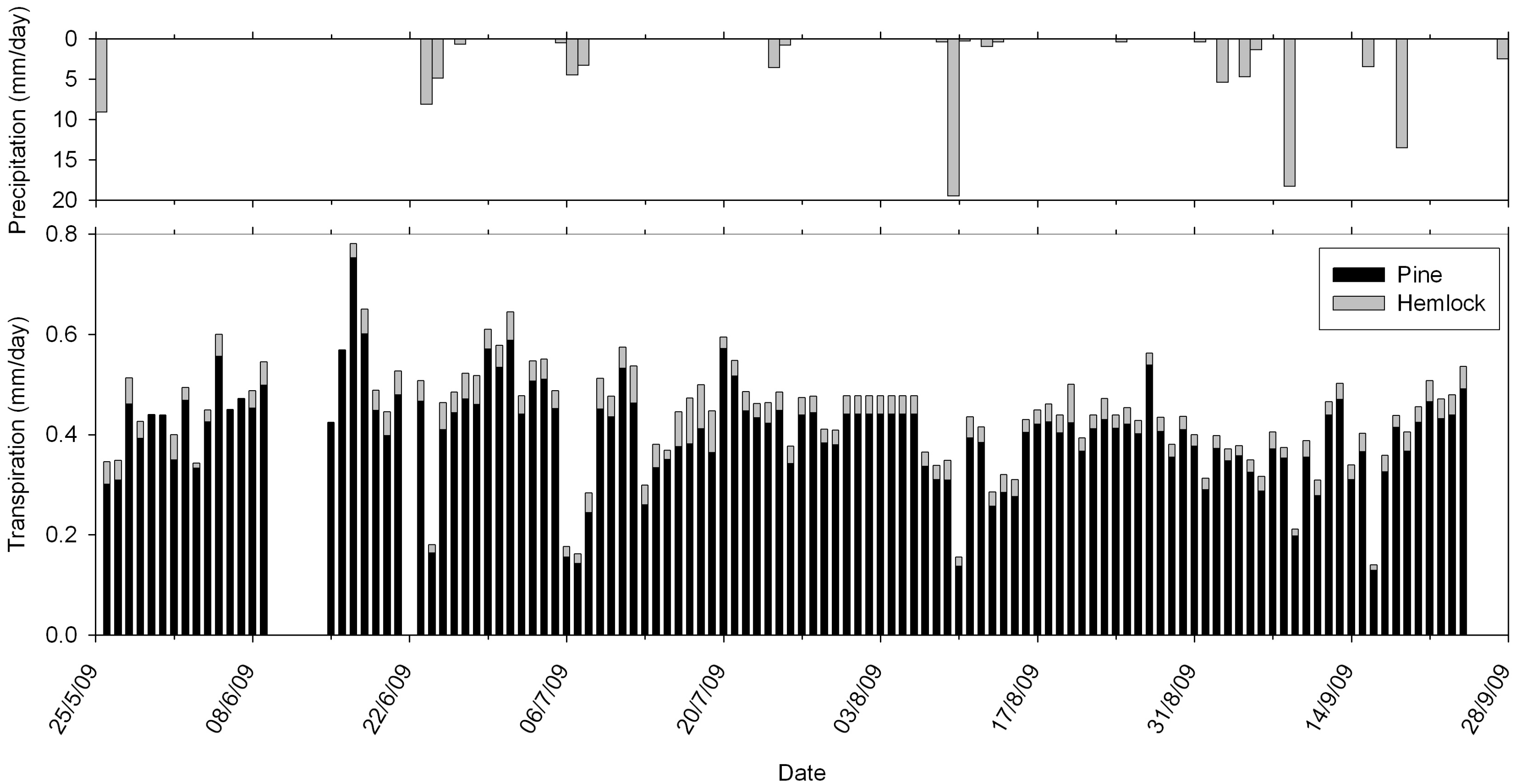

Figure 28: Daily transpiration rates from pine and hemlock trees in the forested site and total transpriation

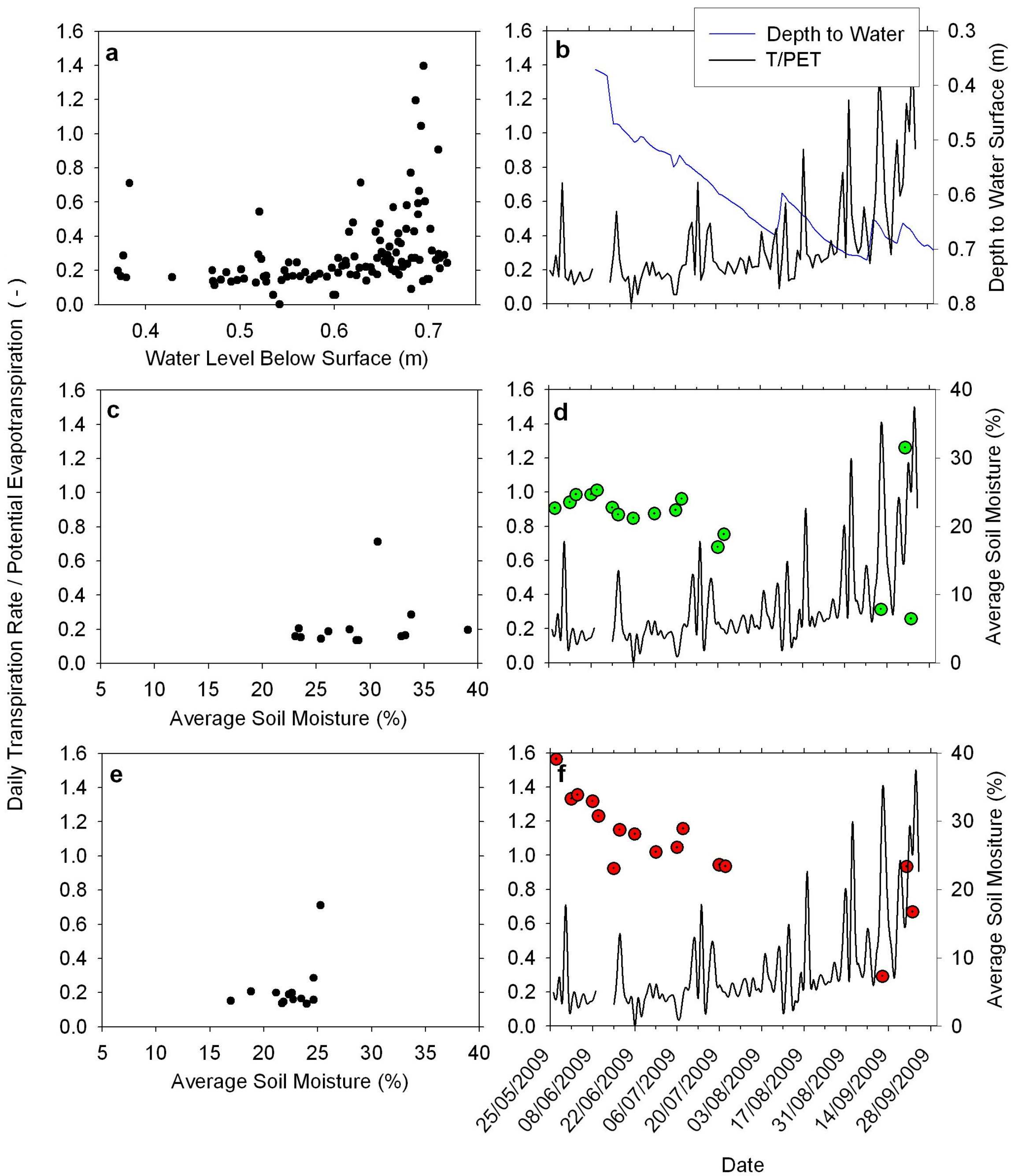

Figure 29: Daily transpiration divided by potential evaporation as a function of the depth to water table from the surface (a and b), average soil moisture in hollows(c and d), and average soil moisture in hummocks (e and f).

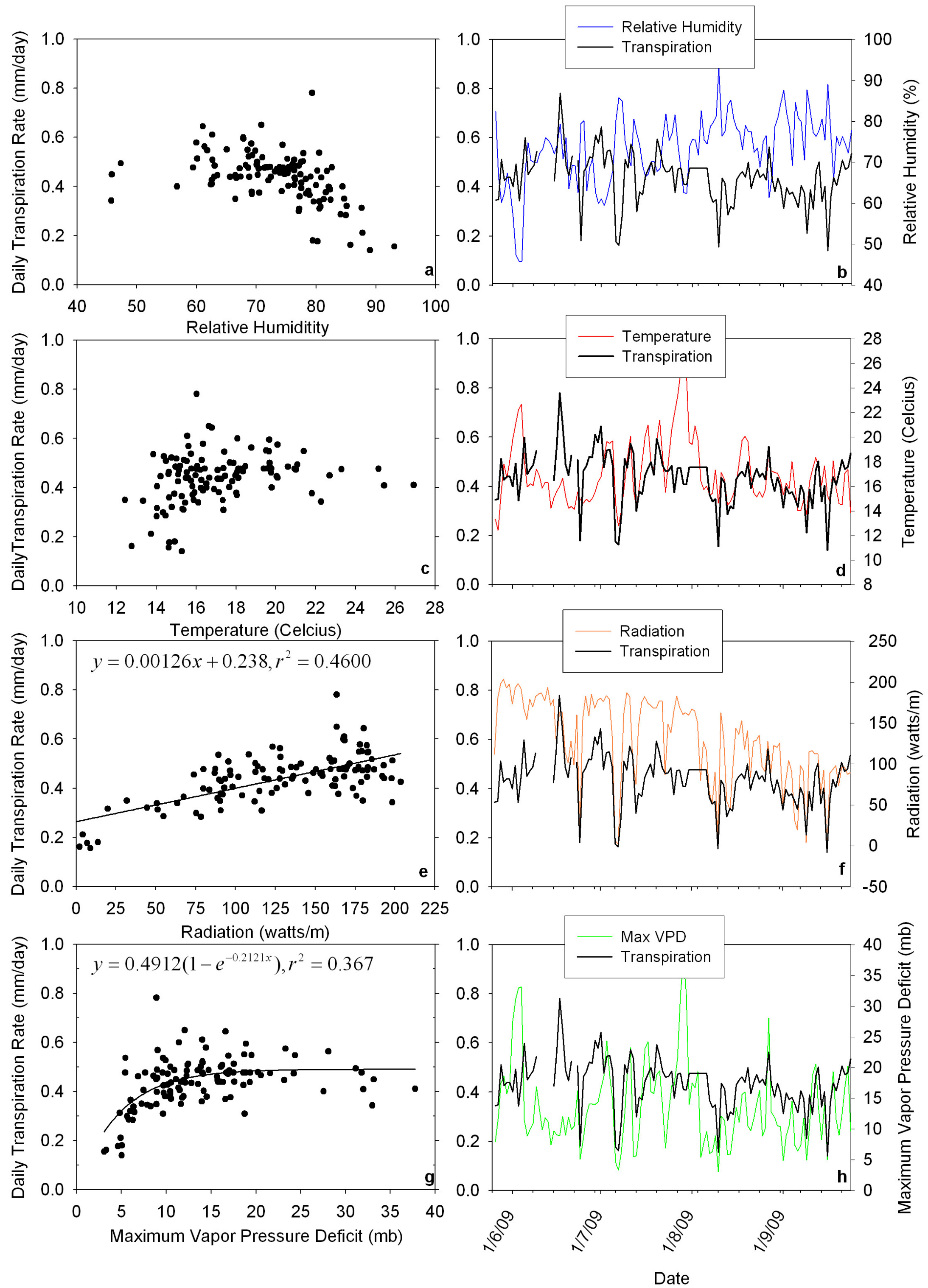

Figure 30: Daily transpiration as a function of relative humidity (a and b), average daily air temperature (c and d), average daily radiation, and the maximum vapour pressure deficit (g and h)

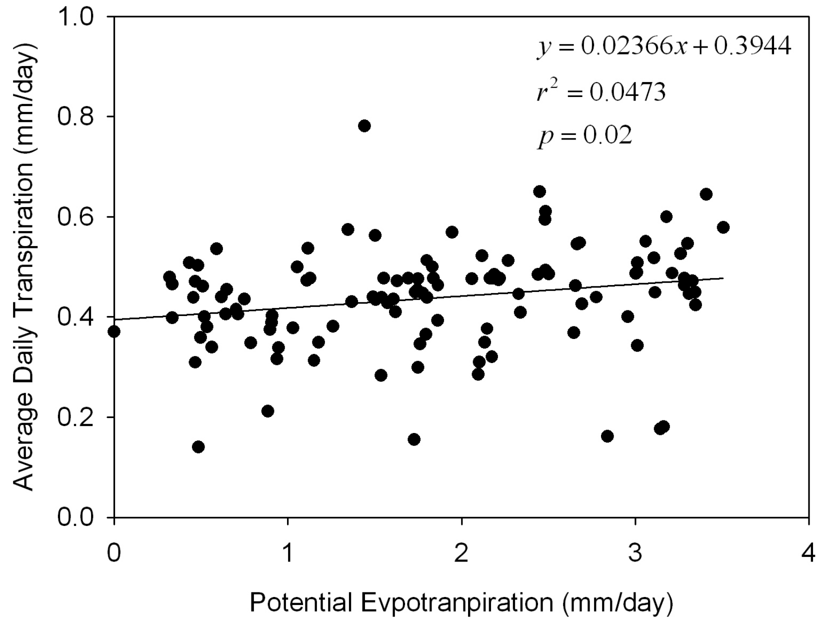

Figure 31: Relation between potential evapotranspiration calculated using Equation 2 and measured transpiration.

2.7.4 Evapotranspiration

The average evapotranspiration from the forested site for the June 10 – September 20, 2009 period was 1.1 mm/day (Table 5). The average evaporation from the open bog site was 0.86 mm/day for the same period, 17% lower than in the evapotranspiration from the forested site. This value is much lower than the evapotranspiration rates reported in the literature. The average evapotranspiration rate measured in a bog along the south shore of the St. Lawrence River, Quebec, Canada was 2.5 mm/day during the summer season (Farrick and Price, 2009). Van Seters and Price, (2001) reported evapotranspiration rates between 2.5 and 6.9 mm/day in wetlands. Roulet and Woo (1986) studied a low arctic bog in Canada and measured evapotranspiration rates of 4.5 mm/day. The average evapotranspiration measured in a continental raised bog with stands of pine trees in the Czech Republic using the heat field deformation method was 1.8 mm/day (Nadezhdina et al., 1998 as cited in Kucerova et al. 2010). However, Campbell and Willamson (1997) reported evapotranspiration rates from the Kopouatai bog in New Zealand of 1.54 mm/day despite receiving enough radiation to evaporate up to 6.8 mm/day. Only when the canopy was wetted by precipitation, did the evaporation rate increase to 77% of the calculated potential evaporation. However, the Kopoutatai bog is dominated by a shrub not present in the Burns Bog. Kellner and Halldin (2002) calculated evapotranspiration with the Bowen-ratio-energy-balance method for a northern Swedish bog with similar vegetation as Burns Bog (pines and *Sphagnum*). They found that evapotranspiration during the summer months (May to October) ranged from 1.0 to 2.5 mm/day, averaging 2.1 mm/day in 1996 and 2.4 mm/day in 1997.

	Forested Bog Evaporation (mm/day)	**Forested Bog Transpiration (mm/day)**	**Forested Bog Evapotranspiration (mm/day)**	**Open Bog Evaporation (mm/day)**	**Potential Evapotranspiration (mm/day)**
June	0.4	0.4	0.8	1.0	1.2
July	1.0	0.4	1.4	1.4	2.2
August	0.3	0.4	0.7	0.8	1.6

Table 5: Potential evapotranspiration (mm/day) and the average summer (June to August 2009) evapotranspiration rates in the forested bog (mm/day) and open bog site (mm/day).

The contribution of transpiration to evapotranspiration varies from study to study. In this study, 35% of the evapotranspiration originated from transpiration, which agrees with the 35% that was measured in the Kopoutai bog in New Zealand (Campbell and Williamson, 1997).

2.8 Hydraulic Conductivity

Most of the bail tests reached the 37% recovery mark relatively quickly, which is important because interference from precipitation and evapotranspiration leads to bias in the calculation of hydraulic conductivity (Hogan et al., 2006). The bail tests were conducted during the winter months to avoid interference from evapotranspiration. All of the piezometers, with the exception of the 5 m piezometers, recovered to more than 90% of their original water levels within 48 hours of pumping. The 5 m depth piezometers required more than 1.5 months for the open bog-piezometer and 4 months for the forested bog site to recover to their original water level (Figure 32).

The calculated hydraulic conductivity values ranged from 1.8 $x10^{-5}$ $^{m}/s$ in the surface layers of the forested bog site to 1.2 $x10^{-8}$ $^{m}/s$ in the underlying silts and decreased with increasing depth from the surface of the bog. This agrees with the hydraulic model of raised bogs with depth-dependent hydraulic conductivity as described by Ingram (1987). In the forested bog area, an exponential decease in hydraulic conductivity with depth was found. However, the hydraulic conductivity was higher at 3 m depth in the open bog than at 1.5 m, which may have been caused by the presence of a lens of relatively higher hydraulic conductivity material. There can be several explanations for the presence of higher hydraulic conductivity layers. It is possible that the area in which the piezometer nest was installed intersects a lens of poorly humified peat with rootlets and remains of old vascular plants. Variably decomposed peat will cause deviations in the decrease in hydraulic conductivity with depth (Eggelsmann et al., 1993). Micropiping in peatlands may also influence in situ measurements of hydraulic conductivity (Chason and Siegel, 1986).

The calculated hydraulic conductivity values in both the open and forested bog sites agreed with the values reported by Hebda et al. (2000). The hydraulic conductivity of the uppermost layer of the acrotelm, which is highly porous and can transmit water easily, was not measured in this study, but has been reported to be 1.6×10^{-2} m/s (Price et al., 2008) and as high as 2.5×10^{-1} m/s (Adema et al., 2005). The acrotelm is generally the only area where vertical hydraulic conductivity is greater than the horizontal hydraulic conductivity due to the structure of the moss, with stem orientation being vertical to facilitate the passage of water from depth to the surface (Chason and Siegel, 1986).

	Name	Depth Below Surface	20-Jan-10 Test		13-Feb-10 Test		Average	
Forested	0.5 m	0.52 m	2.2×10^{-5}	m/s	1.3×10^{-5}	m/s	1.8×10^{-5}	m/s
	1.0 m	0.93 m	3.5×10^{-6}	m/s	4.3×10^{-6}	m/s	3.9×10^{-6}	m/s
	1.5 m	1.43 m	5.0×10^{-8}	m/s	3.7×10^{-7}	m/s	4.4×10^{-7}	m/s
	3.0 m	2.85 m	7.8×10^{-8}	m/s	5.9×10^{-8}	m/s	6.9×10^{-7}	m/s
	5.0 m	4.58 m	-	m/s	1.2×10^{-8}	m/s	1.2×10^{-8}	m/s
Open	0.5 m	0.61 m	2.9×10^{-6}	m/s	2.7×10^{-6}	m/s	2.8×10^{-6}	m/s
	1.0 m	1.08 m	4.8×10^{-6}	m/s	5.4×10^{-6}	m/s	5.1×10^{-6}	m/s
	1.5 m	1.55 m	-	m/s	7.7×10^{-7}	m/s	7.7×10^{-7}	m/s
	3.0 m	3.04 m	7.1×10^{-6}	m/s	1.6×10^{-6}	m/s	4.4×10^{-6}	m/s
	5.0 m	4.91 m	1.8×10^{-8}	m/s	1.1×10^{-8}	m/s	1.5×10^{-8}	m/s

Table 6: Hydraulic conductivity for the forested and open bog sites measured in the 0.5, 1, 1.5, 3, and 5 meter piezometers

The range of hydraulic conductivities measured in Burns Bog are also consistent with the values from numerous studies using different methods that are summarized by Rycroft et al. (1975). In their summary, many of the hydraulic conductivities were listed without context as to the depth of the peat where the conductivity was measured. However, Rycroft et al. (1975) concluded that hydraulic conductivity can vary over 9 orders of magnitude depending on the physical and chemical characteristics of the peat as well as the particular species of moss from which the peat is derived and its state of humification.

The calculated hydraulic conductivity of the silt ($3x10^{-9}$ m/s) is in agreement with Helbert and Balfour's (2000) study of Burns Bog and fit the accepted model of bogs existing above a layer of low hydraulic conductivity material, which precludes the influence of groundwater into the peat mass.

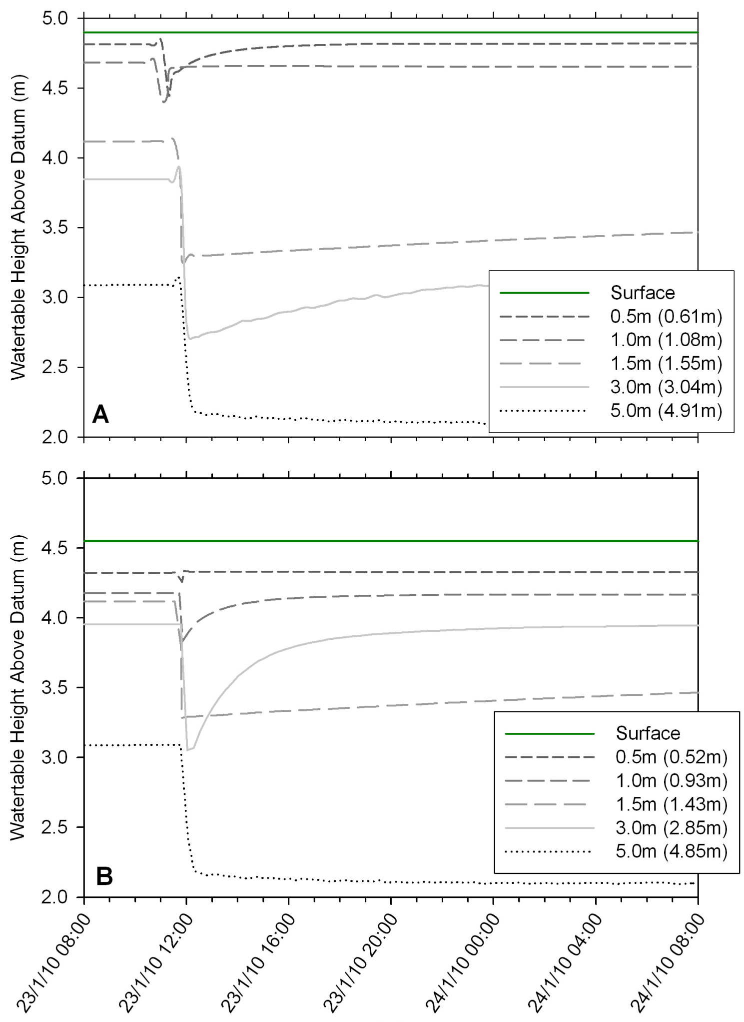

Figure 32 Piezometer recovery in the open bog piezometers (a) and forested bog piezometers (b) after pumping on January 23, 2010. The actual depth below the surface of the piezometers is given in the parentheses.

2.9 Deep Drainage

The hydraulic head in the underlying silt was significantly lower than that in the peat throughout the study period (Figure 12), resulting in deep drainage into the silts. Hydraulic gradients between the 3 and 5 m piezometers remained relatively constant, with the exception of times of hydraulic conductivity testing, which created artificially low water levels in the 5 m piezometer.

Deep drainage into the silt layer was estimated to be approximately 0.27 mm/day and 0.25 mm/day below the open and forested bog sites, respectively (Figure 33). These estimates were calculated using data from the November 30, 2009 to January 20, 2010 period. Water levels in the 5 m piezometers were still equilibrating before this period. After this period, they were affected by pumping for the hydraulic conductivity tests. Deep drainage into the silt layer could not be calculated for periods after February 2010 because of the long time required to re-establish equilibrium in the 5 m piezometer (Figure 32) but was assumed to be similar to the deep drainage flux calculated for the November 2009 to January 2010 period.

Helbert and Balfour (2000) reported that previous work had suggested that groundwater in the vicinity of the study area moved upwards into the peat from the silts. The results of this study contradict these findings, as the hydraulic gradient from 0.5 m to 5.0 m depth indicated a downward movement of water from the peat to the underlying silt. The environmental assessment was completed almost 10 years prior to the start of this study. In 2001, efforts to restore Burns Bog by creating conditions that would encourage *Sphagnum* growth in the forested areas in the south-west portion of the bog began. Remediation included the raising of the water level in the southwest portion of the bog by blocking drainage ditches (Howie et al., 2009), creating substantially different hydrologic conditions relative to 1999 when the environmental assessment was written.

Long-term data (3-year) from one of the piezometers near a ditch that was blocked showed an increase in surface elevation of 11.6 cm due to ditch blocking (Howie et al., 2009) as well as a decrease in seasonal fluctuations in water level. However, the distance over which a blocked ditch can influence the water level remains unclear.

2.10 Discharge

Significant changes were observed in the water level in the southwestern ditch near the Vancouver Landfill (Figure 33). Quick responses to precipitation occurred throughout the year. The efficiency of the ditch in removing water was seen in the rapid drop in water levels in the ditch between rainfall events during the November 2009 to March 2010 period.

There was a large amount of debris in the ditch due to its proximity to the Vancouver Landfill. Most of the debris did not pose a problem, but on several visits, debris created a small blockage in the weir, causing a slight increase in the water level. In November, a large mat of moss and grass had floated to the weir and completely blocked the weir, causing flooding in the ditch. The weir was cleared, and the resulting drop in water level can be seen in Figure 34. During a field visit on March 23, 2010, very little flow was observed despite high water levels. A culvert that partially drained the ditch into a neighbouring stream was clogged with fallen branches and debris from the landfill. The culvert could not be cleared, and its effects were notable as water levels in the ditch decreased significantly slower after this occurred than in the months prior to blockage,

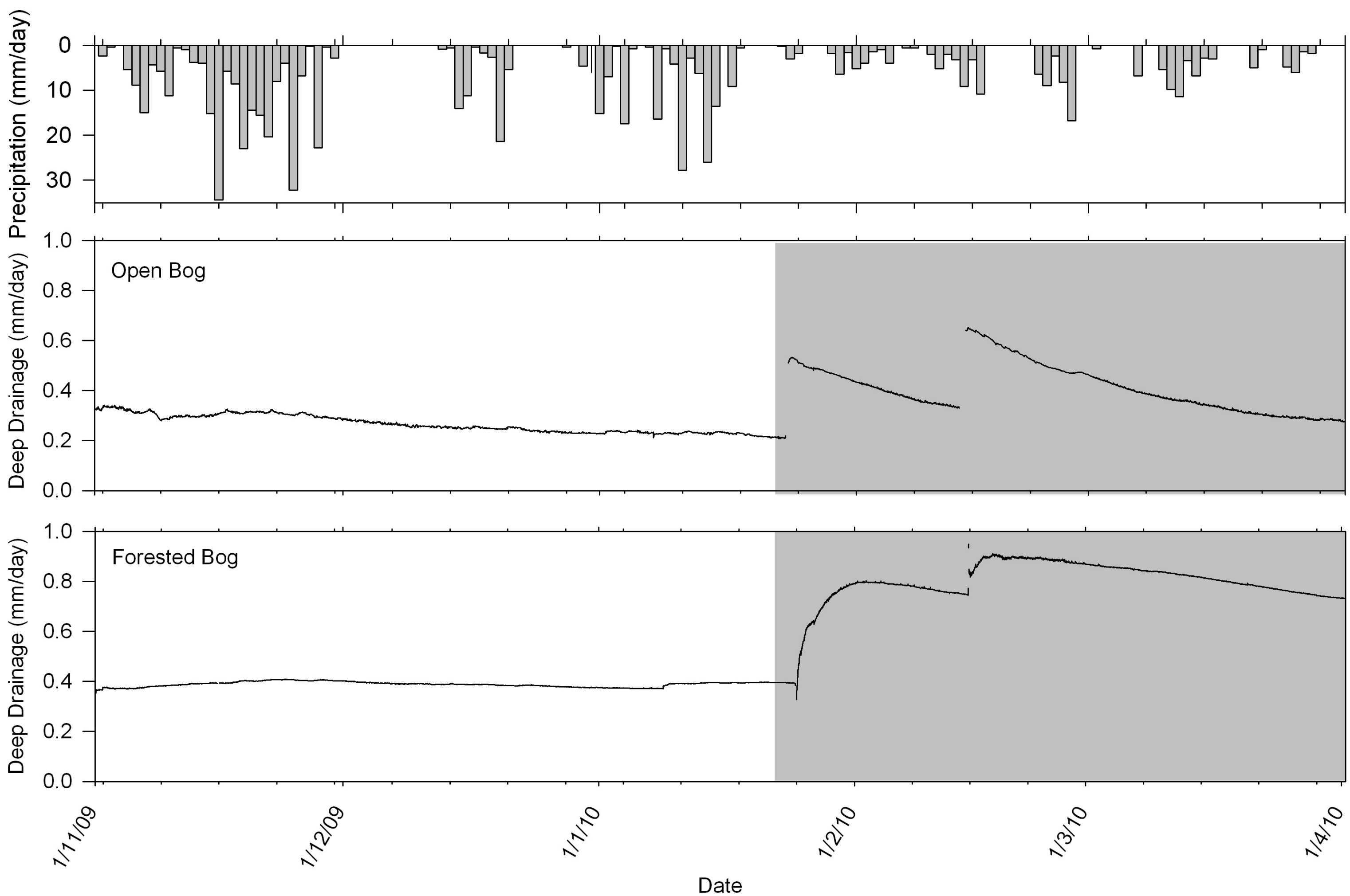

Figure 33: Open and forested bog deep drainage flux calculated from the gradient between the 3 and 5 m piezometers. Shaded areas represent periods affected by pumping from the piezometers for hydraulic conductivity testing.

e.g. in April 2010 water levels did not decrease significantly despite a lack of precipitation, while in November 2009 the water level in the ditch declined rapidly in between rainfall events (Figure 33).

The stage-discharge relation based on ditch flow measurements using a current meter (Figure 35) was used to calculate the discharge from the ditch between November 2009 and March 2010. Data collected after March 23, 2010 was not converted to discharge (Figure 34) because of the change in ditch flow due to the clogged culvert draining the ditch.

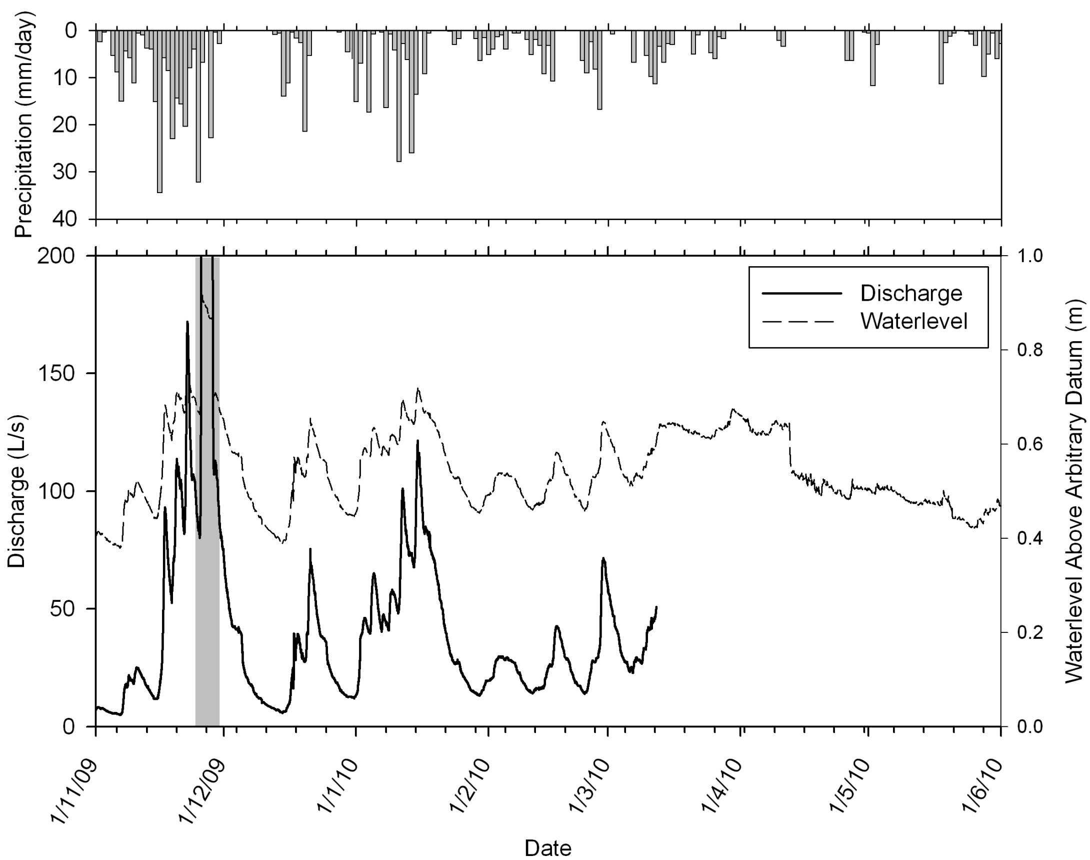

Figure 34: Water level and discharge in the south-west ditch draining toward Boundary Bay from November 2009 to June 2010. Blockage of a culvert downstream from the weir caused the water levels to remain high towards the end of April 2010. Discharge was not calculated after the blockage .

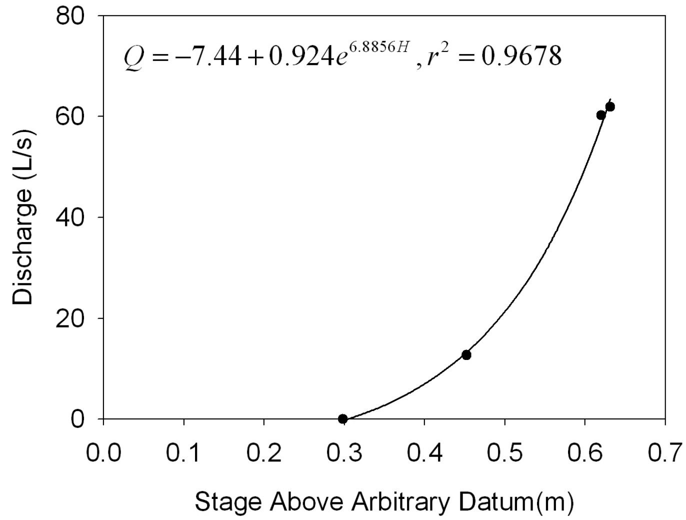

Figure 35: Stage-Discharge relation for the southwest ditch draining towards Boundary Bay. Measurements were taken between November 2009 and March 2010.

The relation between the water level and the discharge measured at the south-western ditch was non-linear (Figure 35). Discharge increased rapidly when the water level elevation reached approximately 4.83 m above the arbitrary datum.

The water level in the north-western ditch also responded very quickly to rainfall events (Figure 37). However, even at the highest water level during the winter, flow was negligible in this ditch, and at times flow appeared to move in the opposite direction. At the highest water level, the weir was completely submerged, and there was substantial flooding upstream. Daily water level fluctuations were recorded throughout the year in this ditch. These fluctuations were not related to precipitation or air pressure variations. They occurred with a period slightly less than 12 hours. The amplitude of these fluctuations increased from May 2010 to August 2010. The cause of these fluctuations is currently unknown.

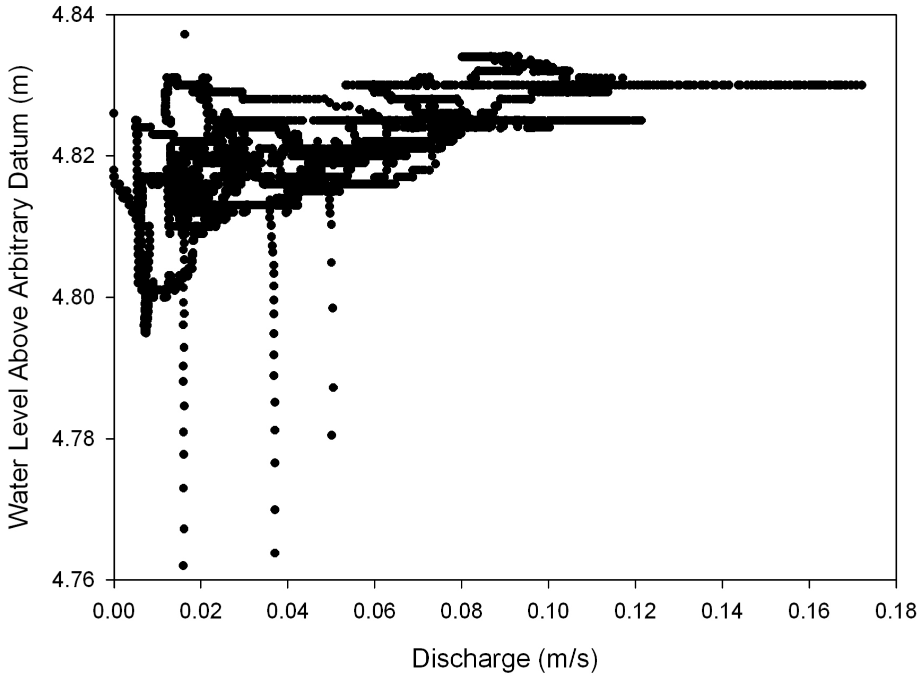

Figure 36: Relation between the water level in the forested bog site and the flow in the south-west ditch draining into Boundary Bay.

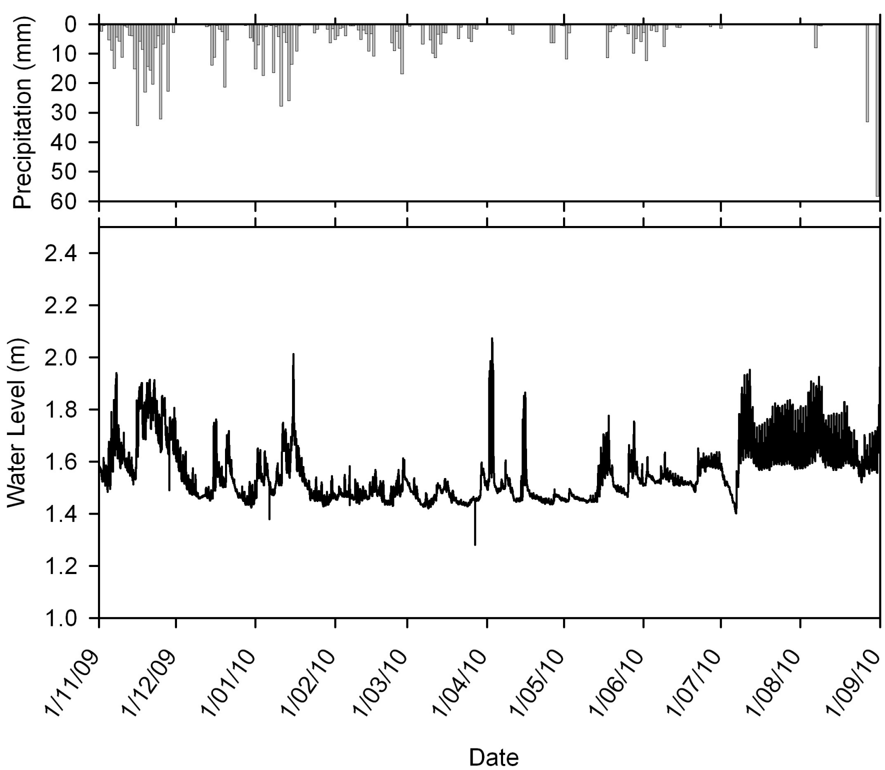

Figure 37: Water level in north-western ditch draining towards the Fraser River.

2.11 Error Analysis and Water Balance

2.11.1 Precipitation

Measurement errors were assumed to be ± 100 mL for the large storage gauge measurement and ± 20 mL for the measurements of with the trough gauges. The total error was 19.1 mm for the annual precipitation measurement at each storage gauge location (Gauges 1, 4, and 9), and 22 mm for the average annual precipitation across Burns Bog.

At the plot scale, precipitation and throughfall were calculated for both the growing season (June 10 to September 20, 2009) and the study period (May 14 2009 to April 26, 2010). The cumulative precipitation for the study period in the open bog was 745.4 mm ± 4.7 mm, and the cumulative throughfall in the forested bog was 654.1 mm ± 4.7 mm. The cumulative precipitation during the period of June 10 to September 20, 2009 was 67.5 mm ± 0.6 mm in the open bog, and cumulative throughfall was 53.1 mm ± 0.6 mm (a).

2.11.2 Evaporation

Evaporation was measured through changes in the weight of the lysimeters. The hanging scale used to weigh the lysimeters had a precision of ± 0.02 kg, equivalent to 0.3 mm of water. Cumulative errors were calculated for evaporation from the open and forested bog hummocks and hollows. The cumulative evaporation from June 10 to September 20, 2009 in the open bog hollows was 114.8 mm ± 3.03 mm, and open bog hummocks was 62.2 mm ± 3.03 mm. The cumulative evaporation from the forested bog hollows was 52.4 mm ± 3.03 mm and 81.9 mm ± 3.03 mm from forested bog hummocks

(Figure 38a and b). Evaporation was assumed to be negligible from October 2009 to the end of the study period in April 2010.

2.11.3 Transpiration

Errors in the values of transpiration come from several sources. Calculation of transpiration using the Granier (1987) method requires the sapwood area for each monitored tree and the total sapwood area of the study plot. To calculate the error in the total sapwood area, the 95% confidence intervals of the tree circumference-sapwood area relationship were used. The error in the sapflow per unit sapwood area was based on the standard deviation of sapflow per unit sapwood area of all monitored trees. This was done separately for the pine and hemlock trees. Total cumulative transpiration during the June 15 to September 20, 2009 period was 51 mm ± 25 mm (Figure 38b).

2.11.4 Deep Drainage

Errors in the calculation of deep drainage resulting from the uncertainty in the value of the hydraulic conductivity of the silt, were assumed to be much greater than the error in the measurement of the water level and the hydraulic gradient. Assuming that the hydraulic conductivity varies by an order of magnitude, the cumulative deep drainage flux from June 10 to September 20, 2009 was 34.1 mm ± 154.61 mm in the open bog and 55.1 mm ± 229.1 mm in the forested bog.

If the deep drainage flux remained constant and similar to that in November 2009-January 2010, for the entire 2009-2010 study period, then deep drainage accounted for 111 mm ±502 mm in the open bog, and 161 mm ±668 mm in the forested bog. This assumption was necessary because the water level in the deepest piezometer was disturbed during the hydraulic conductivity pump tests (Figure 12).

2.11.5 Change in Storage

Due to the expansion and contraction of the peat, as well as the changing water level and peat moisture content, the amount of water stored in the bog does not remain constant. The storage was calculated as:

$$S = 1000(0.9WL + SM\,(SE - WL))$$

Equation 7: Water storage in the peat (mm)

where S is storage (mm), WL is water level elevation above datum (m), SM is the volumetric soil moisture content (m/m), and SE is the surface elevation above datum (m). Soil moisture was assumed to be constant from the surface down to the water table and equal to the soil moisture measured in the top 30 cm. The porosity of the peat was assumed to be 90% (Eggelsmann et al., 1993). Since the water level in the forested bog dropped below 0.5 m from the surface, the water level data from the piezometers at 1 m depth was used to calculate changes in storage.

Errors exist in the measurement of water level (± 0.005 m), surface elevation (± 0.01 m), and soil moisture (± 1%). The 5% and 95% confidence intervals of the relation between measured and actual soil moisture (Figure 14) were used to determine the relative errors due to probe calibration. These errors were propagated through the calculation to determine the storage in the peat. The change in storage between June 10 to September 20, 2009 was –118.6 ± 2.7 mm and –207.9 ± 3.6 mm for the open bog and forested bog site respectively (Figure 38e).

2.11.6 Lateral Discharge

The lateral discharge was calculated as the remainder of the water balance equation after all other variables had been taken into account. Because lateral discharge was not measured at the plot scale, the errors in lateral discharge resulted from the error propagation from the other variables in the water balance equation, and were most influenced by the uncertainty in the deep drainage.

Lateral discharge was calculated as:

$$L = P - D_d - E - T - \Delta S$$

Equation 8: Equation for calculating lateral drainage during the summer months.

where L is lateral discharge (mm), P is precipitation or throughfall (mm), D_d is deep drainage (mm), E is evaporation (mm), T is transpiration (mm), and ΔS is the change in storage (mm).

The total lateral discharge was 164 ± 78 mm for the open bog site and 178 ± 128.2 mm for the forested bog site during the summer months (June 15 to September 20, 2009). For the winter months the evaporation and transpiration (forested bog site only) (Table

Table 7 and Table 8) were combined with the lateral discharge, as evaporation and transpiration were not measured during this period. The combined lateral discharge, evaporation, and transpiration during this period was calculated as:

$$(L + E + T) = P - D_d - \Delta S$$

Equation 9: Equation for calculating unknown losses during the winter months.

The lateral discharge plus the evapotranspiration term was 526 ± 251 mm for the open bog site and 322 ± 247 mm for the forested bog site for the September 20, 2009 to April 26, 2010 period.

2.11.7 Water Balance

A positive water balance is important for the health of a bog (Ingram 1978; 1982; 1987; Moore, 1987). A positive water balance existed in both the open and forested bog sites from October to May, with more water entering as precipitation and throughfall than exiting the bog as evapotranspiration, deep drainage, and lateral drainage during this time (**Error! Reference source not found.** and Table 9). During the summer months, the water balance was negative only in the forested bog site. The forested bog site had greater evapotranspiration, deep drainage, changes in storage, and lateral drainage than the open bog site throughout the year despite receiving less water.

For the open bog, the largest input flux was precipitation during the summer and winter months. The largest output flux was evaporation during the summer months. During the winter months, lateral drainage was the largest output. In the forested bog, the largest input flux was precipitation and the largest output flux was evaporation during the summer months. During the winter months, precipitation was the largest input flux, and lateral drainage was the largest output flux.

		Water Balance Components (mm/day): Open Bog				
		INPUT	OUTPUTS			
Time Period	Duration (days)	Precipitation	Evaporation	Deep Drainage	Change in Storage	Lateral Drainage
June 10 - June 14	4	4.8	0.0	0.6	-1.7	7.1
June 14 - June 22	8	1.1	1.5	0.6	-1.8	2.0
June 22 - June 29	7	1.4	1.4	0.5	-4.3	4.7
June 29 - July 6	7	0.4	2.6	0.5	0.5	-2.2
July 6 - July 20	14	3.4	0.8	0.4	-0.4	3.4
July 20 - Sept 20	62	1.2	0.7	0.3	-1.1	1.8
Summer Average	102	1.6 ± 0.005	0.9 ± 0.002	0.4 ± 0.74	-1.2 ± 0.03	2.2 ± 0.77

Table 7: Summer water balance of the open bog site from June 10 to September 20, 2009.

		Water Balance Components (mm/day): Forested Bog					
		INPUT	OUTPUTS				
Time Period	Duration (days)	Precipitation	Evaporation	Transpiration	Deep Drainage	Change in Storage	Lateral Drainage
June 10 - June 14	4	0.6	0.0	0.0	0.5	-7.9	-7.9
June 14 - June 22	8	0.7	0.9	0.4	0.5	-5.8	-6.6
June 22 - June 29	7	0.7	0.9	0.3	0.5	-2.2	-3.0
June 29 - July 6	7	0.7	2.1	0.5	0.5	-4.1	-6.0
July 6 - July 20	14	0.8	0.8	0.3	0.5	-3.8	-3.9
July 20 - Sept 20	62	0.9	0.5	0.4	0.3	0.0	0.0
Summer Average	102	0.8 ± 0.006	0.7 ± 0.002	0.4 ± 0.16	0.4 ± 1.05	-2.0 ± 0.04	-1.7 ± 1.26
% of Open Bog		49	121		123	163	77

Table 8: Summer water balance of the forested bog site from June 10 to September 20, 2009

	Water Balance Components (mm/day): Open Bog				
	INPUT		OUTPUTS		
Time Period	Duration (days)	Precipitation	Deep Drainage	Change in Storage	Lateral Drainage and ET
Sept 20 - Nov 14	55	2.2	0.2	1.3	3.3
Nov 14 - Dec 12	28	6.2	0.2	1.0	7.0
Dec 12 - Feb 13	63	2.6	0.2	0.2	2.5
Feb 13 - Mar 27	42	2.0	0.2	0.3	2.2
Mar 27 - Apr 10	14	3.9	0.2	1.2	4.9
Apr 10 - Apr 26	16	1.1	0.2	1.1	1.9
Sept 10, 2009 - Apr 26, 2010 (mm/day)	218	3.1 ± 0.02	0.2 ± 1.11	0.4 ± 0.03	2.4 ± 1.15

Table 9: Water balance components from September 20, 2009 to April 26, 2010 for the open bog site. Evapotranspiration was assumed to be negligible and was combined with the lateral discharge.

	Water Balance Components (mm/day): Forested Bog				
	INPUT		OUTPUTS		
Time Period	Duration (days)	Throughfall	Deep Drainage	Change in Storage	Lateral Drainage and ET
Sept 20 - Nov 14	55	1.8	0.4	3.4	-2.1
Nov 14 - Dec 12	28	6.1	0.4	0.5	5.2
Dec 12 - Feb 13	63	2.1	0.4	0.1	1.6
Feb 13 - Mar 27	42	2.1	0.4	-0.3	2.0
Mar 27 - Apr 10	14	3.0	0.4	-1.5	4.2
Apr 10 - Apr 26	16	0.9	0.4	-2.3	2.8
Sept 10, 2009 - Apr 26, 2010 (mm/day)	218.0	2.5 ± 0.02	0.4 ± 1.09	0.6 ± 0.02	1.5 ± 1.13
% of Open Bog		78	193	150	55

Table 10: Water balance components September 20, 2009 to April 26, 2010 for the forested bog site. Evapotranspiration was assumed to be negligible and was combined with the lateral discharge.

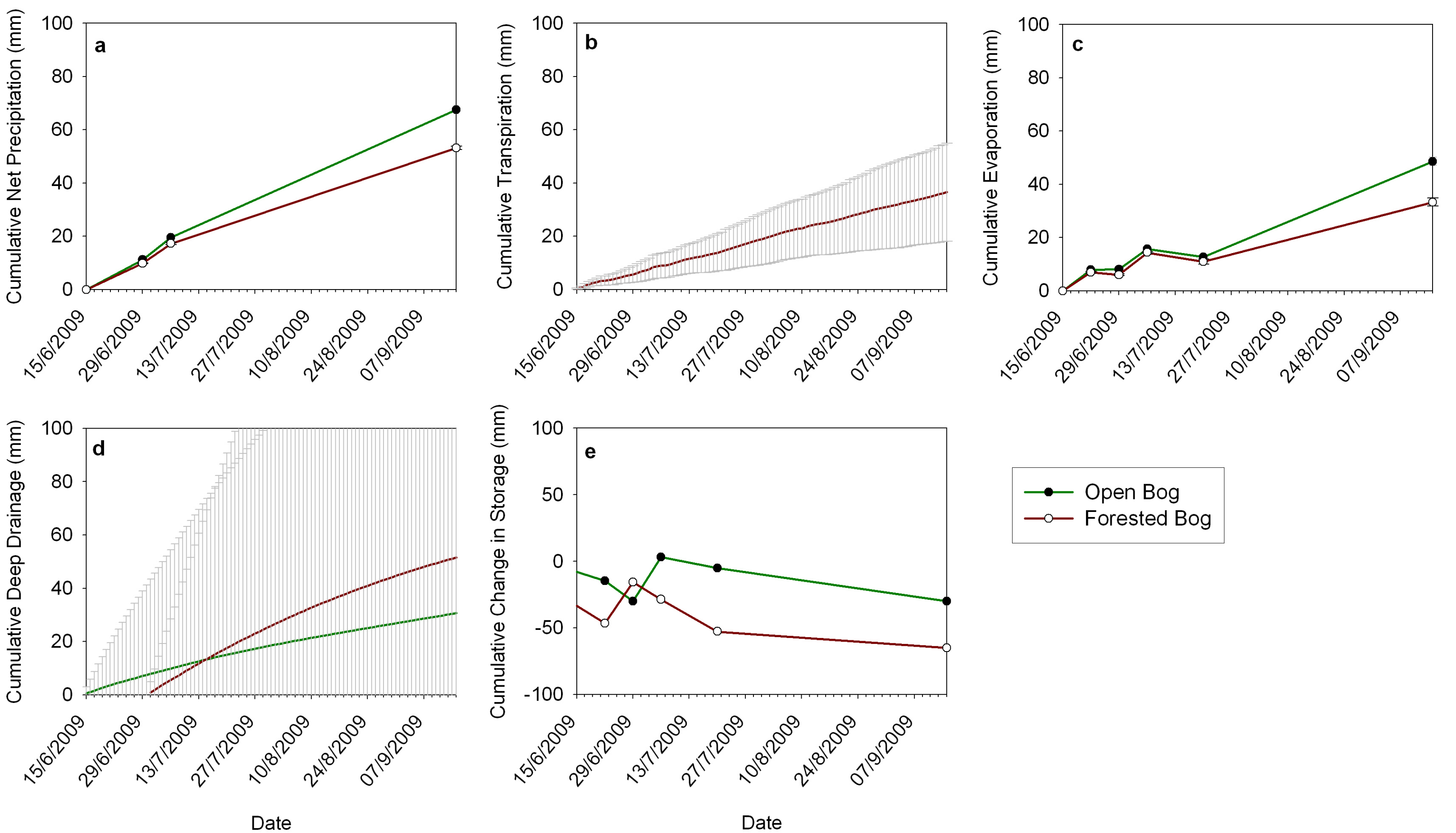

Figure 38: Cumulative precipitation and throughfall (a), transpiration (b), evaporation (c), deep drainage (d), and change in storage (e) in both open and forested bog sites in the June 15 to September 15 period

From June 10 to September 20, 2009, the open bog site received 160 mm of precipitation. A significant difference existed in the water balances between the open and forested bog sites, as the forested bog site received only 52% (84.6 mm) of the precipitation at the open bog site during this period.

Evaporation accounted for 55% (89 mm) of precipitation in the open bog site during the summer months. This value very closely matches the value from in a previous study of Burns Bog by Helbert and Balfour (2000), who found evapotranspiration to be 55% of the total annual precipitation in 2000 based on evaporation pan data and the Thornthwaite method (Thornthwaite and Mather, 1955). However, Helbert and Balfour's (2000) findings were an average for the entire Burns Bog area, and were not specific to open bog areas.

The total evaporation during the summer period from the forested bog site was less than for the open bog site (69.6 mm vs. 89.0 mm) but when compared to the amount of water entering the forested bog site, it is clear that evaporation played a larger role in the water balance of the forested bog site than the open bog site (82 vs. 55% of net precipitation). Evapotranspiration exceeded the total amount of throughfall reaching the surface of the forested bog site by 29% (108 mm) during the summer period. Since evapotranspiration was only monitored during the growing season (June to September), the annual evapotranspiration flux is unknown. However, it was assumed to be small from October to April.

Deep drainage in the open and forested bog sites accounted for 10% and 24% (16.2 mm and 19.8 mm) of the precipitation and throughfall respectively during the summer months. The amount of precipitation and throughfall that deep drainage accounted for during the non-summer months decreased to 9% in the open bog site and 15% in the forested bog site. These decreases were mainly due to increases in the precipitation and throughfall. The deep drainage flux remained relatively constant at 0.2 mm/day in the open bog site (Table 8) and 0.4 mm/day in the forested bog site (Table 10).

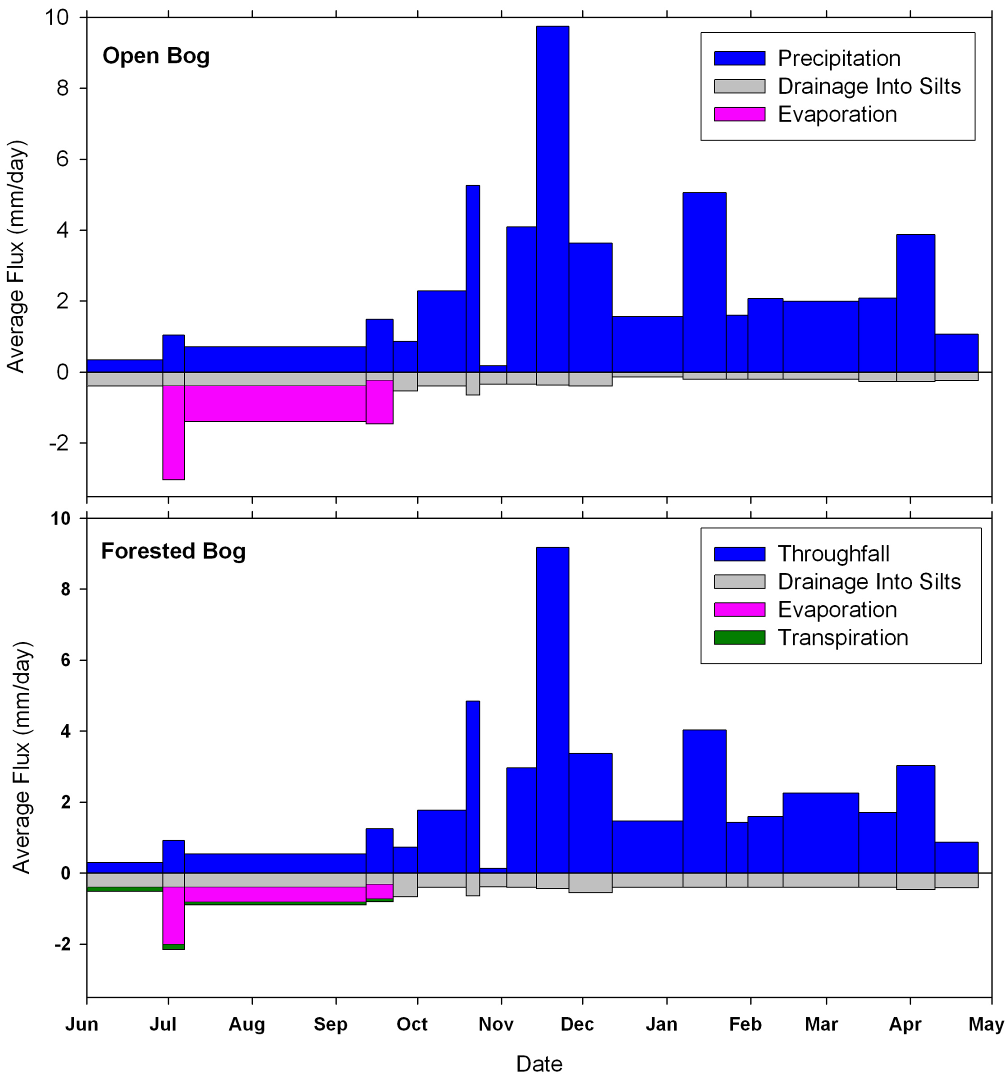

Figure 39: Water Balance from June 2009 to May 2010 for both the open and forested bog sites. Drainage into silt data is estimated from mid-January to March 2010 because pumping created artificially low water levels in the piezometers.

Changes in storage in the forested bog site were much larger than in the open bog (-205.8 mm vs. -118.6 mm) during the summer months. From September 2009 to April 2010, the forested bog showed greater changes in storage than the open bog. 139.1 mm vs. 92.4 mm respectively for two sites. The larger changes in this water balance component are mainly due to the larger fluctuations in water level in the forested bog site than in the open bog site. Soil moisture decreased slightly more in the forested bog site than in the open bog site, which contributed to the greater change in storage as well.

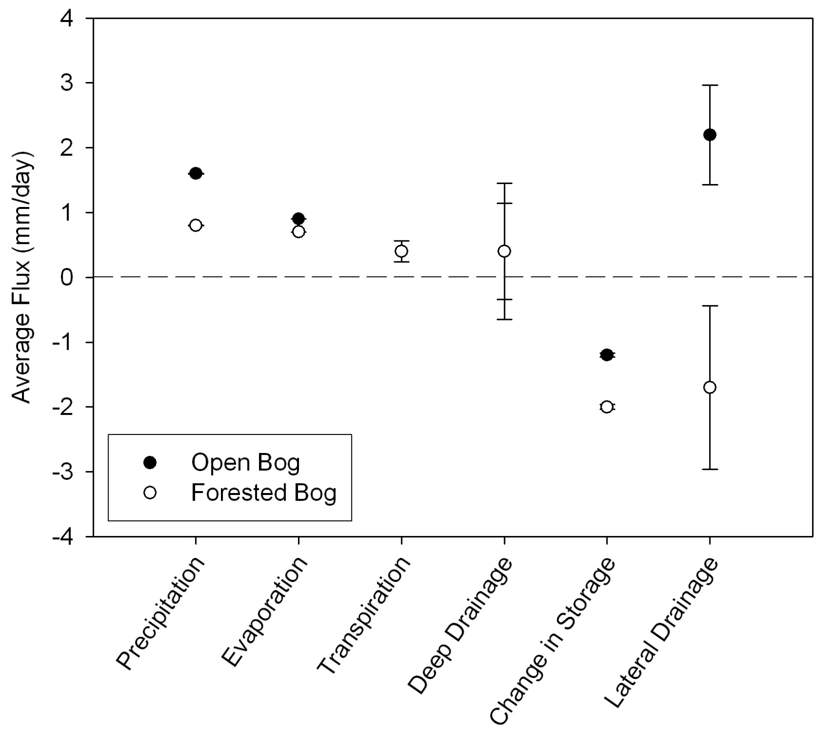

Figure 40: Average flux (mm/day) from the open and forested bog sites with average errors for the summer months (June 10, 2009 to September 20, 2009).

Net lateral discharge during the summer season accounted for 102% (164.2 mm) of precipitation in the open bog site and net precipitation. In the forested bog site it supplemented net precipitation 210% (178.1 mm). During the non-summer months, lateral discharge accounted for 78% (526.3 mm) of the precipitation in the open bog, and

59% (322 mm) of the throughfall in the forested bog. Lateral flow out of the open bog site was thus larger than out of the forested bog site.

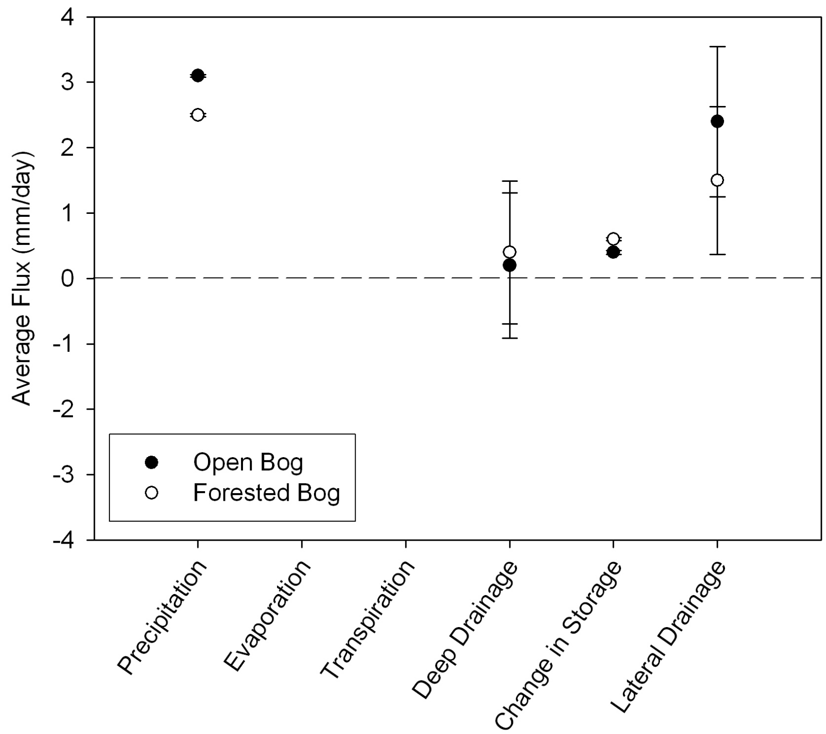

Figure 41: Average flux (mm/day) from the open and forested bog sites with average errors for the winter months (September 21, 2009 to April 26, 2010). Lateral Drainage includes evapotranspiration during the winter months.

3.0 MODEL AND MODEL RESULTS

3.1 Introduction to the model

A simple one-dimension bucket model was created using VENSIM PLE PLUS 5.01e (Ventana Systems 2010) to model the water balance at both plots. Kellner and Halldin (2002) showed that the water balance of Stormossen bog in central Sweden could be modelled as one unit due to uniform fluctuations in water levels for open bog areas and microrelief elements. However, because different processes dominate the water balance in the open bog site and the forested bog site, different models were created for each site in this study.

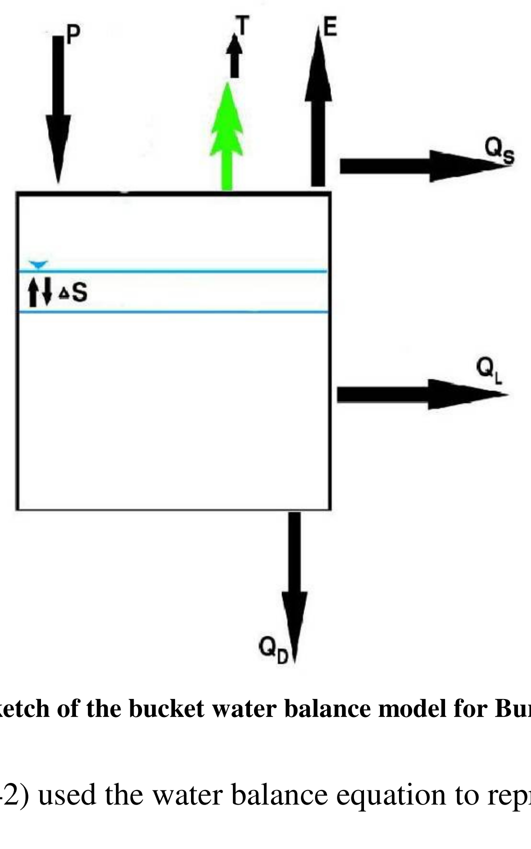

Figure 42: Sketch of the bucket water balance model for Burns Bog.

The model (Figure 42) used the water balance equation to represent the hydrological fluxes at each site. Equation 10 and Equation 11 describe the water balance at the forested and open bog sites respectively,

$$\Delta S = P - I - E - T - Q_T$$

Equation 10: Water balance equation for the forested bog site

$$\Delta S = P - E - Q_T$$

Equation 11: Water balance equation for the open bog site

where ΔS is the change in storage (mm), P is precipitation (mm), I is interception loss (mm), E is evaporation (mm), T is transpiration (mm), and Q_T is discharge (mm). The discharge from each plot is comprised of Q_d, the deep drainage (mm): Q_l, the lateral flow (mm): and Q_s, the surface runoff (mm) (Equation 12):

$$Q_T = Q_d + Q_l + Q_s$$

Equation 12: Discharge components for the bog

The models were created to simulate the water table elevation in the open and forested bog sites of Burns Bog. Both models (Figure 43 and Figure 44) modelled the water level as a stock, but only the open bog model calculated the surface elevation relative to the water table. Both models calculated water level as a level above an arbitrary datum, which was taken as the depth of the lowest piezometer at each site (and is thus different in both models). In the forested bog model, the surface elevation was held constant at 4.57 m above the datum, as measured changes in surface elevation were small (<5 cm). Inputs to the model are daily precipitation (mm), average daily temperature (^oC), daily radiation (MJ/m^2), and season (summer or not summer). Outputs from the model include water level, overland flow, lateral discharge, deep drainage, transpiration (forested bog only), evaporation, and surface elevation (open bog only). The model runs on a daily time step.

Most of the model parameters were based on values measured during the study period of March 2009 to April 2010. However, some parameters were not measured and were either estimated or calibrated (Table 11). Changes in storage were reflected by changes in the height of the water table. A relation between the water level and the discharge was used in the model for the lateral flow calculations. Deep drainage was calculated based on the water level and hydraulic conductivity of the silt. Interception losses were calculated using a relation between open precipitation and throughfall. Evaporation and transpiration losses were calculated using the relation between the ratio of actual evaporation and potential evaporation and the proximity of the water table to the surface of the bog. More details about the calculations are set out in section 4.2.

The model was calibrated by comparing the observed water table elevation measured throughout the summer and fall of 2009 and winter and spring of 2010 to modelled water table elevation. Hydrological modelling studies have shown that calibration and validation based on discharge data is not a reliable test of model success (Seibert and McDonnell, 2002) and that calibration on internal state measures such as water level or soil moisture provide a more robust calibration (Tromp-van Meerveld and Weiler, 2008). Furthermore, a direct volumetric comparison of the estimated discharge and actual outflow was not possible because measuring flow at all ditches draining the bog is not feasible. Once calibration was completed, the model was validated by comparing observed water level data to the values calculated by the model for the June 1, 2010 to May 1, 2011 period.

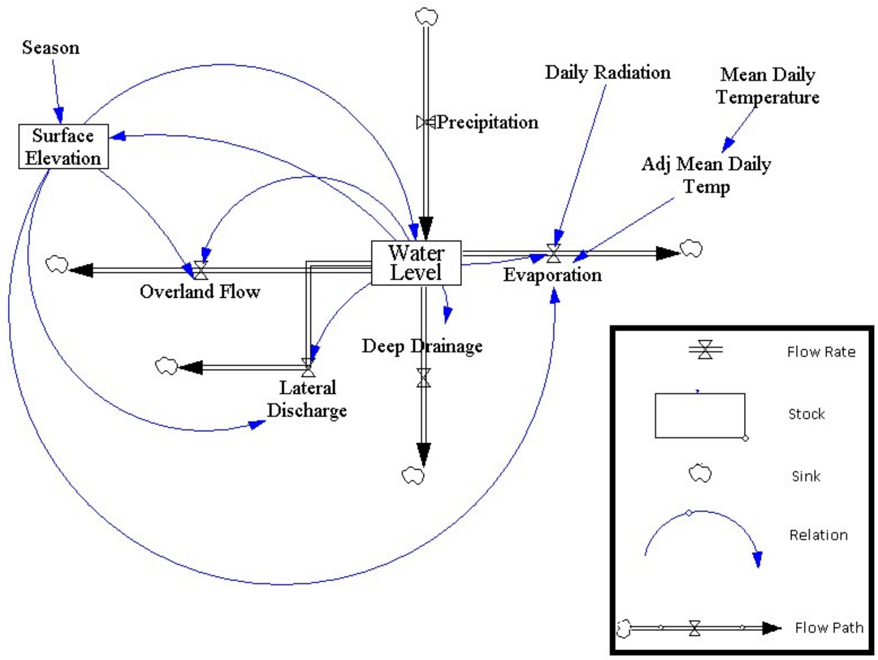

Figure 43: Simulation design in VENSIM PLE PLUS for the open bog site. Sinks in the open bog model are overland flow, lateral drainage, deep drainage, and evaporation. Input data for the model are daily radiation, mean daily temperature, precipitation, and season.

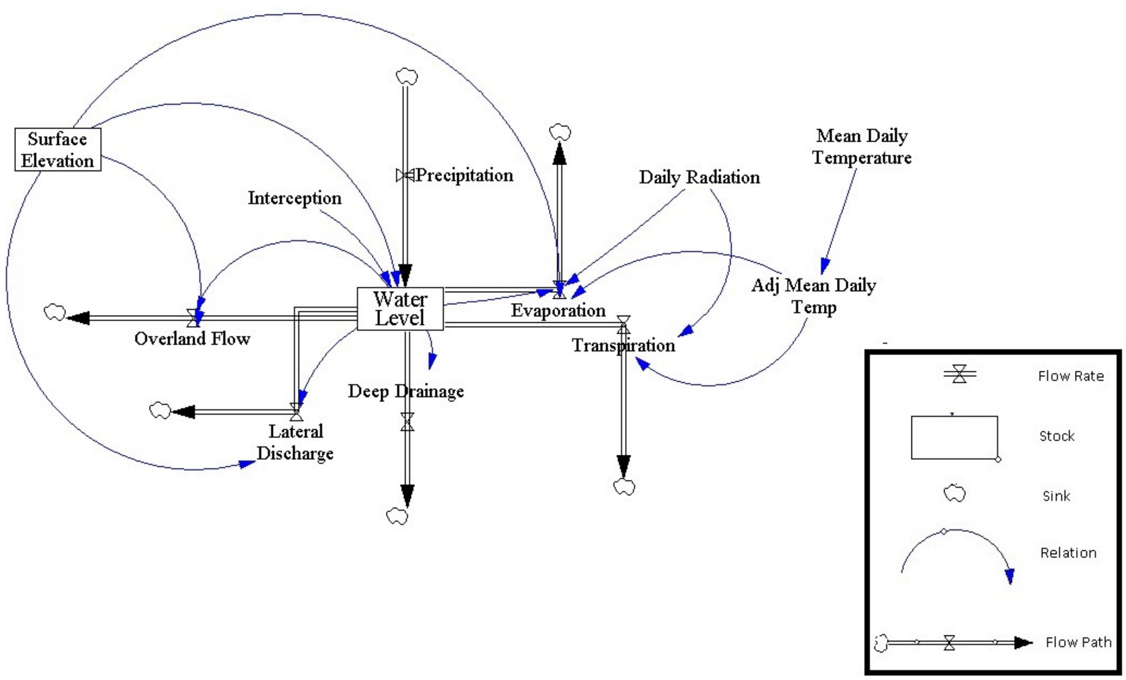

Figure 44: Simulation design in VENSIM PLE PLUS for the forested bog site. Sinks in the forested bog model are overland flow, lateral drainage, deep drainage, evaporation, and transpiration. Input data for the model are daily radiation, mean daily temperature, and precipitation.

Parameter	Open bog model	Forested bog model	Justification
Specific Yield	*See Figure 45*	*See Figure 45*	The size of drainable pores decreases with depth/humification, It was assumed that the decrease was exponential, like the hydraulic conductivity- depth function. The specific yield ranges from 0.2 to 0.5 (Price, 2001)
Overland Flow (Flux)	7 mm/day	7 mm/day	Optimized: A large value was used to model overland flow based on the relatively low resistance to flow when the water is moving over the surface of the peat.
Lateral Drainage (at specified depth below the surface)	0.05 m/m	0.01 m/m	Optimized to fit the observed water table variation
Depth of Constant Lateral Flux	80 mm	400 mm	Optimized to fit the observed water table variation
Lateral Drainage (Flux)	14 mm/day	9 mm/day	Optimized: Large values were justified due to the large pores that allow fast movement of water through the surface layersof the acrotelm.
Evaporation	35% of PET (>10 cm below surface)	37.5% of PET (>10 cm below surface)	Optimized to represent measured values of evaporation during the study period
Transpiration		30% of PET	Optimized to represent measured values of transpiration during the study period

Table 11: List of all parameters that were optimized during model calibration. For a description of these parameters, see section 4.2.

3.2 Components of the model

3.2.1 Water Level

In both the open and forested bog models, the water level was calculated as a function of several fluxes (Equation 13):

$$WL = 1000(P - D_d - D_l - D_o - E - T)$$

when the water level was above the surface

$$WL = \frac{1000}{S_y}(P - D_d - D_l - D_o - E - T)$$

when the water level was below the surface

Equation 13: Water level stock equations for both the open and forested bog models

where *WL* is the water level (m above datum), P is precipitation (mm/day), D_d is deep drainage (mm/day), D_l is lateral discharge (mm/day), D_o is overland flow (mm/day), E is evaporation (mm/day), and *T* is transpiration (mm/day). An exponential relation (similar to the hydraulic conductivity relation to depth to water table) was used for the specific yield (S_y) (Figure 45). The values of specific yield varied from 20% at 2 m depth in the open bog model and 3 m depth in the forested bog model to 50% near the surface.

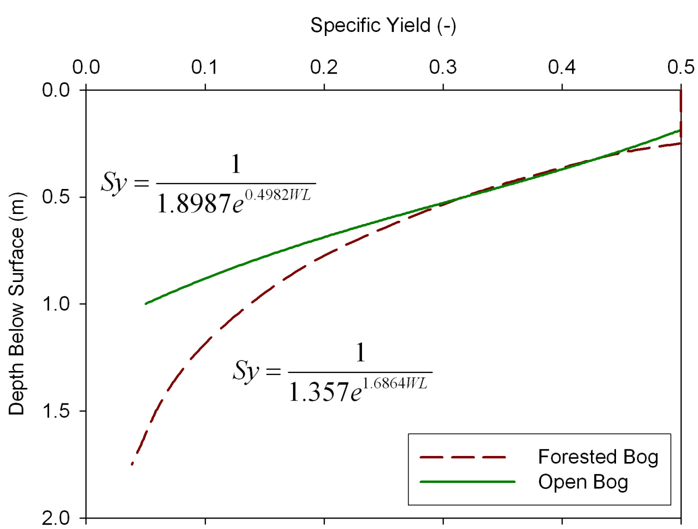

Figure 45: Curves used to estimate the specific yields (S_y) in both the open and forested bogs as a function of water level elevation (*WL*)

3.2.2 Discharge

Overland flow was estimated to be 7 mm/day when the modelled water level elevation was above the surface elevation and 0 mm/day when the water table was below the surface. Deep drainage was modelled based on Darcy's Law:

$$D_d = \frac{dh_{peat}}{dh_{silt}} K_{silt}$$

Equation 14: Deep drainage flux into the underlying silts

where dh_{peat} and dh_{silt} (m above datum) are the elevations of the modelled water level in the peat and in the silts, respectively, and K_{silt} (mm/day) is the hydraulic conductivity of the silt layer. The variable dh_{silt} (mm/day) was assumed to be constant at 3.65 m above datum for the open bog model and at 3.10 m above datum in the forested bog model because the observed variation in water level in the piezometers in the silt was small (Figure 12). K_{silt} was set to the measured hydraulic conductivity: 1.0 mm/day ($1.5\text{x}10^{-8}$ m/s) in the open bog model and 1.3 mm/day ($1.2\text{x}10^{-8}$ m/s) in the forested bog model. In the open bog model, an additional multiplier of 0.88 was used, to represent the average relative difference between the deep drainage flux calculated using the hydraulic head near the surface and that at 3.0 m depth.

When the water level was more than 0.08 m below the surface , lateral discharge in the open bog model was calculated as:

$$D_l = \left(\frac{dh}{dl}\right)0.836e^{-1.865(SE-WL)}$$ Open Bog Model

Equation 15: Lateral Discharge (D_l) equations used when the water level (*WL*) was 0.08 m or more below the surface elevation (*SE*) in the open bog model and 0.4 m or more below the surface in the forested bog model

When the water level was more than 0.4m below the surface, lateral discharge in the forested model was calculated as:

$$D_l = \left(\frac{dh}{dl}\right)0.964e^{-1.5028(SE-WL)}$$ Forested Bog Model

Equation 16: Lateral Discharge (D_l) equations used when the water level (*WL*) was 0.08 m or more below the surface elevation (*SE*) in the open bog model and 0.4 m or more below the surface in the forested bog model

where $\frac{dh}{dl}$ is the estimated lateral hydraulic gradient (m/m), SE is the modelled surface elevation (m above datum), and WL is the modelled water level (m above datum). These equations represent the measured change in hydraulic conductivity with depth (Table 6). $\frac{dh}{dl}$ was assumed to be 0.01 m/m in the forested bog model and 0.05 m/m in the open bog model. When the depth to water level was less than 0.08 m in the open bog model and 0.4 m in the forested bog model, the lateral flux was assumed to be 14 and 9 mm/day respectively. This was justifiable by the high hydraulic conductivity of the acrotelm.

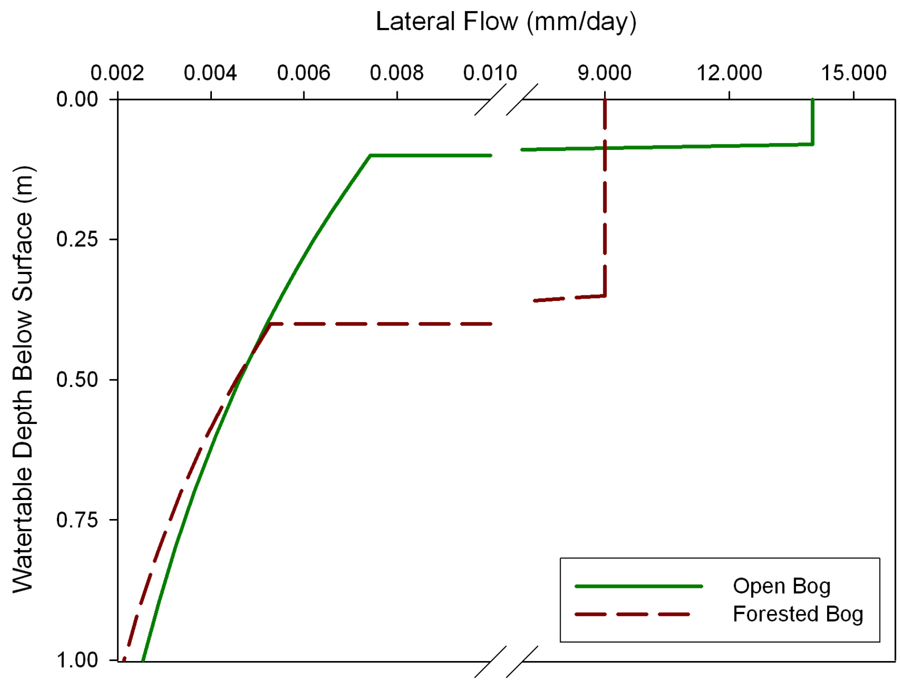

Figure 46: Modelled lateral flow in the open and forested bog models as a function of water table depth below the surface

3.2.3 Evaporation and Transpiration

A comparison between the Kucerova et al. (2010) method (Equation 2) and the Hamon (1963) and Hargreaves (1985) methods to calculate potential evapotranspiration (PET) was made to determine the feasibility of using only temperature data to estimate the potential evapotranspiration. The Hargreaves method (1985) required only maximum and minimum air temperatures, which makes the method very attractive, as fewer variables needed to be monitored:

$$ET_o = 0.0023(T_{\max} - T_{\min})0.5(T_{mean} + 17.8)(R_A)$$

Equation 17: The Hargreaves (1985) method to estimate potential evapotranspiration

where ET_o is the potential evapotranspiration (mm/day), $T_{\max}$ and $T_{\min}$ are the maximum and minimum daily air temperatures (°C), T_{mean} is the mean daily air temperature (°C), and R_A is the average daily extraterrestrial radiation (MJ/m^{-2}/day). R_A is calculated as:

$$R_A = \frac{24(60)}{\pi} G_{sc} d_r [w_s \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(w_s)]$$

Equation 18: Equation for the average daily extraterrestrial radiation

where ϕ is the latitude of the study area in radians, G_{sc} is the solar constant (0.0820 MJ/m^{-2}/min^{-1}) and δ is the declination (in radians), estimated as:

$$\delta = 0.4093 \sin\left(2\pi \frac{284 + J}{365}\right)$$

Equation 19: Equation for the estimation of the declination in the Hargraeves equation

where J is the day of the calendar year and d_r is the relative distance from the sun, calculated as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

Equation 20: Equation for the calculation of the relative distance from the sun

and w_s is the sunset hour angle in radians, calculated as:

$$w_s = \arccos\left[-\tan(\phi)\tan(\delta)\right]$$

Equation 21: Calculation of the sunset hour angle in radians

Solar radiation was estimated from the extraterrestrial radiation as:

$$R_s = 0.16(T_{\max} - T_{\min})0.5 R_A$$

Equation 22: Estimation of the solar radiation from the extraterrestrial radiation

The Hamon (1963) method requires only the mean daily temperature and calculates potential evapotranspiration as:

$$PET = 0.1651 \cdot L_d \cdot \rho_{SAT}$$

Equation 23: The Hamon (1963) equation to estimate the potential evapotranspiration

where PET is the potential evapotranspiration (mm/day), L_d is the day length from sunrise to sunset in multiples of 12 hours, and ρ_{sat} is the saturated vapour density (g/m3), calculated as:

$$\rho_{sat} = \frac{2.167 e_{sat}}{T + 273.3}$$

Equation 24: Calculation of the saturated vapour density

where e_{sat} is the saturated vapour pressure (mbar) at the given temperature, T (^{o}C) and is calculated as:

$$e_{sat} = 6.108 e^{\frac{17.26939T}{T+237.3}}$$

Equation 25: Calculation of the saturation vapour pressure

The calculated solar radiation in the Hargreaves method (1985) was consistently higher than the radiation measured at the Chorus meteorological station (Figure 47). As a result, the Hargreaves method (1985) estimated a much greater potential evaporation than the Kucerova et al. (2010) method and the Hamon (1963) method (Figure 48). Lu et al. (2005) reported similar findings in a study of different methods to calculate PET for the south-eastern United States. They showed that the Hargreaves method overestimated PET compared to other temperature based methods for estimating potential evapotranspiration.

It was decided to use the Kucerova et al. (2010) method for the calculation of the potential evapotranspiration in the model because it was most representative of the measured evapotranspiration during the summer, and fits the assumption that evapotranspiration is negligible throughout the winter months.

Evaporation and transpiration were set equal to the potential evapotranspiration (Equation 2) when the water level was within 0.2 m of the surface. When the water level was lower, evaporation was assumed to be 35% of the potential evaporation in the open bog model and 37.5% of potential evaporation in the forested bog model. Evaporation was set to 0 mm/day when the mean daily temperature resulted in negative values of potential evapotranspiration. Transpiration was treated independent of water level and was set at 35% of the potential evapotranspiration to match the measured transpiration rates.

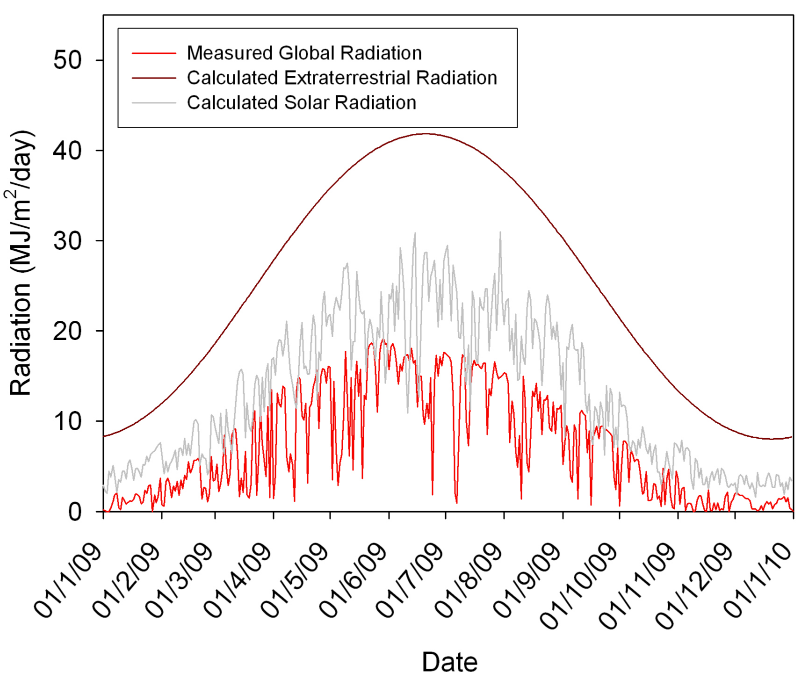

Figure 47: Global radiation measured at the Chorus meteorological station peaked earlier and was lower than the solar radiation calculated from the extraterrestrial radiation (Equation 17).

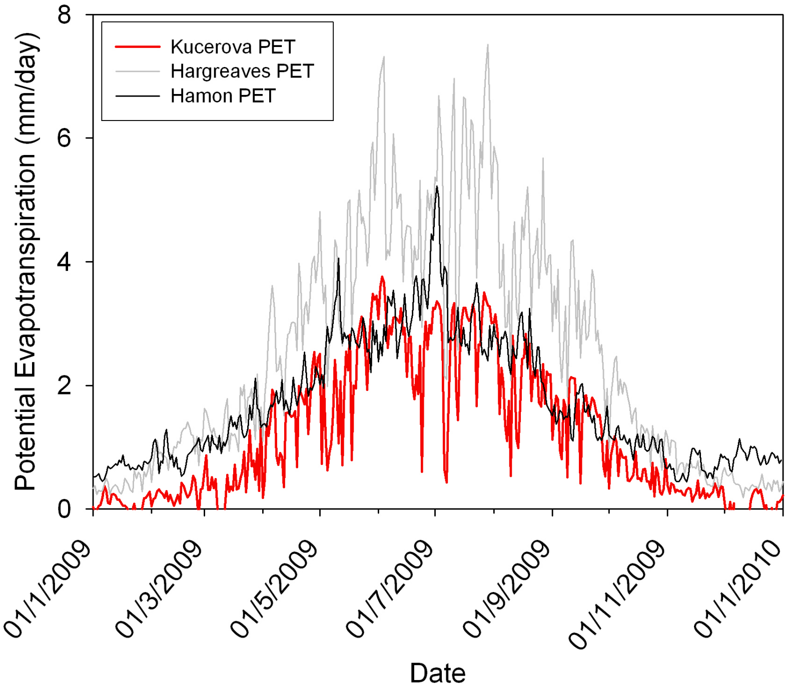

Figure 48: The potential evapotranspiration calculated using the Kucerova method (2010) and Hamon (1963) method were significantly lower than the potential evapotranspiration calculated from the Hargreaves method.

3.2.4 Interception

The average throughfall in the forested bog area was 88% of the precipitation. Thus, in the forested bog model, the interception rate was set at 12%, resulting in a modelled input of 88% of the precipitation.

3.2.5 Surface Elevation

Even though surface elevation data was available for the calibration period, surface elevation was calculated from the water level elevation in the open bog model because it allowed for the development of a model that required less input data. In the open bog model the surface elevation was assumed to be 4.85 m above the datum if the water level was below 4.60 m. If the water level elevation was greater than 4.76 m, then the surface elevation was estimated to be 4.91 m above the datum. Between 4.60 m and 4.76 m above the datum, the surface elevation in summer (June 1 to Sept 30) was calculated as:

$$SE = 0.6313WL + 1.9509$$

(if the water level was between 4.60 and 4.65 m above the datum)

$$SE = 0.1695WL + 4.107$$

(if the water level was between 4.65 and 4.755 m above the datum)

Equation 26: Equations used to calculate the surface elevations in the summer months (June 1 to September 30) when the water level in the open bog site was between 4.6 and 4.755 m above the datum

and in winter as:

$$SE = 0.0741WL + 4.511$$

(if the water level was between 4.64 and 4.775 m above the datum)

$$SE = 0.9034WL + 0.5509$$

(if the water level was between 4.775 and 4.81 m above the datum)

Equation 27: Equations used to calculate surface elevations in the open bog site during the non-summer months (October 1 to June 1) or when the water level was between 4.64 and 4.81 m above the datum set at the base of the 5.0 m piezometer.

The surface elevation was held constant in the forested bog model at 4.57 m above the datum because mire breathing during the 2009/2010-study period was less than 5 cm.

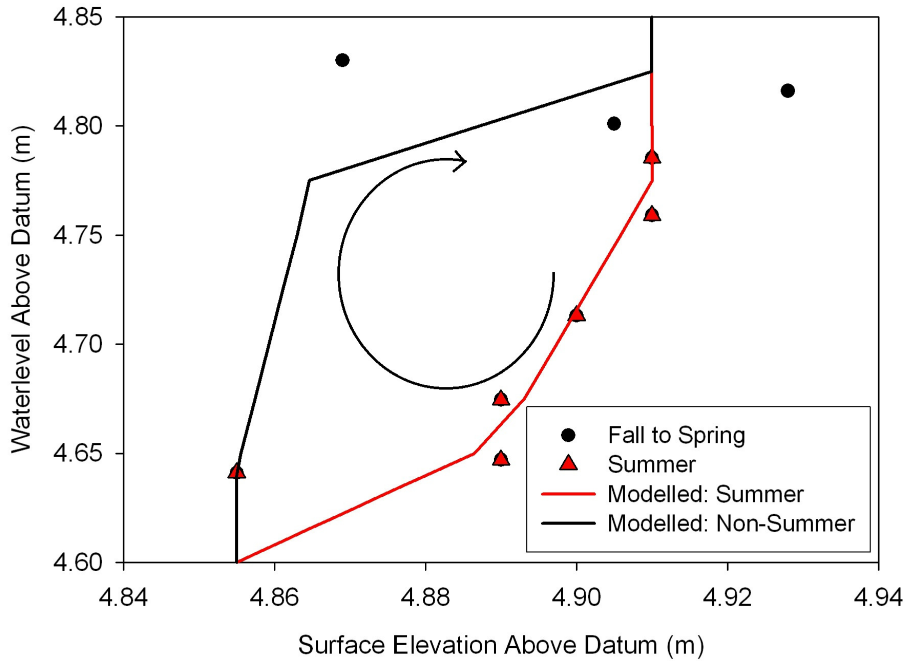

Figure 49: Observed surface elevation-water level data for the open bog site and the modeled relation used to calculate the surface elevation during the summer (June – Sept) and 'non-summer' (October-May) months.

3.3 Model Results

The models were calibrated with water level data from the June 1, 2009 to June 1, 2010 period. The models were evaluated using the Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{\sum_{t=1}^{T} (WL^t_o - WL^t_m)^2}{\sum_{t=1}^{T} (WL^t_o - \overline{WL_o})^2}$$

Equation 28: Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) for the fit of the model against observed data

where E is the Nash-Sutcliffe efficiency, WL^t_o is the observed water level at time t, WL^t_m is the modelled water level at time t, WL_o is the observed mean water level throughout the modelling period. A Nash-Sutcliffe efficiency of 1 represents a perfect fit. A value of 0 represents a fit that is as good as the average water level, and a negative value represents a fit that is worse than the average. The mean absolute difference between the observed and modelled water level and the correlation coefficient between the observed and modelled water level were also calculated (Table 14 and Table 15).

Both models were successful in representing the water levels. The modelled rise in water level in fall was slower than observed (Figure 50), leading to the hysteresis in the observed vs. modelled water level graphs (Figure 51). Modelled water levels during the summer months were underestimated during some periods and overestimated during other periods (Figure 52). The water levels were over-estimated during the non-summer months (Figure 50 and Figure 51).

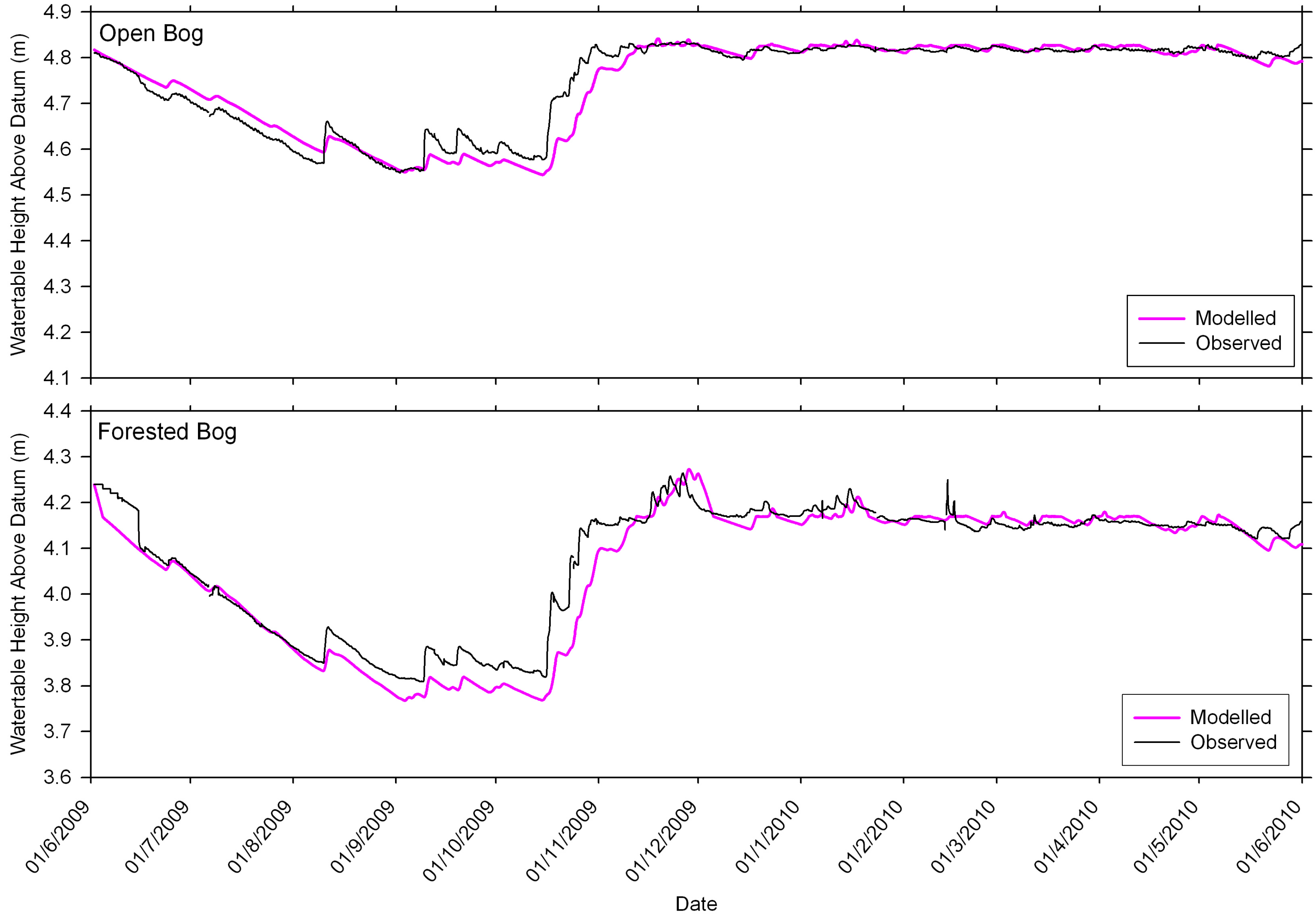

Figure 50: Observed and modelled water level in the open and forested bog site for the calibration period (June 1, 2009 to June 1, 2010). The Nash-Sutcliffe efficiency was 0.975 and 0.906 for the open bog and forested bog model respectively. The mean absolute difference was 0.02 and 0.03 m for the open and forested bog model respectively.

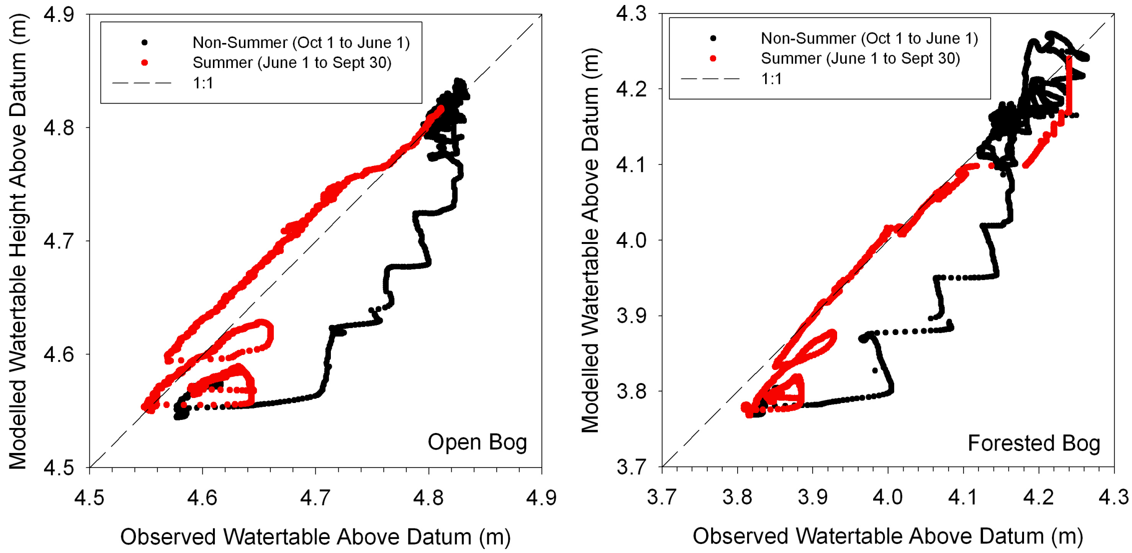

Figure 51: Scatter plots of observed and modelled water table elevations for both the open and forested bog model. The R^2 was 0.96 and 0.97 for the open bog and forested bog models respectively.

3.4 Sensitivity Analysis

A one parameter-at-a-time sensitivity analysis was performed to evaluate the model's sensitivity to the parameters that were estimated or are known to have a large uncertainty. The open bog and forested bog models were very sensitive to the changes in the hydraulic conductivity in the silt layer, as it controls the amount of water leaving the bog through deep drainage (Table 14 and Figure 53). A Changee of an order of magnitude in the hydraulic conductivity of the silt resulted in large changes in the modelled water level. The model was more sensitive to increases in the hydraulic conductivity of the silt than decreases in the hydraulic conductivity of the silt (Table 15 and Figure 54). Furtherstudies of Burns Bog will thus need to measure the hydraulic conductivity of the underlying silts at more locations to obtain a better estimate of the hydraulic conductivity.

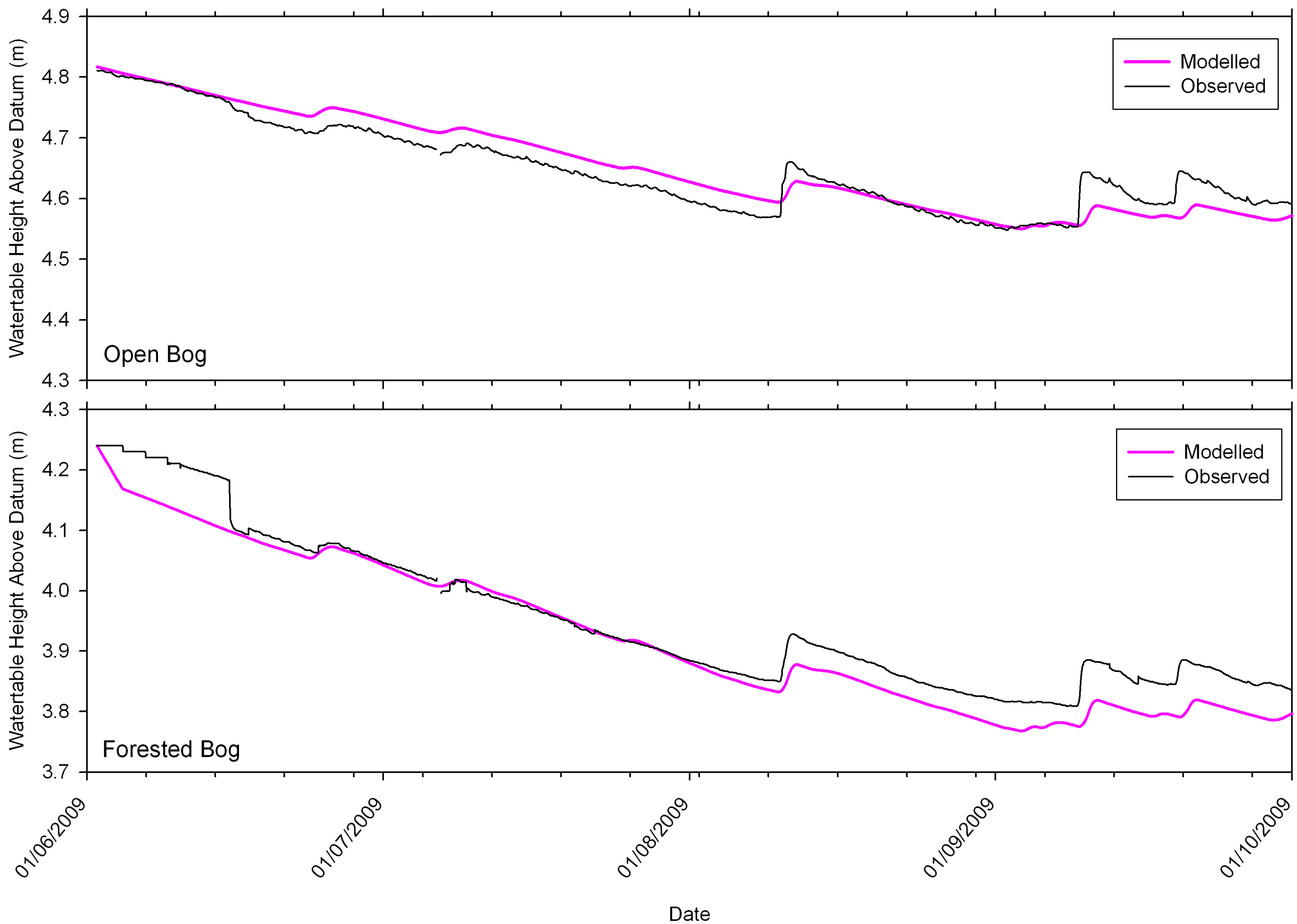

Figure 52: Observed and modelled water level during the summer months (June 1 to September 30, 2009) for the open bog and forested bog sites. The model had a Nash-Sutcliffe efficiency of 0.999 and 0.895 for the open bog model and the forested bog model the summer period respectively. For the model fit for the entire calibration period, see Figure 50

The open bog model was also sensitive to changes in the evaporation, with increases in evaporation leading to an underestimation of the water level in the summer period. In both models, changes in overland flow parameters did not affect the model results much.

3.5 Validation

The model was also validated by comparing the measured water balance components and the modelled fluxes (Table 16 and Table 17). Lateral drainage was not measured but calculated through the water balance equation, whereas lateral drainage in the model was simulated as a function of an optimized lateral hydraulic gradient parameter and a fitted relationship between hydraulic conductivity and water level. The observed lateral drainage was much greater than the modelled lateral drainage. The

	Original Value	**New Value**	**New Goodness of Fit**	**New Value**	**New Goodness of Fit**
Overland Flow	7 mm/day	5 mm/day	E=0.975 R^2=0.962 AAE=0.02 m	11 mm/day	E=0.975 R^2=0.9628 AAE=0.02 m
Lateral Discharge	14 mm/day	5 mm/day	E=0.964 R^2=0.952 AAE:0.02 m	20 mm/day	E=0.975 R^2=0.963 AAE=0.02 m
Lateral Discharge (gradient)	0.05 m/m	0.1 m/m	E=0.971 R^2=0.960 AAE=0.02 m	0.01 m/m	E=0.978 R^2=0.964 AAE=0.02 m
Deep Drainage (Conductivity)	$1.47x10^{-8}$ m/s	$6.47x10^{-8}$ m/s	E=0.880 R^2=0.989 AAE=0.04 m	$6.47x10^{-9}$ m/s	E=-0.823 R^2=0.743 AAE=0.44 m
Evaporation	35% of PET	15% of PET	E=0.936 R^2=0.982 AAE=0.03 m	55% of PET	E=0.864 R^2=0.943 AAE=0.04 m

Table 12: Sensitivity of the model parameters that were optimized for the open bog model. Parameters were increased and decreased to determine the model's sensitivity to the estimated and calibrated values. The calibrated model had an E=0.975, R^2=0.963, and AAE=0.02 m. E=Nash-Sutcliffe Efficiency, AAE= average absolute error.

	Original Value	New Value	New Goodness of Fit	New Value	New Goodness of Fit
Overland Flow	7 mm/day	5 mm/day	E=0.906 R^2=0.972 AAE=0.03 m	11 mm/day	E=0.906 R^2=0.972 AAE=0.03 m
Lateral Discharge	7 mm/day	5 mm/day	E=0.868 R^2=0.957 AAE=0.03 m	20 mm/day	E=0.891 R^2=0.971 AAE=0.03 m
Lateral Discharge (gradient)	0.01 m/m	0.1 m/m	E=0.888 R^2=0.971 AAE=0.03 m	0.01 m/m	E=0.907 R^2=0.972 AAE=0.02 m
Deep Drainage (Conductivity)	$1.2x10^{-8}$ m/s	$6.47x10^{-8}$ m/s	E: 0.920 R^2=0.981 AAE:0.04 m	$6.47x10^{-9}$ m/s	E=-10.248 R^2=0.838 AAE=0.43 m
Evaporation	30% of PET	15% of PET	E=0.957 R^2=0.980 AAE=0.03 m	55% of PET	E=0.074 R^2=0.956 AAE=0.07 m
Transpiration	35.7% of PET	15% of PET	E=0.914 R^2=0.978 AAE=0.02 m	55% of PET	E=0.476 R^2=0.946 AAE=0.02 m

Table 13: Sensitivity of the model parameters that were optimized for the forested bog model. Parameters were increased and decreased to determine the model's sensitivity to the estimated and calibrated values. The calibrated model had an E=0.906, R^2=0.93, and AAE=0.03 m. E=Nash-Sutcliffe Efficiency, AAE= average absolute error.

modelled deep drainage flux was also much greater than the calculated deep drainage flux. This can in part be due to the fact that there is no lateral inflow into the forested bog model, while a net lateral influx into the plot was observed (Table 17).

The surface elevation in the open bog was represented well during the summer and winter months (Figure 55). Some overestimation occurred during the transition period between summer and winter, however, higher resolution data was not available to provide a more accurate measure of the goodness of fit.

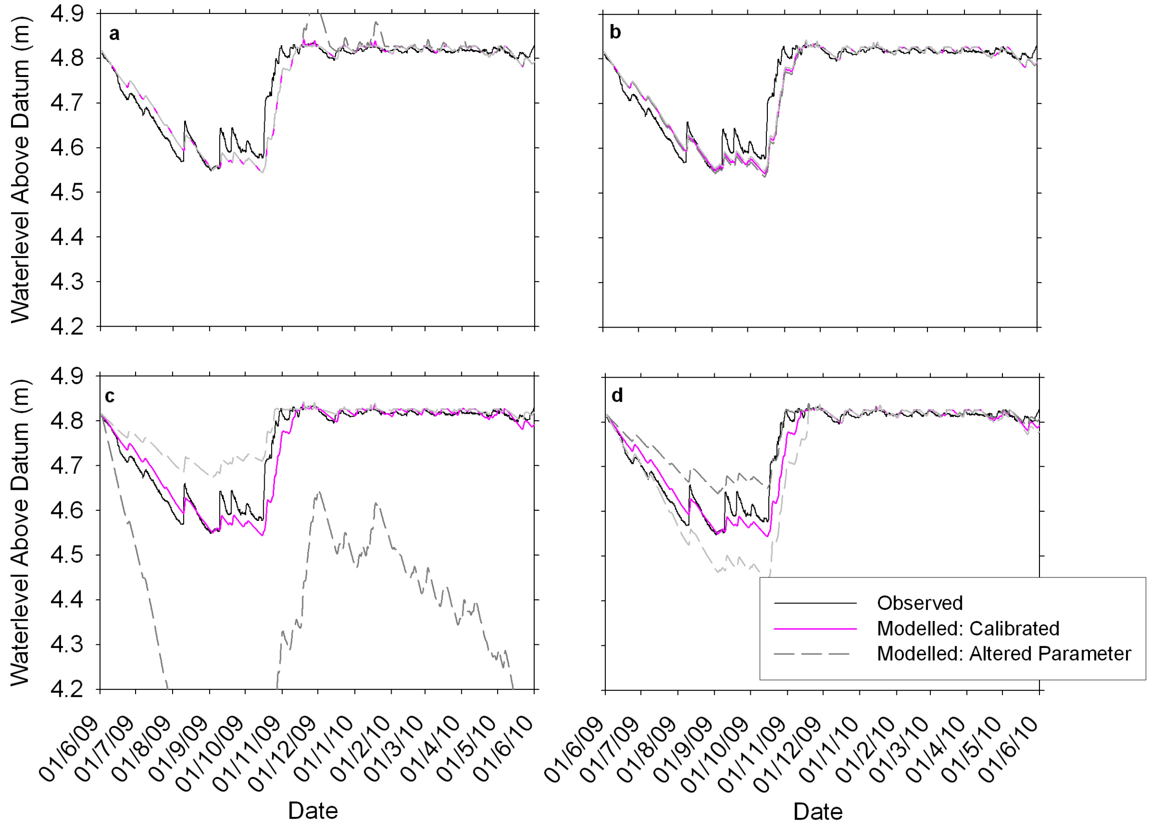

Figure 53: One parameter-at-a-time sensitivity analysis results for the lateral discharge (a), deep drainage (b), hydraulic conductivity of the silt (c), and evaporation (d) parameters (see Table 18) in the open bog model.

The model was also validated for the June 1, 2010 to May 1, 2011 period. Both models were successful in representing the water levels during this period (Figure 56). The forested bog model performed well early in summer (May to July), but progressively overestimated the amount of water leaving the bog through evapotranspiration and deep drainage thereafter. The open bog model represented the data during the validation period better than the forested bog model (Table 14 and Table 15), as the end of the summer period was better modelled in the open bog model. The modelled water level in the open bog model was slightly lower than the observed water level during summer of 2010 and spring of 2011, whereas the forested bog model calculated water levels slightly above the observed water level. Both models were neither able to model the quick changes in water level at the end of September 20010, similar to the calibration results.

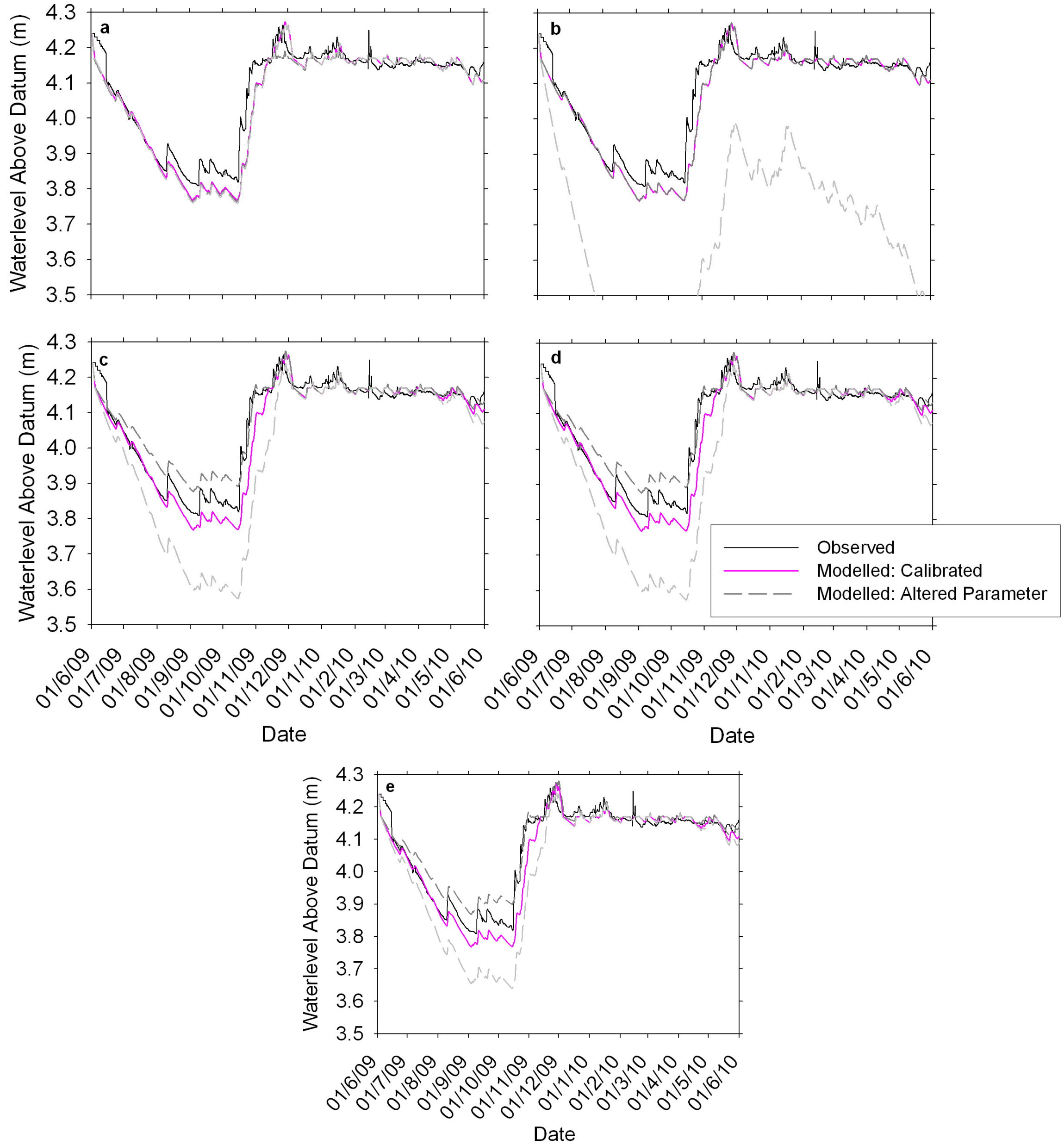

Figure 54: One parameter-at-a-time sensitivity analysis results for the lateral discharge (a), deep drainage (b), transpiration (c), evaporation (d), lateral discharge (e), parameters (see Table 18) of the forested bog model.

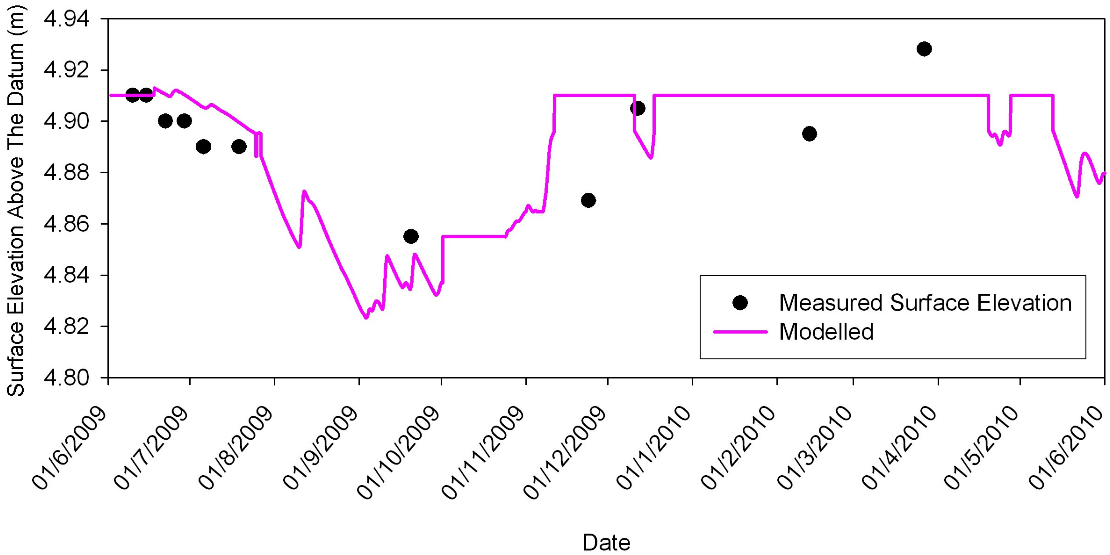

Figure 55: Observed surface elevation and modelled surface elevation calculated from water level elevation for the open bog model (average error=0.005 m, R2=0.438)

OPEN BOG	Calibration Period	Validation Period
Nash-Sutcliffe Efficiency	0.975	0.999
Correlation Coefficient	0.96	0.96
Average Absolute Error (m)	0.02	0.03

Table 14: Goodness of fit of the open bog model during the calibration (June 1, 2009 to June 1, 2010) and validation (June 1, 2010 to May 1, 2011) periods.

FORESTED BOG	Calibration Period	Validation Period
Nash-Sutcliffe Efficiency	0.906	0.497
Correlation Coefficient	0.97	0.93
Average Absolute Error (m)	0.03	0.05

Table 15: Goodness of fit of the forested bog model during the calibration (June 1, 2009 to June 1, 2010) and validation (June 1, 2010 to May 1, 2011) periods.

		Open Bog: Averaged Daily Water Balance Components (mm/day)					
		Evaporation		Deep Drainage		Lateral Drainage	
Period	Duration (days)	Observed	Modelled	Observed	Modelled	Observed	Modelled
June 10 - June 14	4	0	1.9	0.6	3.1	7.1	0.1
June 14 - June 22	8	1.0	0.6	0.6	0.8	2.0	0.0
June 22 - June 29	7	1.1	0.9	0.5	1.2	4.7	0.0
June 29 - July 6	7	2.2	1.9	0.5	2.4	-2.2	0.1
July 6 - July 20	14	0.9	3.2	0.4	4.7	3.4	0.1
July 20 - September 20	62	0.8	1.3	0.3	1.9	1.8	0.1
SUMMER TOTAL (mm)	***102***	***94.0***	***81.4***	***38.4***	***115.2***	***164.2***	***3.3***

Table 16: Average daily observed and modelled fluxes in the open bog. Negative lateral drainage means water entering the site from adjacent areas.

		Forested Bog: Averaged Daily Water Balance Components (mm/day)							
		Evaporation		Transpiration		Deep Drainage		Lateral Drainage	
Period	Duration (days)	Observed	Modelled	Observed	Modelled	Observed	Modelled	Observed	Modelled
June 10 - June 14	4	0.0	0.6	0.0	1.2	0.5	1.1	-7.9	0.0
June 14 - June 22	8	0.9	0.5	0.4	1.0	0.5	1.3	-6.6	0.0
June 22 - June 29	7	0.9	0.4	0.3	0.8	0.5	0.7	-3.0	0.0
June 29 - July 6	7	2.1	0.5	0.5	1.0	0.5	1.0	-6.0	0.0
July 6 - July 20	14	0.8	0.5	0.3	1.0	0.5	0.9	-3.9	0.0
July 20 - September 20	62	0.5	0.4	0.4	0.8	0.3	0.8	0.0	0.0
SUMMER TOTAL (mm)	***102.0***	***34.2***	***46.5***	***38.4***	***87.2***	***39.6***	***86.7***	***-178.1***	***0.4***

Table 17: Average daily observed and modelled fluxes in the forested bog. Negative lateral drainage means that more water is entering the site from adjacent areas than is leaving the site as lateral drainage.

MONTH	INPUTS (mm/month)	OUTPUTS (mm/month)				
	Precipitation	**Deep Drainage**	**Evaporation**	**Lateral Drainage**	**Overland Flow**	**Change in Storage**
June	38.0	38.0	22.6	1.1	0.0	-51.6
July	0.4	35.5	31.7	1.0	0.0	-130.8
August	83.4	31.9	23.2	0.9	0.0	51.5
September	175.0	36.9	19.9	34.8	0.0	277.0
October	123.1	40.4	10.6	42.5	0.0	3.0
November	142.5	53.9	7.1	165.6	0.0	5.0
December	183.6	25.3	3.1	95.6	0.0	-1.9
January	217.7	40.8	5.6	173.4	0.0	1.0
February	86.7	37.2	4.1	45.3	0.0	-15.3
March	151.6	40.0	12.3	57.6	0.0	11.0
April	100.8	40.4	17.0	86.1	0.0	8.8
TOTAL	**1337.8**	**435.7**	**168.4**	**726.3**	**0.0**	**-22.4**

Table 18: Monthly modelled fluxes for the open bog between June 1, 2010 to May 1, 2011

June 1, 2010 to May 1, 2011 Model Results: FORESTED BOG model

MONTH	INPUTS (mm/month)	OUTPUTS (mm/month)						
	Precipitation	Interception Loss	Deep Drainage	Evaporation	Transpiration	Lateral Drainage	Overland Flow	Change in Storage
June	38.0	4.6	30.3	12.9	25.9	0.1	0.0	-91.8
July	0.4	0.0	25.8	18.1	36.2	0.1	0.0	-207.9
August	83.4	10.0	20.5	13.2	26.5	0.1	0.0	57.6
September	175.0	21.0	28.0	8.2	16.4	5.4	0.0	463.9
October	123.1	14.7	34.0	4.6	9.3	45.1	0.0	5.6
November	142.5	17.1	45.7	2.0	4.0	163.6	0.0	32.2
December	183.6	22.0	21.7	0.7	1.5	110.7	0.0	-27.3
January	217.7	26.1	34.8	1.2	2.3	181.6	0.0	1.3
February	86.7	10.4	31.3	1.1	2.1	49.2	0.0	-16.3
March	151.6	18.2	33.7	3.8	7.7	67.2	0.0	10.4
April	100.8	12.1	34.2	6.3	12.7	90.5	0.0	12.7
TOTAL	**1337.8**	**156.2**	**353.2**	**75.7**	**151.3**	**740.7**	**0.0**	**-55.2**

Table 19: Monthly modelled fluxes for the forested bog between June 1, 2010 to May 1, 2011

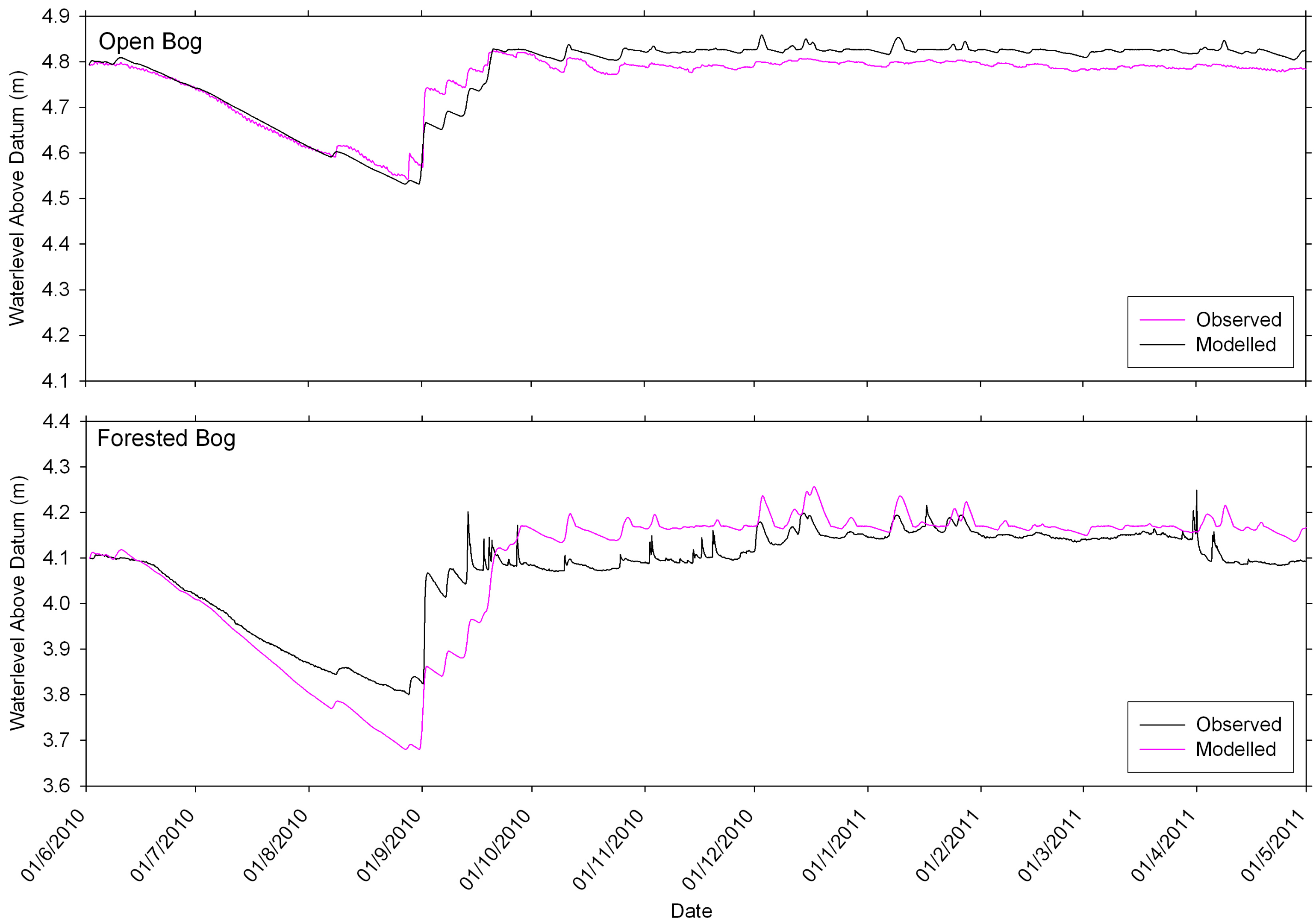

Figure 56: Observed and modelled water levels for the open bog and forested bog during the validation period. The open bog model had a Nash-Sutcliffe efficiency of 0.999, an average absolute error of 0.03 m, and an r^2 of 0.965. The forested bog model had a Nash-Sutcliffe efficiency of 0.497, an average absolute error of 0.05 m, and an r^2 of 0.929.

3.6 Climate Change and Land Use Scenarios

3.6.1 Land Use Scenario

A simulation without transpiration and interception loss was done to model the effects of tree removal from the forested bog site on water levels. Since transpiration and interception contribute to water loss from bog areas, a possible remediation strategy would be to remove the trees from the forested areas. The model showed significant differences in the water level elevation when transpiration and interception were both removed from the model. However, caution needs to be used when interpreting these results, as the model does not take into account factors such as potential wind resistance changes and shading that the tree stands may provides. Also, it is uncertain if the removal of the trees would alter the structure of the peat and thus and as a result, hydraulic conductivity and other characteristics of the peat, and thus the timing and magnitude of the response of the water level elevation to precipitation events and lateral flow out of the forested site. Furthermore, the calibration results show that while the model can simulate the water levels reasonably well it does not accurately simulate the individual fluxes. Thus caution must be used when the model is used.

More research is required to create a better understanding of the effects that tree stands have on the forested bog water balance. However, this modelling experiment suggests that the model can be used this way and that removing trees may be useful in bog restoration when forests have encroached into previously open bog areas.

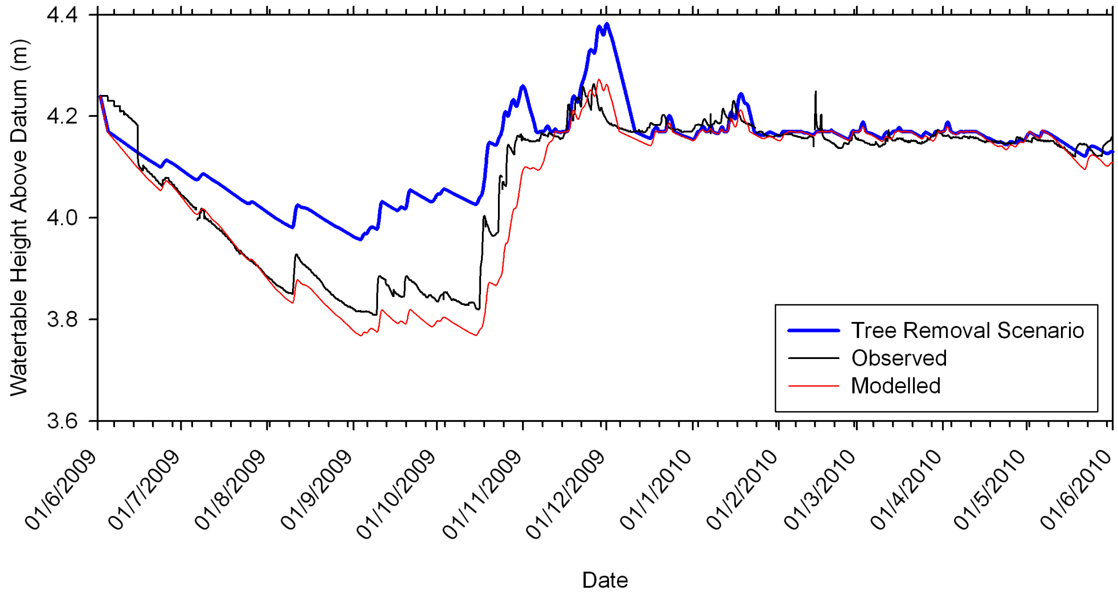

Figure 57: Observed and modelled water levels for the forested bog site from June 1, 2009 to June 1, 2010 compared with modelled water levels without interception loss and transpiration losses.

3.6.2 Climate Change Scenario

The Coupled General Circulation Model and the Hadley Centre Model project an increase of global temperature of up to 3.5 ˚C by 2100 for the Greater Vancouver Regional District (Taylor and Langlois, 2000). Further, the climate models also project an increase in precipitation of up to 30% from September to March, and a decrease of up to 30% in April to June (Taylor and Langlois, 2000). Decreases in precipitation in April to June could impact the health of the bog as it results in a longer dry season. As established earlier, the bog receives ample precipitation during the winter months. However, it is during the dry season that the health of a bog is determined.

Both models were run with the predicted changes in temperature and precipitation . Data from June 1, 2009 to June 1, 2010 was altered to create a new time series of input data by (1) increasing the temperature by 3.5°C or (2) changing the precipitation by 30%

or (3) changing both temperature and precipitation. The third scenario caused the water level to decrease more rapidly at the beginning of the summer months (June to July), reaching lower water levels than were observed in 2009 at the end of the summer period (Figure 58).

However, caution must be used when interpreting the results of these model simulations, as the adjustments in temperature and precipitation are based on only one year of meteorological data and the models are sensitive to some of the optimized parameters. Also these models do not take into account any changes to vegetation or any of the other feedback processes (such as changes in peat structure during severe droughts). However, these results show that this model could be useful for future climate impact studies.

3.7 Model Conclusion

The models can represent the observed water level well but do not accurately represent all the observed fluxes. This is in part because these 2-dimensional models do not take lateral inflow into account. For this, 3-dimensional models should be created. However, the results of this study show that simple models can be useful to understand the hydrology of Burns Bog and likely, changes due to land use and/or climate change.

In undisturbed bogs, water level changes may be modelled as a unit (Kellner and Halldin, 2002), but in the case of Burns Bog, where significant areas of the bog are still recovering from peat mining, a large fire, and where other areas are influenced by forest encroachment, such an approach may not be appropriate and different models may be required for each environment. The models created in this study represent undisturbed open bog areas and forested bog areas. Caution must be used when utilizing the results of these models for the entire bog, as there are large areas of Burns Bog that have been severely disturbed by mining, or have been affected by fire. For example, it is unknown how the large 2005 forest fire may have altered the hydrology of the bog.

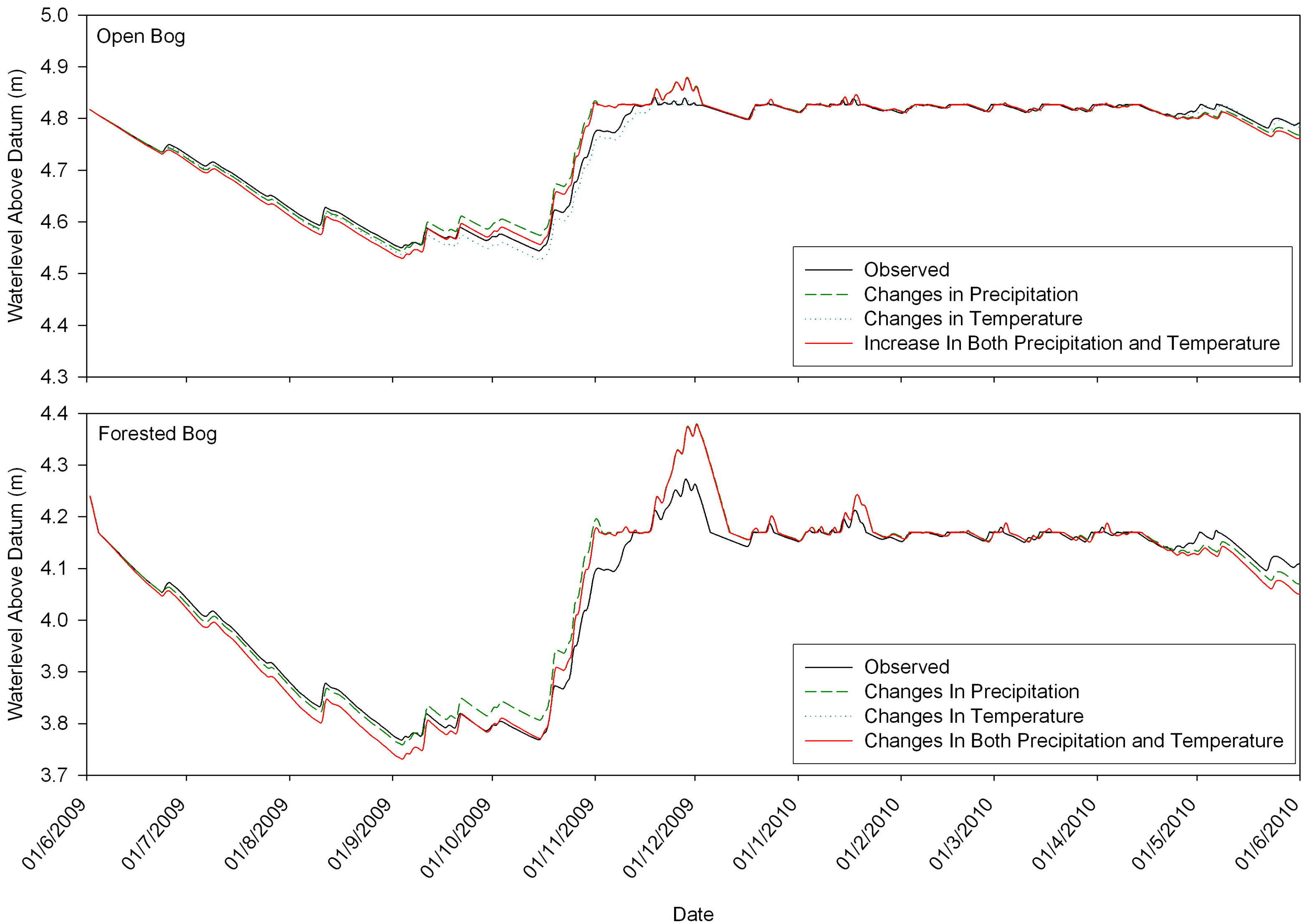

Figure 58: Open and forested bog models runs with when the temperature is increased by 3.5°C and precipitation is increased in the winter months and decreased in the summer months.

4.0 CONCLUSIONS

A water balance study of an open bog and a forested bog site in Burns Bog was conducted between April 2009 and April 2010. Measurements of transpiration and evaporation were taken during the summer of 2009 (June 15 to September 30). Precipitation, throughfall, and soil moisture were measured throughout the study period. The depth to water level was recorded from May 2009 to May 2010.

The amount of water stored in the peat profile varied significantly throughout the year, with decreases in water level up to 205 mm occurring throughout the summer. The water level the open bog was much closer to the surface than in the forested bog site. In both sites, the water level decreased from June through September 2009, and increased sharply in October. In both sites, the water level reached the winter level by November 2009 and remained high until June 2010.

Surface elevation changed by 0.07 m in the open bog and 0.05 m in the forested bog. Surface elevations were lowest at the end of summer (September 2009) and highest in the winter (March 2010). The relation between the surface elevation and the water level in the bog was complex and characterized by hysteresis. Similar to the changes in water level, the surface elevation decreased throughout the summer month. However, it did not increase in response to precipitation in October as quickly as the water level.

Soil moisture in the top 0.3 m of the peat also decreased throughout the summer months and increased in October. Variability in soil moisture in the hollows was lower in the open bog site than in the forested bog site. Variability in soil moisture decreased further in the winter months (November 2009 to May 2010) in the open bog site due to saturation and the water level being above the surface of the hollows. The soil moisture was consistently higher in the open bog site than in the forested bog site. However, soil moisture variability was higher in the hummocks of the open bog than those in the forested bog site.

Precipitation varied across Burns Bog. The average precipitation from March 31, 2009 to March 24, 2010 was 1278 mm,. A difference of approximately 340 ± 19 mm existed between the two geographic extremes of the bog with 1156 mm falling at the south-western portion of the Bog and 1513 mm at the north-eastern portion of the bog. In the forested site only 88% of the precipitation reached the surface due to canopy interception losses. Variability in throughfall increased with increasing storm size, with coefficient of variations up to 0.32 for large precipitation events (116 mm) and as low as 0.10 for a small event (16 mm). Shrub interception was more variable than interception by the forest canopy, with individual throughfall measurements being 45 to 265% of the precipitation measured at the open bog site.

Evaporation between June 10 and September 20, 2009 from hollows was higher in the open bog (1.3 mm/day) than hollows in the forested bog area (0.6 mm/day). This is most likely due to the shading effect of the tree canopy and shrubs, as well as decreased wind speeds due to the trees and shrubs. However, hummock evaporation was greater in the forested bog (0.9 mm/day) than in the open bog (0.6 mm/day) during the same period.

Transpiration from the forested bog site was less than 0.44 mm/day for the June 10 to September 15, 2009 period. Large errors existed in the measurement of transpiration due to the uncertainty in the sapwood area of the study area and large variability in measured sap flow rates. Although there were large hemlock trees in the study site that transpired up to 60 L per day, the number of hemlock trees was low, thus contributing little to the overall transpiration from the forested bog site. There was no correlation between the water level below the surface or soil moisture and transpiration. Radiation, air temperature, and relative humidity were correlated with transpiration. Evapotranspiration was less than the calculated potential evapotranspiration for most of the summer.

Deep drainage was estimated using the Darcy equation and the hydraulic conductivity measured in the silt layer below the bog. The amount of water leaving the bog through deep drainage was not negligible, as up to 150 mm per year or up to 10% of the annual precipitation moved into the underlying silts. Large uncertainties exist in the deep drainage for both the open and forested bog sites because of uncertainty in the calculation of the hydraulic conductivity of the silt. However, it is clear that the water leaving the bog through deep drainage is more significant than previously thought.

Lateral drainage was calculated to flow out of the open bog site during the summer months at an average rate of 2.2 mm/day. In the forested bog site, there was a net influx of lateral drainage, with 1.7 mm/day flowing into the site. During the winter months, both the open and forested bog sites were calculated to have an output of lateral drainage of 2.4 and 1.5 mm/day respectively. Large uncertainty exists for this variable because of the errors from the deep drainage term in the water balance.

The water balance of the forested bog site was significantly different from that of the open bog site. The surface of the forested bog site received less water than the open bog due to interception from both the trees stand and the shrubs. Only 88% of precipitation (on average) reached the surface as throughfall. Although the forested bog had lower evaporation rates than the open bog, transpiration from the trees was greater than the difference in evaporation rates. During the summer, evaporation accounted for 55% of precipitation in the open bog site, whereas evapotranspiration was more than the total throughfall by approximately 28% in the forested bog site. Deep drainage accounted for 10% of the precipitation in the open bog site and 23% of throughfall in the forested bog. Additionally, the change in storage in the forested bog area was much less than the open bog due to consistently lower soil moisture and lower water level during the summer months.

The results of this study suggest that the removal of trees would increase the amount of water reaching the bog surface as well as decrease the amount of water leaving through evapotranspiration. Caution must be used, as this study has shown that large uncertainties exist within other water balance variables such as deep drainage and lateral drainage.

A hydrological model of both sites was successfully created using Vensim PLE Plus version 5.10e (Ventana Simulation Environment). The conceptual model was based on the water balance equation and the results from the field measurements. The water level was modelled based on input data from the meteorological station. Using precipitation, average daily temperature, radiation, and the season, the model simulated the daily evaporation, transpiration (forested bog model only), deep drainage, lateral drainage, overland flow, the water level, and surface elevation (open bog model only). Several parameters were optimized to fit the observed water table variation, including parameters for the lateral hydraulic gradient and overland flow velocity. These parameters could not be measured during the study period. Evaporation and transpiration were calculated as an optimized fraction of the potential evapotranspiration to represent the measured values during the study period. The model was very sensitive to changes in the hydraulic conductivity of the silt and thus the deep drainage. The model was not very sensitive to the other parameters that were optimized, but still showed some sensitivity to changes in the amount of evaporation and transpiration.

The models were calibrated using data collected during the study period (June 1, 2009 to June 1, 2010) and validated with the water level data collected from June 1, 2010 to May 15, 2011. The open and forested bog models had a Nash-Sutcliffe efficiency of 0.975 and 0.906 respectively for the calibration period, and 0.999 and 0.895 respectively for the validation period. The mean absolute error for the water level was 0.02 m for the open bog model and 0.03 m for the forested bog model for the calibration and validation period.

More research is required to better understand the hydrology of peatlands, specifically the hydrology of Burns Bog. Due to the size of the study sites relative to the entire bog, this study is likely only representative of the somewhat undisturbed southwestern portion of Burns Bog. The large tracts of severely disturbed peat in the centre and north-eastern portions of the bog are likely to have a different water balance due to the absence of undisturbed *Sphagnum* moss, hummock and hollow microtopography, and possibly different peat characteristics.

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6.0 APPENDIX I

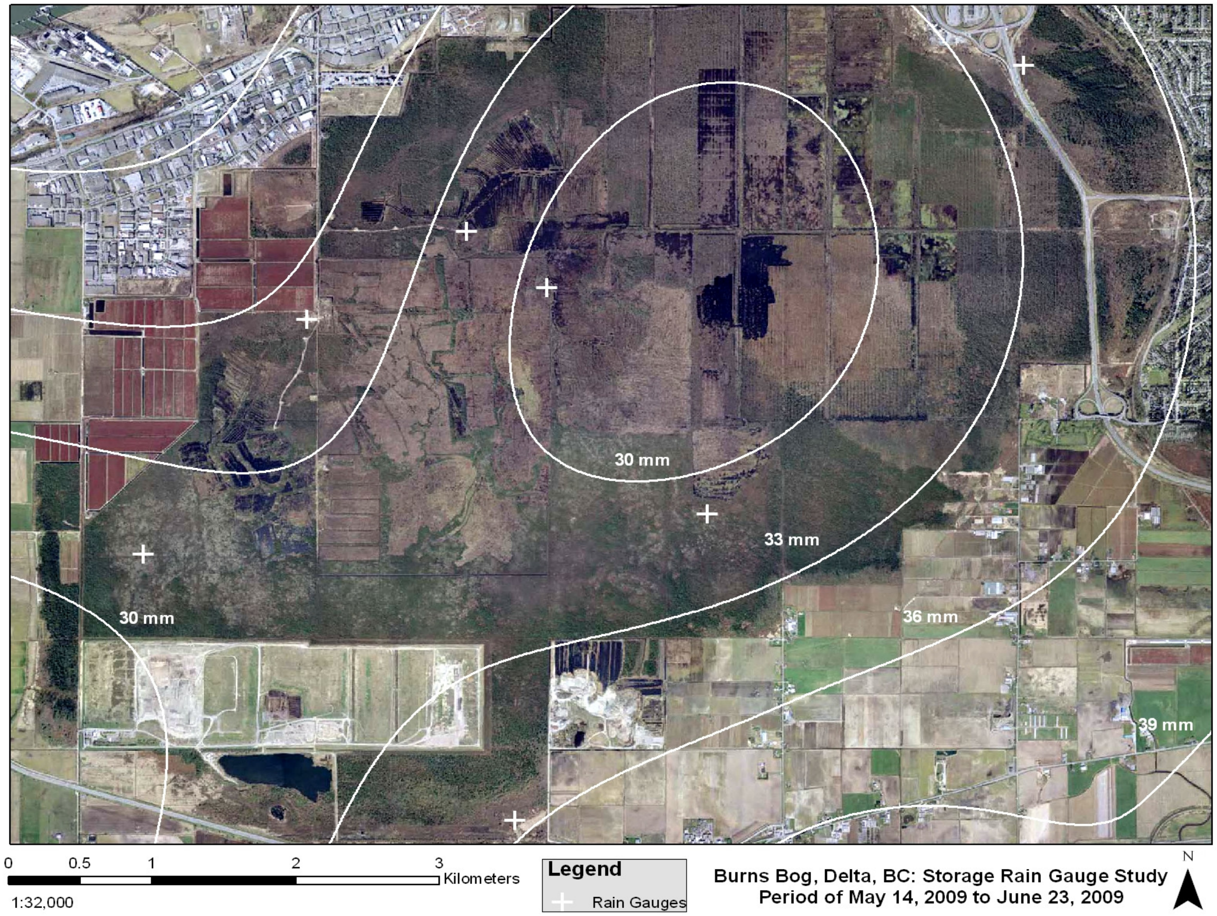

Figure 59: Precipitation contours for the May 14, 2009 to June 23, 2009 period. Contour lines were drawn by hand.

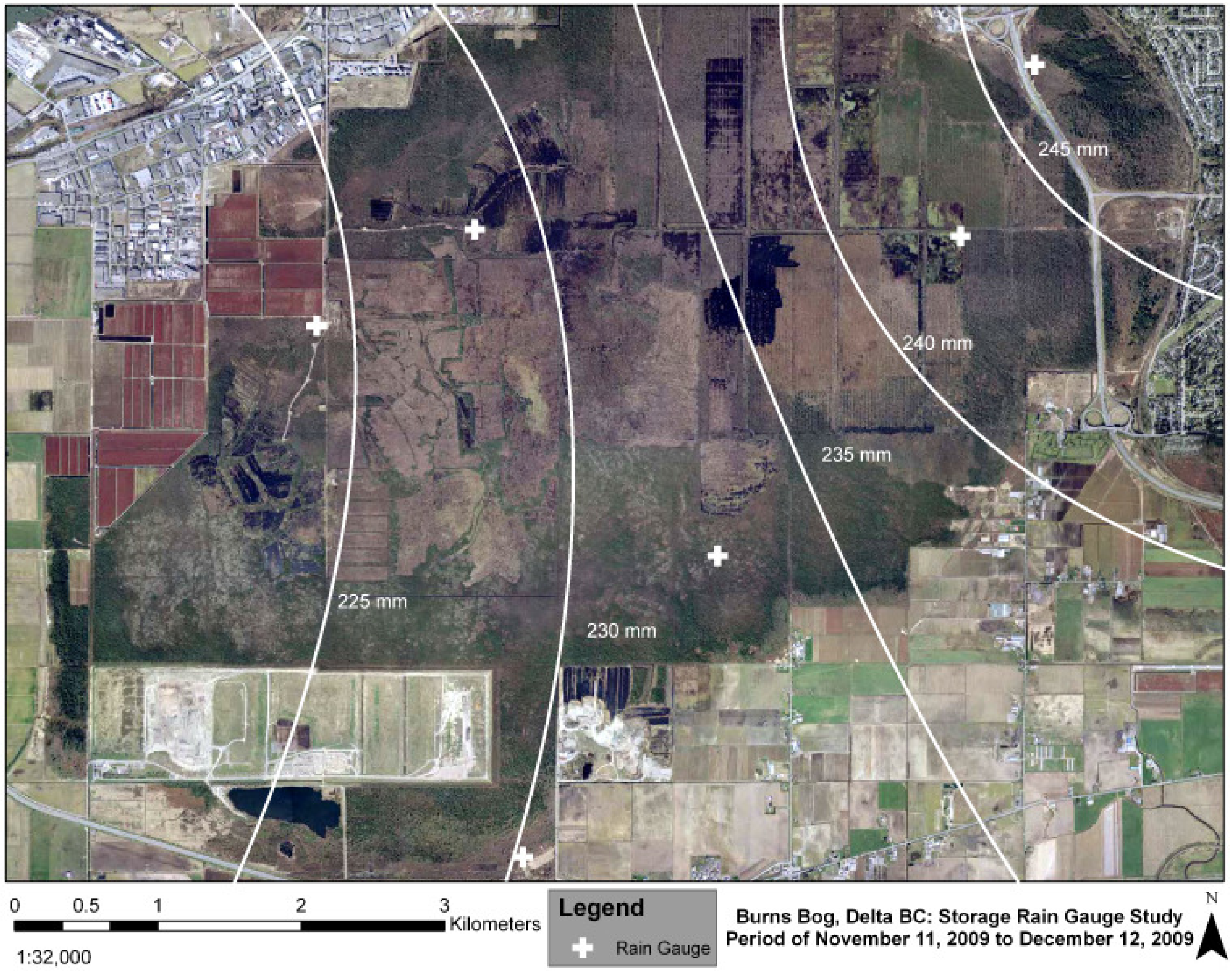

Figure 60: Precipitation contours for the November 11, 2009 to December 12, 2009 period showing the highest precipitation in the northeast corner of Burns Bog, with decreasing amounts towards the southwest. Contour lines were drawn by hand.

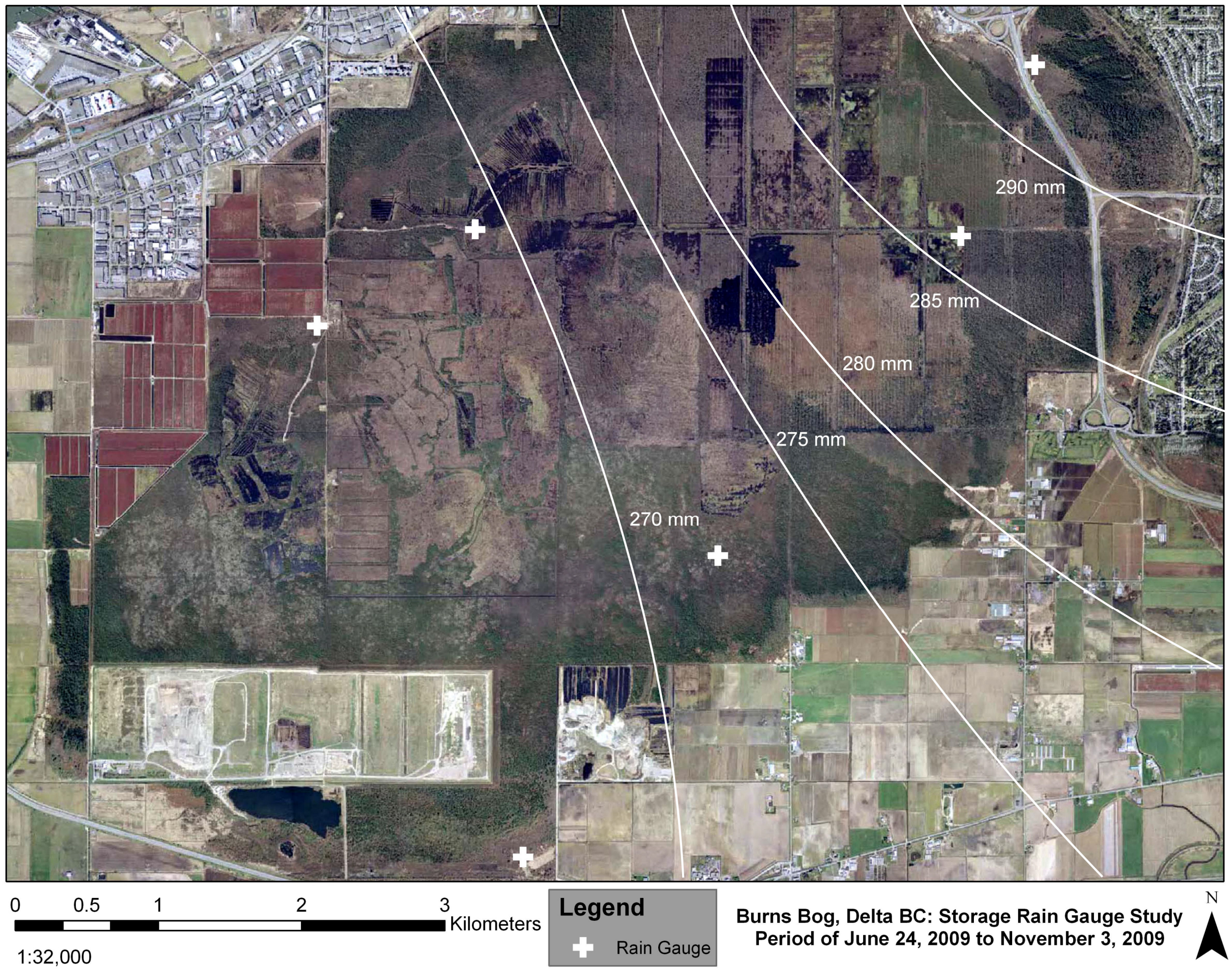

Figure 61: Precipitation contours for the June 24, 2009 to November 3, 2009 period showing the highest precipitation in the northeast corner of Burns Bog, with decreasing amounts towards the southwest. Contour lines were drawn by hand.

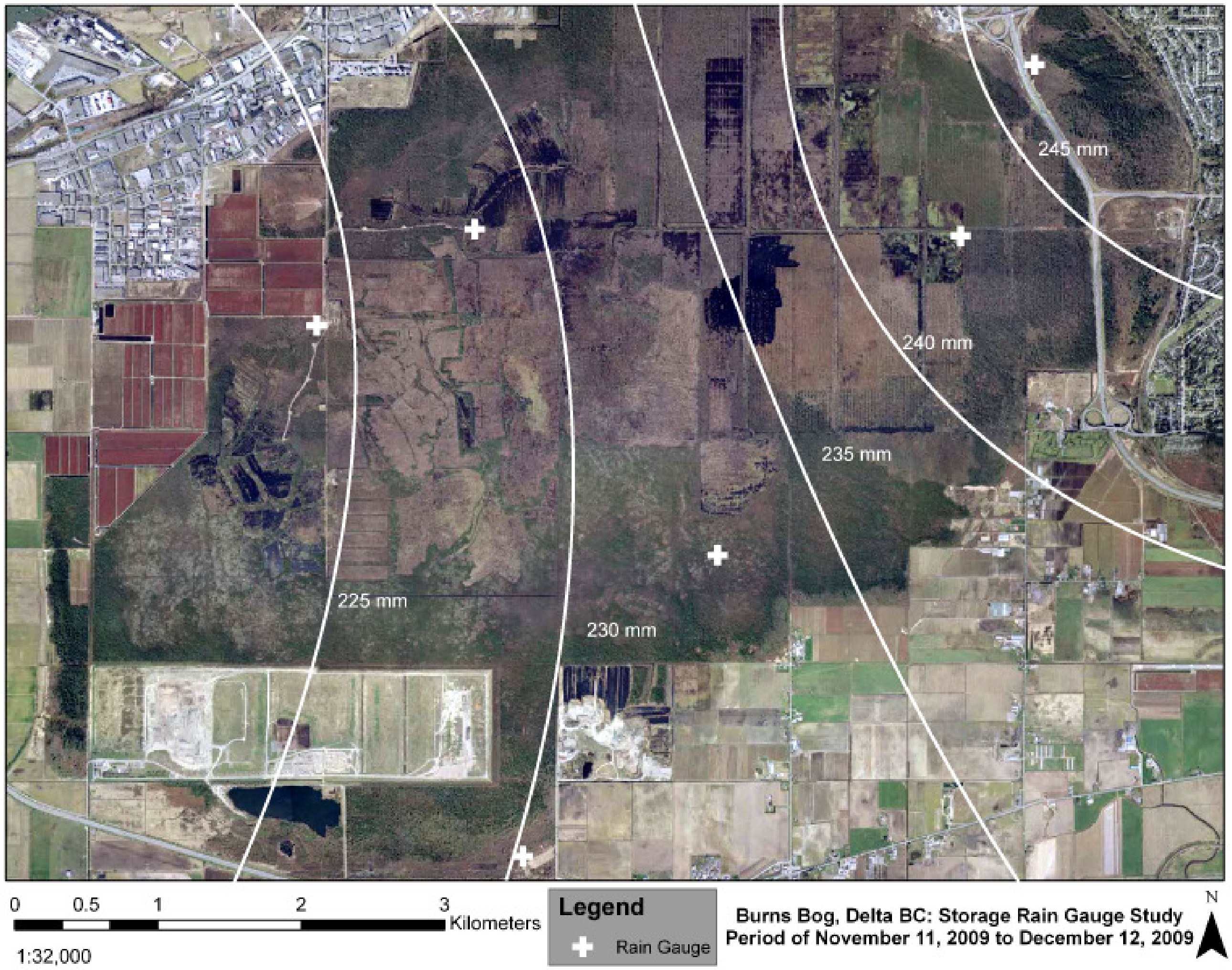

Figure 62: Precipitation contours for the November 11, 2009 to December 12, 2009 period showing the highest precipitation in the northeast corner of Burns Bog, with decreasing amounts towards the southwest. Contour lines were drawn by hand.

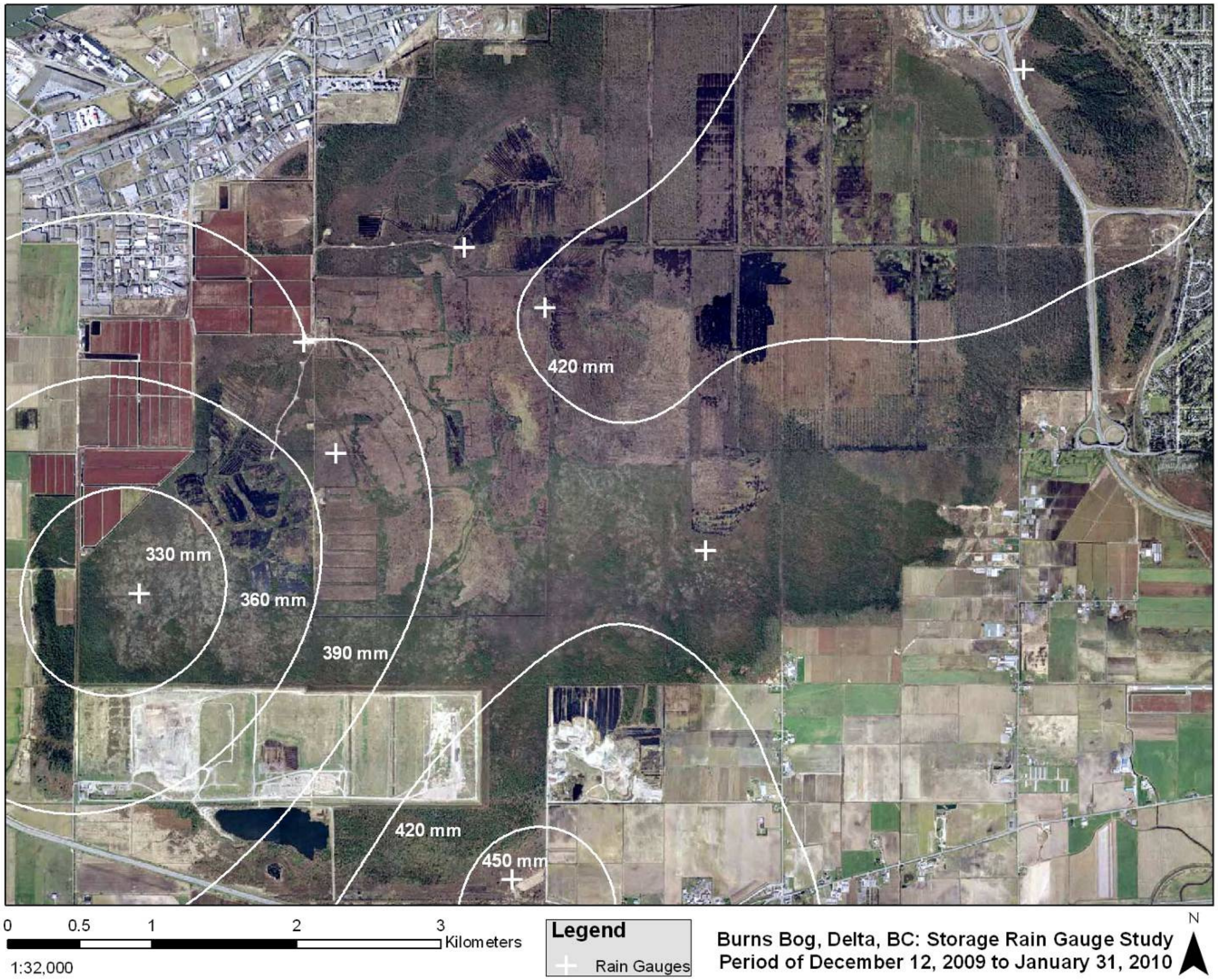

Figure 63: Precipitation contours for the December 12, 2009 to January 31, 2010 period.

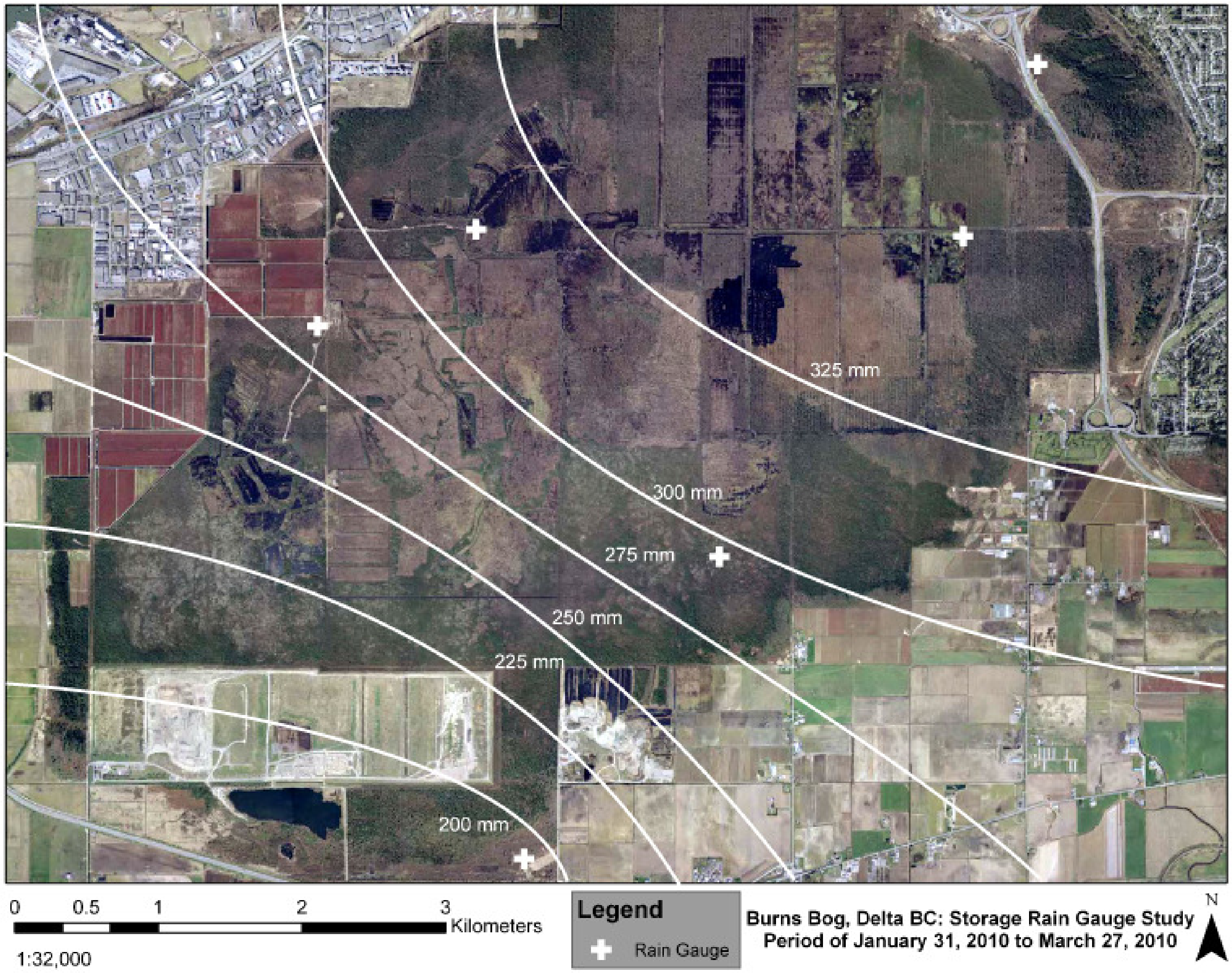

Figure 64: Precipitation contours for the January 31, 2010 to March 27, 2010 period showing the highest precipitation in the northeast corner of Burns Bog, with decreasing amounts towards the southwest. Contour lines were drawn by hand.