University of Alberta

The Short-term Impacts of Aspen Clear-cutting on Upland Groundwater Recharge

by

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Abstract

The impacts of aspen clear-cutting on upland groundwater recharge are presented based on two years (2007-2008) of the five year (2005-2009) HEAD2 NSERC-CRD paired-catchment experiment. Research was conducted at the Utikuma Region Study Area (URSA), 370 km north of Edmonton, Alberta, Canada, in the Boreal Plain ecozone. Results show greater soil water content in the root zone and potential for recharge into the deeper unsaturated zone during the first year of regeneration. Sites with shallow water table levels (<600 cm) increased more than sites under uncut conditions. Sites with deeper water table levels (>600 cm) responded minimally, if at all, to spring-melt and summer storms suggesting that water exchanges with the atmosphere occurred to and from the unsaturated zone only during the first-year regeneration. Upland groundwater gradients to adjacent pond-peatland complexes persisted at least ten times longer under clear-cut than under uncut conditions. Water table trends recovered to uncut conditions by the second year of regeneration.

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“If we knew what it was we were doing, it would not be called research” - Einstein

Table of Contents

List of tables

List of figures

List of Acronyms

ABS	Acrylonitrile Butadiene Styrene
AET	Actual evapotranspiration
BG	Belowground
CA	Catchment Area
DEM	Digital Elevation Model
ET	Evapotranspiration
FHLU	Fundamental Hydrological Landscape Unit
HEAD 2	Hydrology, Ecology and Disturbance Phase 2
HRA	Hydrological Response Area
LIDAR	Light Detection and Ranging
NFS	North-Facing Slope
PR1	Profile Probe 1 soil moisture instrument (older model)
PR2	Profile Probe 2 soil moisture instrument (newer model)
PVC	Poly Vinyl Chloride
RC	Runoff Coefficient
SF	Stem Flow
SFS	South-Facing Slope
SWE	Snow Water Equivalent
TF	Throughfall
VMC	Volumetric Moisture Content in the unsaturated zone
WC	Water Content in saturated zone

List of symbols

$\Delta h/\Delta l$	Lateral hydraulic head gradient
$\Delta h/\Delta z$	Vertical hydraulic head gradient
g	Acceleration due to gravity
h	Hydraulic head
I	Leaf interception
Ksat	Saturated hydraulic conductivity
P	Gauge pressure
Q	Discharge
q	Darcy flux
R	Monthly runoff
s	Seconds
SSZ	Saturated zone storage
SUSZ	Unsaturated zone storage
Sy	Specific yield
YPR1	PR1 millivolt reading
YPR2	PR2 millivolt reading
$\text{YPR2}_{\text{Equivalent}}$	PR2 equivalent millivolt measurement taken with PR1instrument
z	Elevation above sea level
Δ	Change
ρ	Density of water
Ψ	Negative pressure head (i.e. suction)

Chapter 1: Background Information

1.1 Climate and Landuse Issues

Observational records and climate projections strongly suggest that global freshwater resources are vulnerable and threatened by climate change, with wide-ranging consequences for human societies and ecosystems (Bates *et al*., 2008). Canada is of special concern as it contains more than a quarter of the world's freshwater in its wetlands, lakes and rivers (DUC, 2008). Sub-humid climates are especially at risk and are projected to suffer a decrease in water resources (Bates *et al*., 2008) in response to the high evaporative demand (LaBaugh *et al*., 1996). Areas where the water supply is controlled by melting snow or ice, like the northern prairie region of Canada (Hayashi *et al*., 1998), are especially susceptible to predicted increase in surface temperature (Barnett *et al*., 2005).

Freshwater resources are further threatened in the western Boreal Plain of Canada by clear-cutting disturbances resulting from oil and gas exploration and exploitation (AEP, 1998), forest harvesting for wood products (Holroyd and Retzer 2005; DUC, 2008), and road building for forestry (Buttle *et al*., 2005). The increase in clear-cutting has been stimulated in part by the recent economic importance of aspen (*Populus tremuloides*) for pulp and paper (Bates *et al*., 1993; Devito *et al*., 2005a) and is occurring within the extensive stands of aspen that cover large portions of uplands in the Boreal Plain (Hall *et al*., 1997).

Climate change and landuse impacts on freshwater resources remain uncertain in the sub-humid Boreal Plain. There are important knowledge gaps in western Boreal Plain hydrology due to the temporal variability in climate and spatial variability in lithology influencing antecedent soil storage conditions (Devito *et al*., 2005a). Understanding how vegetation, climate and soil storage regulate upland groundwater recharge and groundwater linkages to adjacent surface water bodies is key to predicting the long-term sustainability of freshwater resources (Redding and Devito, 2009). Accurate conceptual models of upland hydrology need to be developed to determine the dominant components of the water cycle and guide the effective management of surface water bodies (Devito *et al*., 2005b).

1.2 Inconsistent Outcomes of Clear-cutting Experiments

Developing accurate conceptual models of upland hydrology in the western Boreal Plain is challenging because the majority of studies have been conducted on the Boreal Shield of eastern Canada. Recent studies carried out on the Canadian Boreal Shield, where the climate conditions are humid, have accumulated evidence to suggest that clear-cutting results in increased base and peak flows following decreased snow and rainfall interception by vegetation, and increased infiltration at the ground surface (Buttle *et al*., 2000). Under these conditions, the soil storage capacity is regularly exceeded and the shallow depth to bedrock facilitates lateral runoff, increasing the potential impacts of clear-cutting on adjacent ecological systems (McDonnell, 2003).

Unlike the humid climate of the Boreal Shield, the drier climate and deep surficial deposits of the sub-humid Boreal Plain create complex surface-groundwater interactions (Buttle, 1994) where soil storage and evapotranspiration processes dominate the hydrology of the landscape (Devito *et al*., 2005a). The complex hydrology of the sub-humid Boreal Plain precludes generalizations made from the simple hydrological systems found in the Boreal Shield.

A few empirical studies have been conducted on the western Boreal Plain; however, results remain controversial because of the lack of consistent response from one experiment to the other (Pomeroy *et al*., 1997; Swanson and Hillman, 1977; Swanson and Rothwell, 2001). Studies indicate that clear-cutting generally increases water yield, but the magnitude of increase varies widely across different experiments. In west-central Alberta, clear-cutting on the North Western Pulp and Paper Company Ltd. lease near Hinton resulted in 59% more streamflow during snow-melt, 27% increase in water yield during the monitoring season (April 25 to September 15) and storm peaks increasing up to two times (Swanson and Hillman, 1977). Similarly, the Prince Albert Model Forest project in central Saskatchewan showed that after 15 years of replanting aspen, the regenerating clear-cut showed only partial recovery with respect to its evaporation and runoff regime (Pomeroy *et al*., 1997).

On the other hand, results from a paired-catchment experiment in north-western Alberta demonstrated that the generated runoff averaged 16.3 mm for the 5 years following clear-cutting, maintaining changes in peak flows below the threshold limit set by Alberta Environment (Swanson and Rothwell, 2001). Similarly, a study in north-central Minnesota in the Northern Glaciated Plains found that an aspen clear-cut from the upland portion of a peatland increased rainfall peak discharge and storm flow volumes due to a reduction in soil storage potential, with impacts lasting only 2 years (Verry *et al*., 1983). Simulations by Swanson and Rothwell (2001) suggest that the wide range in clear-cutting response can be attributed to differences in precipitation, where the effects can vanish in as little as 2 years under low precipitation conditions or persist for as long as 45 years under conditions of high precipitation. The inconsistency in the results of empirical studies on water yield in the sub-humid Boreal Plain highlights the need to conduct more process-based research.

Process-based research is gaining recognition by describing the underlying processes and flow paths that control water yield from a catchment (Devito *et al*., 2005a; Redding and Devito, 2008). Soil moisture has been suggested as an appropriate indicator of the magnitude of clear-cutting impacts due to the importance of soil storage as a hydrologic control in sub-humid climates (Rodriguez-Iturbe, 2000). However, the impacts of clear-cutting on upland soil moisture also remain inconclusive (Elliott *et al*., 1998; Whitson *et al*., 2005; Macrae *et al*., 2005). Recent research in northern Alberta shows that clear-cut sites are significantly wetter in the rooting zone only in the month of July (Whitson *et al*., 2005). Another experiment in north-central Alberta found no difference in surface soil moisture (to 1 m) between clear-cut and uncut portions of aspen stands in several headwater catchments (Macrae *et al*., 2005). The absence of significant change in soil water content was attributed to the fast aspen regeneration and/or the drought conditions that were observed during the measurement period. On the other hand, evidence from studies in the Boreal Plain of northern Saskatchewan showed that clear-cutting resulted in wetter soils compared to uncut conditions, suggesting a vegetation control (Elliott *et al*., 1998).

The large discrepancy in the results of clear-cutting studies in the sub-humid Boreal Plain suggests conflicting controls on the components of the water cycle. Our traditional understanding is insufficient for making accurate predictions of clear-cutting impacts, potentially jeopardizing the sustainability of freshwater resources. Process-based studies addressing upland groundwater recharge and groundwater linkages to adjacent surface water bodies are required to understand the scale of hydrological impact to upland clear-cutting. A better understanding of hydrological processes is essential to developing accurate conceptual models of upland hydrology required to guide the effective management of Canada's freshwater resources (Devito *et al*., 2005b).

1.3 The Concept of Hydrological Landscapes

Winter (2001) put forward the concept of hydrological landscapes as a framework to objectively conceptualize the movement of surface water, groundwater and atmospheric water in different types of terrain in order to standardize the approach to hydrological problems. Winter (2001) began by defining hydrological landscapes as made up of multiple fundamental hydrological landscape units (FHLUs). The basic land surface form of an FHLU is depicted by an upland and a lowland (e.g. pond-peatland complex) separated by a slope forming a hillslope. FHLUs have complete hydrological systems consisting of surface runoff, groundwater flow and the interaction with atmospheric water. Winter (2001) generalized the hummocky landscape of the western Boreal Plain by proposing that each hummock was made up of at least two hillslopes. This conceptual model is useful because once the controls on the hydrology of a single hillslope are characterized, then understanding the hydrology of the hummocky terrain is simplified by superimposing several similar consecutive hydrological models.

Ferone and Devito (2004) began the hydrological characterization of a hillslope by examining the dominant hydrological fluxes that controlled shallow pond-peatland complexes in the hummocky terrain of the Boreal Plain. Hydrometric and geochemical measurements showed that precipitation and evaporation dominated the annual water balance. Furthermore, the uplands did not contribute groundwater to the adjacent pond-peatland complex despite large hydraulic gradients due to the low saturated hydraulic conductivity of the mineral soil. Having precipitation and evaporation dominate the water balance suggests that the hydrological regime of some pond-peatland complexes in clay-rich till may be more sensitive to local disturbances that impact flow dynamics and near shore peatlands than larger scale disturbances occurring in adjacent mineral upland regions.

The dominant hydrological processes and flow paths in the upland portion of the hillslope still need to be investigated to help complete the conceptual model proposed by Winter (2001) for the hummocky terrain of the western Boreal Plain. A general review of the literature highlights several hydrological processes and flow paths that can take place in the upland portion of a forested hillslope (Golding and Stanton, 1971; Freeze and Cherry, 1979; Pomeroy *et al*., 1997; Rodriguez-Iturbe, 2000; Startsev and McNabb, 2000; Redding and Devito, 2008). The upland water cycle can be described during a precipitation event, where rain droplets enter the forest canopy and either (1) are intercepted (I) by vegetation and subsequently evaporated, (2) run down the stems and trunk of vegetation through stem flow (SF) or (3) fall directly to the ground surface uninterrupted as throughfall (TF) (Pomeroy *et al*., 1997). The amount of precipitation that can make it through the forest canopy to the ground surface is referred to as the net precipitation. The net precipitation is the water input in Figure 1, which describes the general upland water movement in the western Boreal Plain in the form of a flow chart.

The net precipitation reaching the ground surface can either be stored in the forest floor (FF) or infiltrate into the A horizon (Golding and Stanton, 1971). From the top of the A horizon, water can either (1) be stored in the root zone (Rodriguez-Iturbe, 2000),

(2) flow laterally at the interface between the FF and the start of the mineral horizons through a process called overland flow (Freeze and Cherry, 1979), (3) return to the atmosphere via transpiration (Rodriguez-Iturbe, 2000) and/or (4) drain vertically through the A horizon (Startsev and McNabb, 2000) (Figure 1). If water drains vertically past the root zone, water can either (1) be intercepted by a layer of lower permeability resulting in lateral flow via the transmissivity feedback mechanism or (2) continue to drain vertically into the deeper unsaturated zone and potentially recharge the water table (Redding and Devito, 2008) (Figure 1).

Following groundwater recharge, water movement can be limited to the upland scale or move across the hillslope to the adjacent pond-peatland complex depending on the saturated hydraulic conductivity of the soil (Figure 1). Upland groundwater linkage refers to the hydrological connection via groundwater between upland areas and adjacent pond-peatland complexes. The groundwater linkages are defined by the difference in water table elevation between uplands and pond-peatland complexes. The uplands are said to be hydrologically linked if the upland water table elevation is above that of the adjacent pond-peatland complex resulting in positive hydraulic gradients. Groundwater flux is the rate of groundwater moving across the hillslope and is a function of the hydraulic gradient and the lateral saturated hydraulic conductivity. The lateral hydraulic conductivity refers to the ability of water to flow through a porous medium. Uplands may or may not be hydrologically linked to adjacent pond-peatland complexes depending on the magnitude and direction of hydraulic gradients as well as the lateral hydraulic conductivity (Ferone and Devito, 2004) (Figure 1).

1.4 Potential Hydrological Controls

1.4.1 Soil Storage

There is no agreement on which hydrological process exerts the most important influence on upland hydrology and groundwater linkages to adjacent pond-peatland complexes. The short-term impacts of upland clear-cutting on the different water cycle components are likely a product of soil storage, vegetation and/or climate in regulating upland groundwater recharge and groundwater linkages to adjacent surface water bodies. Devito *et al*., (2005a) suggests that soil storage plays an important role in regulating the impacts of clear-cutting on upland groundwater recharge because soil storage in the unsaturated zone has the potential to accommodate the increase in net precipitation at the ground surface (Figure 1). The western Boreal Plain of Canada is characterized by a hummocky terrain where rolling hills of crests and troughs spread across a relatively flat landscape. Soil storage, as determined by the depth to the water table and soil properties, is thought to be a dominant hydrological control, because hummocks are generally rich in silt and spatially heterogeneous with areas of high clay or sand content, thus creating high potential to store large quantities of water (Fenton *et al*., 2003; Vogwill, 1978).

Furthermore, the water table elevation in the uplands (i.e. the crests of hummocks) is generally lower than the water table elevation in the adjacent water body, making uplands behave like hydrological sinks (Devito and Mendoza, 2006). This conceptual model is contrary to most traditional models of water table configuration, which assumes that groundwater beneath the uplands discharges to the adjacent water body (Vidon and Hill, 2004; Devito *et al*., 2005a). In addition, the infiltration capacity of the upland soils is often greater than the rainfall intensity in this environment, causing the bulk of the rain to drain vertically into the soil (Redding and Devito, 2008). While mechanical disturbances do reduce the infiltration capacity, Startsev and Mcnabb (2000) show that the rate of infiltration is still above the typical precipitation intensities found in the Boreal Plain, suggesting a dominance of vertical flow during the growing season. The high rates of infiltration suggest that overland flow is unlikely to take place in this environment despite a clear-cutting disturbance (Figure 1) (Redding and Devito, 2009). Thus, the high soil storage potential of upland areas can accommodate the expected increase in net precipitation in response to clear-cutting, due to a reduction in evapotranspiration and leaf interception, limiting the impacts on the natural groundwater dynamics.

1.4.2 Vegetation

Studies of aspen in the sub-humid climate of the Boreal Plain have shown that these trees can exert an important control on upland hydrology because the evapotranspiration regime is synchronized in time with precipitation (Marshall *et al*., 1999). Aspen exerts an important control via leaf interception storage, which can be as high as 5-10 % of the seasonal precipitation (Pomeroy *et al*., 1997). The amount of interception storage is a function of storm size and intensity, where a greater percentage of rainfall will be intercepted with relatively low rainfall intensities. In an environment where the precipitation regime is characterized by a majority of small rain events, like the western Boreal Plain of Canada, leaf interception storage exerts an important control in minimizing the amount of throughfall past the aspen canopy (Redding and Devito, 2008).

Most years, potential evapotranspiration is greater than precipitation, maintaining a prolonged water deficit in the root zone under forested conditions (Rodriguez-Iturbe, 2000). Evapotranspiration refers to the sum of transpiration and evaporation (Pomeroy *et al.*, 1997; Brown, 2010). The increase in net precipitation due to clear-cutting can exceed the water holding capacity in the root zone, favouring either lateral flow via the transmissivity feedback mechanism (Redding and Devito, 2008) or upland groundwater recharge through vertical flow (Freeze and Cherry, 1979) (Figure 1). The transmissivity feedback mechanism describes the process where water flows preferentially, in a vertical direction to a clay rich layer, where soil storage is slowly filled to a point where a perched system is created inducing lateral flow (Redding, 2008). Redding and Devito (2008) showed that while clear-cutting would allow soils to wet up to a deeper depth in the profile during the growing season compared to uncut conditions, vertical flow was still the dominant flow path (Figure 1).

Thus, if vegetation is the dominant control on the upland water regime, then releasing the control by clear-cutting can increase the probabilities of exceeding the upland soil storage threshold, favouring upland groundwater recharge (Figure 1). This process can raise water table levels, induce positive hydraulic gradients in the saturated zone, and hydrologically link previously isolated uplands to the adjacent pond-peatland complex via groundwater for longer periods of time when compared to uncut conditions. For example, the upland water table elevation under clear-cut conditions could remain above the water table elevation of the adjacent pond-peatland complex longer than under uncut conditions.

Vegetation also exerts a strong control on the upland water regime by the rapid regeneration of aspen through root suckering after a clear-cutting disturbance (Bates *et al*. 1993; Frey *et al*., 2003; Fraser *et al*., 2004). Aspen regenerates quickly because clear-cutting does not dramatically damage the clonal root system below the ground surface. In fact, clear-cutting is the recommended silvicultural system for aspen, because it stimulates suckering on the greatest amounts of clonal roots and minimizes shading from residual vegetation (Bates *et al*., 1993). Injured aspen roots have also been shown to produce more suckers per root, with taller saplings having greater leaf area as compared to uninjured roots (Fraser *et al*., 2004). Suckers have also been shown to grow between 1 and 2 m tall during the first year of regeneration (Perala, 1978). The high resilience of aspen to clear-cutting disturbances suggests that these trees are able to recover water deficit conditions in the root zone quickly following a clear-cutting disturbance. Fast aspen regeneration may limit the opportunity for considerable hydrological impacts via upland groundwater recharge to the first growing season after clear-cutting when the vegetation influence is at a minimum.

1.4.3 Climate

Finally, the natural climatic variability may overpower the hydrology of the sub-humid Boreal Plain of western Canada by controlling antecedent soil moisture conditions and consequently the depth to the water table. The balance between precipitation and evapotranspiration varies greatly between years, resulting in highly variable soil storage potential in time (Devito *et al*., 2005a). Generally, the magnitude and seasonality of evapotranspiration and precipitation result in dry fall conditions, low soil moisture, and deep water tables below the ground surface, which can accommodate subsequent spring-melt and summer storms (Devito *et al*., 2005a). The precipitation regime is characterized by short-duration, low-intensity, and small convective storms that come during the growing season. These conditions sustain a prolonged water deficit in the root zone, because the majority of the events are intercepted by the canopy and seldom make it to the root zone (Devito *et al*., 2005a). Wet climate years occur on a 10 to 15 year cycle and are characterized by a large snowpack, cool summer temperatures and high-intensity and long-duration rain events. Soil storage thresholds are more readily exceeded under wet conditions and the depth to the water table is reduced. The high climate variability in time suggests that the hydrological impacts of clear-cutting will be a function of storage thresholds, at a particular area at the time of disturbance. If clear-cutting increases the quantity of water infiltrating past the root zone, the hydrological impacts could be offset by the soil storage potential at that time and the location of the water table relative to the ground surface. Under conditions where soil storage has already been filled, the increase in water infiltration and water table impacts would more likely be noticeable. On the other hand, the impacts of clear-cutting will likely go unnoticed where the soil storage has not been filled to its potential and the water table is deep below the ground surface.

1.5 Research Gap

Currently, the scientific literature highlights large gaps in our understanding of hydrology in forested uplands, wetlands and ponds in the Boreal forest of western Canada (Buttle *et al*., 2005). Many empirical studies have addressed the impacts of clear-cutting on water yield with inconsistent results (Swanson and Hillman, 1977; Verry *et al*., 1983; Pomeroy *et al*., 1997; Swanson *et al*., 2001; Devito *et al*., 2005a). Process-based studies are attempting to clarify the dominant flow paths and hydrological processes by addressing the impacts of aspen clear-cutting on soil moisture (Whitson *et al*., 2005; Macrae *et al*., 2005), soil temperature (Whitson *et al*., 2005), soil storage and infiltration capacities (Whitson *et al*., 2003), and lateral flow (Whitson *et al*., 2003; Redding and Devito, 2008).

However, studies have not synthesized these processes at the upland scale and addressed the potential for groundwater linkages across the hillslope. The large temporal variability in climate and large spatial variability in surficial geology create complex non-linear and threshold dependent surface-groundwater interactions (Buttle, 1994; Devito *et al*., 2005). These conditions complicate the interpretation of the impacts of anthropogenic disturbance like clear-cutting. Understanding the balance between soil storage, vegetation and climate in regulating upland groundwater recharge and the conditions under which uplands become hydrologically linked via groundwater to adjacent pond-peatland complexes is essential to predicting the sustainability of freshwater resources in the Boreal Plain of western Canada.

1.6 Research Question

The ongoing goal of the Hydrology, Ecology and Disturbance 2 (HEAD 2) project is to study the impacts of aspen clear-cutting and recovery on the water cycle in the western Boreal Forest. The HEAD 2 project is located in the Utikuma Region Study Area where three major glacial landforms characteristic of the Boreal Plain have been studied. These landforms include: (1) the sandy outwash, (2) the hummocky disintegration moraine and (3) the lacustrine plain. These different landforms act as unique hydrologic response areas (HRA) with groundwater interactions ranging from local to regional scale (Devito *et al*., 2005b).

Hydrological research has focussed on the water balance in the lacustrine plain (Ferone and Devito, 2004) and the hummocky disintegration moraine (Ferone and Devito, 2004; Redding and Devito, 2008), hydrological processes of perched ponds in the transition area between outwash and moraine sediments (Riddell, 2008) and the hydrological dynamics of the sandy outwash (Smerdon *et al*., 2005). To date, the research has shown a dominance of vertical flow from the ground surface and the importance of precipitation timing relative to vegetation water demand and antecedent soil moisture conditions in controlling the upland hydrology of each HRA.

The HEAD 2 project examined the influence of aspen upland clear-cutting on the water cycle of a reference and experimental headwater catchment located on the disintegration moraine landform (HRA) two and three years before and after experimental clear-cutting from the years 2005 to 2009. In the framework of the HEAD 2 project, my Master of Science thesis presents the findings from two of those five years following clear-cutting, in 2007 and 2008, to address the research question "Does soil storage, vegetation, and/or climate regulate upland groundwater recharge on a hummocky disintegration moraine in the sub-humid Boreal Plain of Alberta, Canada?"

1.7 Research Objectives

1. Determine how aspen clear-cutting may influence soil moisture, soil tension and upland groundwater recharge.

2. Evaluate the potential for groundwater linkages from the uplands to adjacent pond-peatland complexes.

3. Infer the scale of hydrological impact in response to upland clear-cutting.

1.8 Hypotheses

I hypothesize that vegetation controls soil moisture and water table recharge by keeping the root zone near water deficit conditions during the growing season because of leaf interception storage and evapotranspiration. If vegetation is a dominant control on the upland water regime, then upland clear-cutting will increase soil water content, favour water table recharge conditions, and induce positive saturated hydraulic gradients linking the clear-cut uplands to the adjacent pond-peatland complexes via groundwater for a longer period of time than under uncut conditions. Alternatively, the unsaturated zone above the deep water table has the potential to hold excess water which could result in little change in upland and pond-peatland complex interactions in the cut compared to the uncut catchment. I predict that soil water content will increase in the uplands while staying within the water holding capacity of the soil. Depending on the soil storage potential of the year as defined by the depth to the water table, considerable recharge and a water table rise in response to summer rainfall may or may not occur in the cut versus the uncut upland. If clear-cutting increases the quantity of water that infiltrates past the root zone, clear-cutting impacts could be offset by the depth of the water table. Under conditions where the water table is deep below the ground surface, the increase in water infiltration may not be noticeable.

1.9 Thesis Format

My Master of Science thesis follows the traditional format and consists of 5 chapters. This first chapter introduced the thesis by providing a brief literature review on the climate and landuse issues and potential hydrological controls of uplands areas in the sub-humid Boreal Plain of western Canada. Chapter 1 also highlights the research question, objectives and hypotheses in context of the larger HEAD 2 project. Chapter 2 describes the materials and methods used to test the hypotheses addressed in Chapter 1. The impacts of aspen upland clear-cutting on soil water content, soil tension, groundwater recharge and groundwater linkages to adjacent pond-peatland complexes are presented in Chapter 3. The results of the study are discussed in context of the current literature in Chapter 4. Finally, a summary of the major findings, inferences about the scale of disturbance, management implications and limitations of the study are addressed in Chapter 5.

Chapter 2: Materials and Methods

2.1 Study Area

2.1.1 Climate

The research site was located at the Utikuma Region Study Area (URSA), north of Utikuma Lake (Lat: 56°04'27 N; Long: 115°28'27 W), 370 km north of Edmonton, Alberta, Canada in the Boreal Plain ecozone (Ecoregions Working Group, 1989) (Figure 2). The climate at URSA is defined as sub-humid (Winter and Woo, 1990) where the potential evapotranspiration (517 mm) is larger than the annual precipitation (481 mm) (Bothe and Abraham, 1993; Marshall *et al*., 1999). Wet years resulting from a combination of cool summer temperatures and greater than normal annual precipitation, occur on a 10 to 15 year cycle (Devito *et al*., 2005a).

Thirty-year climate normals (1971 to 2000) at the Slave Lake meteorological station (100 km south of the study site) indicate that average monthly temperatures range from -14.5 ºC in January to 15.6 ºC in July (Environment Canada, 2003). Most of the annual precipitation at URSA falls between the months of June and August, the fall months are usually dry, and winter snowfall is typically < 30% (<100 mm) of the total annual precipitation (Devito and Mendoza, 2006). The long-term (1998-2008) mean annual runoff for Red Earth Creek (619 km^2, 70 km north of the study site) is 37 mm/year and ranges from 5 to 90 mm/year (median 27 mm/year), corresponding to runoff coefficients of 1-21% (median 8%) (Environment Canada, 2008) (Table 1).

2.1.2 Effective Catchment and Upland Boundaries

The effective catchments in the study area are dynamic in nature because they are dominated by pond-peatland complexes. The annual water balance of pond-peatland complexes is dominated by precipitation and evapotranspiration processes making them susceptible to changes in climate. Under dry climate conditions, adjacent pond-peatland complexes are likely isolated from one another, due to a lowering of the water table into the catotelm. The catotelm is located in the deeper peat layers where the low saturated hydraulic conductivity limits the ability of water to move from one area to another constraining the effective catchment area. Under wet climate conditions, the water table is located in the shallower peat layers, called the acrotelm, where the saturated hydraulic conductivity is higher. The relatively higher saturated hydraulic conductivity of the acrotelm favours the movement of water between adjacent pond-peatland complexes extending the effective catchment area under wet climate conditions.

Under average climate conditions, preliminary delineations suggest that the experimental catchment area is about 9 ha and extends to 11 ha under extremely wet conditions. The aspen uplands on the experimental catchment cover 2.5 ha on the south-facing slope and 2 ha on the north-facing slope for a total upland area of 4.5 ha equivalent to 41-50 % of the effective catchment area. Under average climate conditions, preliminary delineations suggest that the reference catchment area is about 16 ha and extends to 22 ha under extremely wet conditions. The aspen uplands cover 10 ha of the catchment area which is equivalent to 45-63% of the effective catchment. The effective catchment boundaries during the study period likely lay between average and extremely wet conditions in response to the relatively wet year in 2007 and drier year in 2008 (Figure 3).

2.1.3 Topography

The study site lies on a regional topographic high in the hummocky terrain of the western Boreal Plain. Natural drainage patterns flow northward towards the Peace River

Basin but are not well defined due to the many depression lakes and wetlands (Brown, 2010). Vertical recharge rates through the gyttja and the underlying clay till beneath the surface water bodies adjacent to the study uplands are low (5 mm/year) virtually disconnecting the study area from regional groundwater for the timescale of this study (Ferone and Devito, 2004). The hydrological disconnection of the study catchments from regional groundwater suggests that water flow patterns will be controlled by local flow systems from the adjacent forested uplands to the adjacent pond-peatland complexes maximizing potential for clear-cutting impacts (Tóth, 1963). The local topography of the study site is characterized by low relief, gentle slopes and a maximum elevation difference of 6 m between the lowest pond-peatland complex and the top of the highest upland (Figure 3).

2.1.4 Water Table Configuration

The water table elevations in the uplands are generally equal to or lower than the adjacent pond-peatland complex (Ferone and Devito, 2004). The water table configuration features deep water tables in the uplands sloping from pond-peatland complex to upland areas. The depth to the water table varies spatially based on the soil storage of the unsaturated zone and is influenced by soil properties and topographic position (Rosenberry and Winter, 1997). The spatial variability of the water table location is high in the uplands due to the high clay content characteristic of the disintegration moraine soils (Redding and Devito, 2008).

2.1.5 Vegetation

The uplands were vegetated with aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*), with occasional stands of white spruce (*Picea glauca*). Prickly rose (*Rosa acicularis*) and low bush-cranberry (*Viburnum edule*) were dominant in the understory, while twinflower (*Linnea borealis*) was abundant in the herb layer. The adjacent wetland was defined as a peatland and dominated by mosses (*sphagnum spp.),* labrador tea (*Ledum groenlandicum*), and some larch (*Larix laricina*) and black spruce (*Picea mariana*). The major vegetative differences between the deciduous uplands and conifer dominated pond-peatland complexes can be observed on the air photo in Figure 4.

2.1.6 Lithology and Hydraulic Conductivity

In the study region, glacial till deposits range from 20 to 240 m in thickness and overlay the Upper Cretaceous Smoky Group shale bedrock (Vogwill, 1978). The uplands at the study site were characterized by Gray Luvisolic soils (Soil Classification Working Group, 1998) that developed from disintegration moraine deposits. These soils are generally rich in silt but vary spatially with areas high in clay or sand content (Fenton *et al.*, 2003). Oxidized clay till of 5 to 8 m deep overlay unoxidized till to ~60 m (Ferone and Devito, 2004).

Redding (2009) characterized the upland soil profile during the installation of 4 runoff plots about one metre deep and observed that upland soil profiles were generally made up of a forest floor ~10 cm thick containing wood and leaf debris (litter, fibric, and humic layers). The A horizons below the forest floor were also about 10 cm thick and contained a mix of organic material and bleached sand and silt. The B horizons extended to ~70 cm and were made up of clay loam material. The C horizons below were made of silty clay loam with thin sand lenses (Redding and Devito, 2008). Redding (2009) also observed that the soils at the study area have no clear flow restricting layers.

Riddell (2008) and Smerdon *et al*., (2005) showed that the saturated hydraulic conductivity (K_{sat}) of the mineral soils in the area ranged from 10^{-6} m/s for sandy silt, 10^{-7} to10^{-8} m/s for silts, and 10^{-9} to 10^{-10} m/s for clays. The geometric mean of the lateral saturated hydraulic conductivity of 14 site specific locations in the uplands (8) and riparian zone (6) was determined to be 9×10^{-9} m/s with individual measurements ranging from 6×10^{-12} to 9×10^{-7} m/s (Figure 5). The forest floor had extremely high porosity (~0.9) characterized by a hydraulic conductivity of 10^{-4} m/s (Redding *et al*., 2005). The hydraulic conductivity of the active peat layer, acrotelm, was estimated at 10^{-4} to10^{-5} m/s and the catotelm had a hydraulic conductivity of 10^{-7} to 10^{-9} m/s (Ferone and Devito, 2004).

2.2 Field Methods

2.2.1 Experimental Manipulation

The HEAD 2 project examined the influence of aspen upland clear-cutting on the water cycle of a reference and experimental headwater catchment located on the disintegration moraine landform (HRA) two and three years before and after experimental clear-cutting (Figure 4, Table 2a). The greatest influence of aspen clear-cutting on upland hydrology is predicted in catchments located in this landscape position because of the dominance of local scale flow to and from fine-textured upland soils. In the framework of the HEAD 2 project, the vegetation, soil storage and climate hypotheses were tested during two years (2007-2008) of the five year (2005-2009) HEAD2 NSERC-CRD project using a combined paired-catchment and before/after approach to control for short-term climate variability and geology respectively.

Hydrometric, geochemical, and isotopic measurements were conducted in the pond-peatland complexes and uplands sequentially from 2005-2009 (Table 2b). The experimental design ensured that one to two years of sampling occurred before and after clear-cutting on each experimental clear-cut hillslope. Measurements were conducted on the north and south-facing slopes of the reference catchment to compare with the experimental catchment (Figure 4)

My thesis presents the hydrometric results for the 2007 and 2008 hydrologic year. The results are considered preliminary as they represent a two year portion of the five year measurement period of the larger HEAD 2 project. A hydrologic year was defined from November 1 to October 31 to capture key hydrologic events characteristic of this climate like antecedent soil moisture conditions, timing and magnitude of spring-melt and summer precipitation. The experimental catchment contained three hummocks: one on the south-facing slope (SFS) and two on the north-facing slope (NFS). The experimental SFS had a perched peatland located at the top of the hummock which has the potential to act as a source of water to the entire experimental SFS. The reference catchment contained two hummocks: one on the SFS and one on the NFS. The study was focussed on the aspen-dominated upland portion of the hummocks.

The SFS upland of the experimental catchment was clear-cut on March 8, 2007. At this time about 66 cm of snow had accumulated at the ground surface and soils were frozen. Tolko Industries Limited, a forest company operating in the region, was responsible for the clear-cutting during both years of study. A winter clear-cut was selected to minimize soil disturbance. Road building near the topographic high and wood cutting, processing, and hauling was done using a feller buncher and skidder and finished by mid-April 2007 with slash and small log dumps remaining (Table 2c). The slash was piled in July 2007 and burned by mid-January 2008. Small piles were left behind for habitat use. The road was not reclaimed due to insufficient materials on this cutblock. Hydrometric data from this cutblock is presented following clear-cutting through the first (2007) and second (2008) year of regeneration.

The NFS upland on the experimental catchment was monitored during 2007 prior to clear-cutting on February 8, 2008. At this time, about 48 cm of snow had accumulated at the ground surface and soils were frozen. Similar to the SFS, clear-cutting was done using a feller buncher and skidder and finished by mid March 2008. The slash was piled on March 30, 2008 and burned in January 2009. Unlike the SFS upland, the road was reclaimed by dragging over adjacent materials (Table 2c). Rapid forest regeneration occurred on the cutblocks. Visual observations suggest that aspen suckers exceeded 1 m by the end of the first year of regeneration and 1.5 m by the end of the second year of regeneration.

The NFS upland on the reference catchment was instrumented midway through the 2007 field season. Hydrometric data from the SFS upland on the reference catchment is presented under uncut conditions. For this thesis, hydrometric data were collected on this upland starting mid-growing season in 2007 and continued during 2008 representing uncut conditions. Foot traffic was limited to specific hiking trails as best as possible to avoid disturbance.

2.2.2 Catchment Delineation, Upland Boundaries, and Site Elevations

Preliminary catchment and upland boundaries were determined from air photos (1:20 000), topographic maps (1:5 000) derived from a 5 metre digital elevation model (DEM) and personal communication with Kevin Devito (Sept. 2009). The DEM was collected during a light detection and ranging (LIDAR) flight survey in 2002 and was provided by Irena Creed at the University of Western Ontario. A contour map for plan-view illustrations of upland sites and instrumentation was built using ARC GIS 9.0 (ESRI software). Detailed study site elevations (e.g. ground surface, top of the piezometer and well casings) were determined through manual surveys, using a stadia rod and automatic level.

2.2.3 Precipitation

Gross snow water equivalent (SWE) was measured using two to three anti-freeze filled automated tipping buckets located in open areas during the winter period on the reference and experimental catchment. Daily rainfall amounts were measured using the same automated tipping bucket on each study catchment during the growing season. Precipitation measurements in open areas were complemented using five manual bulk rain gauges during the growing season. Tipping buckets and manual hand gauges selected for analysis are listed in Table 3 and instrument locations are depicted in Figure 4.

2.2.4 Soil Water Content

Soil water content (mm) was determined in the bulk of the root zone. The bulk of the root zone was defined by the top 50 cm of mineral soil below the forest floor (Elliott *et al*., 1998; Whitson *et al*., 2005; Brown, 2010 and Snedden pers. comm.). The soil water content was monitored through manual in-situ measurements using the Delta T PR1 and PR2 profile probes. The manual measurements collect soil water values at vertical depths of 10 cm, 20 cm, 30 cm, and 40 cm below the ground surface. At each depth, three measurements were collected by rotating the profile probe (PR1 or PR2) 120 degrees.

Three to five access tubes representing each aspect were used to capture some of the soil variability. Access tubes were installed on the reference NFS in July 2007 to complement the existing network of access tubes set up prior to clear-cutting (Redding, 2009). Access tubes were installed into the soils of all land cover units (i.e. uplands, riparian zone, peatland) in both the reference and experimental catchment but only those access tubes located in aspen uplands are reported here. Access tubes selected for analysis are listed in Table 3 and instrument locations are depicted in Figure 4.

The access tubes were installed using a 2.5 cm hand auger and the factory insertion rod. Soil characteristics were documented every 10 cm during installation using finger rubs. The access tubes were monitored twice a month during the growing season in 2007 and every 3 days in 2008. The profile probes do not sense ice due to the low dielectric constant, and therefore measurements were not made during the frozen period.

2.2.5 Soil Tension

Soil tension was measured in the root zone through manual in-situ measurements of nested Jet Fill manual tensiometers (Soil Moisture Equipment Corp.). A minimum of two tensiometer nests with a minimum of three measurement depths (25 cm, 50 cm, 75 cm and/or 100 cm) were installed on each of the uplands. Manual tensiometer nests selected for analysis are listed in Table 3 and instrument locations are depicted in Figure 4. The tensiometers were inserted in the ground using a 2.5 cm hand auger. The porous cup was pushed to the target depth by gently pounding the tensiometer body using a rubber mallet and subsequently sealing the borehole with a soil slurry mixture to assure effective contact with the substrate. Manual tensions were monitored every three days during the summer field season 2007 (end of May to mid-September) and every day (of the 10-day work shift) during the summer field season 2008.

2.2.6 Groundwater Levels

An extensive network of wells and piezometer nests were installed in previous years, starting in 1999, across both experimental and reference uplands to assess site variability and subsurface flow path at the upland scale. Wells and piezometers selected for analysis are listed in Table 3 and instrument locations are shown in Figure 4. The last set of wells and piezometers were installed on the NFS upland in the reference catchment halfway through the growing season in July 2007.

Piezometers were constructed with PVC or ABS piping with 15 to 150 cm long slotted ends installed at depths between 50 and 2200 cm. Groundwater wells were also constructed with PVC or ABS piping slotted along their length and were installed at most piezometer nests in addition to various other locations within the catchments. The pipe diameters range from 2.5 cm to 5 cm. Most pipes were placed in the ground with sand around the slotted portion but this was not the case for all of the pipes. Wells and piezometers were sealed with bentonite clay when necessary to prevent contamination by surface water. Pipes installed in the pond-peatland complex were inserted into holes with a smaller diameter than the pipe to ensure a tight fit with the surrounding peat. Upland lithology was determined from visual inspection and finger rubs of cores collected during piezometer and well installation.

Groundwater levels were monitored in the uplands through manual in-situ measurements using the TLC (temperature, level and conductivity) water level tape (Solinst brand). Groundwater levels were monitored once every 6 weeks during the winter, every couple of days during the melt period (April-May) and once a day (during the 10 day work shift) for the rest of the summer in 2007. Groundwater levels were monitored monthly in the fall (September-November). Groundwater levels were monitored at a similar frequency in 2008.

2.2.7 Lateral Saturated Hydraulic Conductivity

The lateral saturated hydraulic conductivity was measured in the field at several upland locations using bail tests (Freeze and Cherry, 1979). The water inside the wells and piezometers was removed using a bailer or waterra. The recovery of the water level was monitored over time using manual measurements or continuous water level recorders (HOBO brand) every 30 seconds. The recovering water levels were monitored until a constant level was reached. The sites measured represent a sub-set of all the sites located across the study catchments.

2.3 Hydrometric Approach

The upland water regime under uncut and first- and second-year regeneration conditions was assessed based on a hydrometric approach using precipitation, root zone water content, soil tension, water table, and piezometric measurements (Figure 6). Due to the possible dominance of vertical flow in this environment (Elliott *et al*., 1998; Whitson *et al*., 2003; Whitson *et al*., 2004; Redding and Devito 2008), the analysis began at the top of the soil profile with the estimation of gross precipitation input for 2007 and 2008. The second step of the analysis was to assess the change in root zone water content to determine whether or not the potential storage was exceeded under clear-cut compared to under uncut conditions. The third step of the analysis was to determine whether the water content in the root zone was taken up by the vegetation via up flux or infiltrated past the roots into the deeper unsaturated zone. The difference between vegetation uptake and recharge was assessed using the soil tension measurements. The last step of the analysis was to assess changes in the water table under different depths below the ground surface and address groundwater linkages by comparing the water table elevation between uplands and adjacent pond-peatland complexes. Water table elevations were also used to address groundwater linkages between the perched peatland at the top of the experimental SFS hummock and the uplands downslope. These results were used to infer the scale of hydrological disturbance in response to upland clear-cutting (Figure 6).

2.3.1 Precipitation

The first step of the analysis consisted of separating the precipitation into SWE and rain inputs for the 2007 and 2008 hydrologic year. The proportion of gross SWE and rain was estimated using an air temperature threshold of 2ºC (Murray, 1952). The net SWE input during spring-melt was estimated by compiling the gross SWE from November 1 to April 31 and applying a 30% loss due to winter sublimation (Maidment, 1993; Devito and Mendoza, 2006). The total net spring input was estimated based on the net SWE and rain that occurred during this time. Total summer precipitation was calculated based on the gross precipitation from May 1 to August 31 and the total precipitation was determined using gross precipitation from November 1 to October 31. The precipitation during both hydrologic years was depicted using a bar graph with rain and SWE input. Monthly precipitation was shown using a time series and the precipitation event frequency distribution was shown using a bar graph.

Precipitation measurements were subsequently compared with those from the nearest Environment Canada meteorological station at Red Earth Creek, located about 70 km north of the study site, to assure reasonable precipitation inputs into the catchment area. Furthermore, the hydrologic years at the study site were put into climatic context by comparing the precipitation, runoff and runoff coefficient trend for Red Earth Creek from 1998-2008. Monthly runoff was estimated using the following equation (Equation 1):

$$R = \frac{QS}{CA} \times 1000 \qquad \text{(Equation 1)}$$

where R is the monthly runoff (mm), Q is monthly discharge (m/s), S is the number of seconds for a given month (s) and CA is the catchment area for Red Earth Creek (619 km^2). Annual runoff was then estimated by the sum of the monthly runoff values. Annual runoff coefficients were estimated by dividing the annual runoff with the total precipitation input for a given hydrological year. These precipitation results were organized in a data table.

2.3.2 Root Zone Water Content

The second step of the analysis was to calculate water content in the upland root zone. Access tube sites were not randomly selected for analysis because of the variability in topographic characteristics. Sites selected for soil water content analysis had to meet four requirements: (1) sites needed to be located at the crest and slope position on the hummock, (2) the depth to the water table had to be $\geq$ 50 cm from the ground surface during the entire measurement period, (3) the forest floor had to be 6-10 cm deep and (4) all soil moisture sites needed to be measured during every monitoring day to avoid measurement bias due to site selection.

The three measurements collected in the field were subsequently averaged at each sensor depth. The field measurements in the root zone were collected in mV units using the PR1 and PR2 soil moisture instruments. Instrument calibration showed that these instruments are reasonably insensitive to differences in soil texture (Figure A.1, Table A.1). However, each instrument proved to generate considerably different volumetric moisture content (VMC) measurements on the same day and site location. To address this issue, a relationship between the PR1 and PR2 instrument was developed using the data collected on two different days at six different locations by both instruments. All PR1 measurements were then converted to an equivalent PR2 value using the following relationship (Equation 2; R^2= 0.89):

$$Y_{PR2\ equivalent} = 1.80Y_{PR1}+71.23 \qquad \text{(Equation 2)}$$

where $Y_{PR2\ Equivalent}$ is the PR2 equivalent reading in mV and Y_{PR1} is the PR1 mV reading (Figure A.2). All PR2 and PR2 equivalent mV measurements were then converted to a VMC using an exponential equation applied to the factory calibration data. The exponential equation assured a physical basis in the lower range of the soil moisture spectrum so that no below-zero soil water content values would be observed (Equation 3; R^2=0.99).

$$VMC= 0.013^{\ 0.0039Y_{PR2}} \qquad \text{(Equation 3)}$$

In Equation 3, VMC is the volumetric moisture content (m^3 of water/m^3 of soil) and Y_{PR2} is the raw mV reading of the PR2 and PR2 equivalent value (Figure A.3). The Y_{PR2} can be measured directly using the profile probe (PR2) or calculated using Equation 1. Subsequently, the VMC values at 10, 20, 30 and 40 cm below the ground were integrated over 50 cm. The water content in mm was calculated in soil increments using the corresponding VMC measurement and summed across 50 cm. For example, the water content in the top 10 cm of mineral soil was calculated using the first sensor at 10 cm below the ground. The VMC at this sensor depth was multiplied by 10 to account for the depth of soil and multiplied by 10 again to convert the value into millimetres of water. This procedure was done for each soil increment up to 50 cm. The water content in the top 50 cm of mineral soil was calculated by the sum of the water content in each of the soil increments and expressed as water content in millimetres.

To assess change in storage over time, the growing season was separated in three time periods referred to as “Early Green,” “Green,” and “Senescence.”Each time period was defined based on visual changes in the daily potential evapotranspiration. The delineation of the different time periods was verified using soil tension measurements in the root zone. In 2007, the Early Green period was constrained from the first measurement of the season on April 27 to June 10. The Green period was defined from June 11 to September 2. The Senescence period started from September 3 to the last measurement on September 30. In 2008, the onset of the growing season began later, limiting the Early Green period to the time from May 8 to June 16. The Green period was defined from June 17 to August 28. The Senescence period started from August 29 to October 19. Box plots were built for each of these periods to represent the variability in root zone water content observed in the uplands under uncut and first- and second-year regeneration conditions for 2007 and 2008.

2.3.3 Soil Tension

The third step of the analysis was to assess the balance between vegetation water demand and infiltration past the root zone. The water potential measurements collected using the manual tensiometers were converted to negative pressure head values using the following equation (Equation 4):

$$\psi = \frac{P}{\rho g} \qquad \text{(Equation 4)}$$

where Ψ is the negative pressure head (m), P is the gauge pressure (Pa) measured in the field, ρ is the density of water (1000 kg/m^3), and g is acceleration due to gravity (9.81 m/s^2). The negative pressure head was subsequently converted to total unsaturated hydraulic head using the following equation (Equation 5):

$$h = z + \psi \qquad \text{(Equation 5)}$$

where h is the total unsaturated hydraulic head (m), z is the elevation above sea level of the ceramic cup (m), and ψ is the negative pressure head at a particular depth below the ground (m). The vertical hydraulic gradient between the root zone (25 cm) and below the roots (75 cm) was calculated using the following equation (Equation 6):

$$= \frac{\Delta h}{\Delta z} \qquad \text{(Equation 6)}$$

where Δh is the difference between the hydraulic head in the bulk of the root zone at 25 cm and below the bulk of the roots at 75 cm (m) and Δz is the difference in elevation between the middle of the ceramic cup in the roots and below the root zone (m). The hydraulic gradient in the unsaturated zone provided insight on whether upflux (i.e. water moving from below the roots towards the root zone suggesting vegetation water demand) or potential recharge (i.e. water moving from the roots to below the root zone suggesting infiltration) was accountable for changes in soil moisture and subsequent water table dynamics. The unsaturated hydraulic gradients between the roots and below the root zone were calculated and depicted as a time series for the 2007 and 2008 growing season.

2.3.4 Water table levels below the ground surface

To address the impacts of clear-cutting on the water table, the water table levels were plotted as a time series based on depth below the ground surface to depict the yearly trend, including the timing of spring-melt and water table recession. The water table levels were also plotted under different depths below the ground surface to address the threshold where the surface hydrological processes become disconnected from the water table. The water table levels were also plotted as a time series under uncut and first- and second-year regeneration conditions to address the impacts of clear-cutting down the soil profile.

2.3.5 Groundwater Linkages to Adjacent Pond-Peatland Complexes

Groundwater linkages were addressed by calculating the water table elevations and the lateral hydraulic head gradients from the upland crest and slope positions to the adjacent pond-peatland complexes. Lateral hydraulic head gradients from the upland crest and slope positions to the adjacent pond-peatland complexes were calculated using the following equation:

$$= \frac{\Delta h}{\Delta l} \qquad \text{(Equation 7)}$$

where Δh is the water table elevation difference between the upland site and the pond-peatland complex site and Δl is the distance between both sites.

The number of days where the upland slope and crest positions were hydrologically linked via groundwater to the adjacent pond-peatland complexes was determined by adding up the days where the upland water table elevation was above that of the respective pond-peatland complex. Lateral hydraulic head gradients and the number of days of hydrological linkage were calculated under uncut and first- and second- year regeneration.

Unlike the other uplands, the experimental SFS has a perched peatland located at the top of the hummock which has the potential to act as a source of water to the entire experimental SFS. To address the influence of the perched peatland, the water table elevation in the perched peatland was plotted with the water table elevation on the experimental SFS upland. The lateral hydraulic head gradients from the perched peatland to the adjacent upland crest and slope area were calculated throughout the measurement period (Equation 7). These values were then compared to the lateral hydraulic gradients from the experimental SFS to the adjacent pond-peatland complex.

2.3.6 Vertical Hydraulic Head Gradients

Water table elevations were also used to calculate the vertical hydraulic head gradients in the upland aquifer to compare the balance between the horizontal and vertical component of the upland water movement. The vertical hydraulic gradients were measured between the higher permeability oxidized layer and the lower permeability anoxic confining layer at piezometer nests located at the crest positions in the uplands. The vertical hydraulic head gradients were calculated using the following equation:

$$= \frac{\Delta h}{\Delta z} \qquad \text{(Equation 8)}$$

where where Δh is the water table elevation difference between the water level in the oxidized layer and the anoxic layer (m asl) and Δz is the distance between the mid-screen point of both piezometers (m).

2.3.7 Lateral Saturated Hydraulic Conductivity

The lateral saturated hydraulic conductivity was estimated using the Hvorslev (1951) method. Hvorslev (1951) reasoned that the rate of inflow through the well and/or piezometer screen is proportional to the lateral saturated hydraulic conductivity of the soil as well as the uncovered head difference at any given time. The water level recovery over time, collected in the field, was normalized using the following equation (Equation 9):

$$\frac{\mathrm{H-h}}{\mathrm{H-Ho}} \qquad \text{(Equation 9)}$$

where H is the water level at equilibrium, h is the recovering water level and Ho is the initial water level following the bail test. The normalized head difference was then used to estimate the basic time lag, To, using the following equation (Equation 10):

$$\frac{\mathrm{H-h}}{\mathrm{H-Ho}} = e^{-t/To} \qquad \text{(Equation 10)}$$

where t is the time elapse at a particular h. Using the fact that for H-h/H-Ho = 0.37, ln (H-h/H-Ho) = -1, the time lag To = t. The specific value of To is measured graphically and the lateral saturated hydraulic conductivity is determined from the following equation (Equation 11):

$$\mathrm{Ksat} = \frac{R^2 \ln\mathrm{(L/R)}}{\mathrm{2LTo}} \qquad \text{(Equation 11)}$$

Where R is the radius of the screen and L is the length of the screen. The R and L value are constants and determined during the well and/or piezometer installation.

Chapter 3: Results

3.1 Precipitation

The climate variability during the study period provided the opportunity to contrast the impacts of clear-cutting on upland hydrology during a relatively wet year in 2007 and dry year in 2008 (Figure 7a). The total annual precipitation in 2007 was 530 mm, consisting of 344 mm of rain and 186 mm of snow water equivalent (SWE). The SWE accounted for 35% of the total annual precipitation with the bulk of the remainder falling as rain between May and October. The net spring input (November to April) in 2007 was 164 mm with a SWE component of 125 mm and rain of 39 mm. The 2007 net SWE is the highest observed in the last 10 years when compared to the data collected at the government meteorology station of Red Earth Creek (Table 1). Similar to the typical trend of the area, the majority of the precipitation (>50%) fell between the months of May and August (Figure 7b). Seven daily precipitation values exceeded the interception storage of a mature aspen stand in 2007, estimated at 15 mm (Riddell 2008) (Figure 7c).

The total annual precipitation in 2008 was 26 mm less than 2007 with a total input of 504 mm, where 325 mm entered the system in the form of rain and 179 mm as SWE (Figure 7a). The SWE accounted for 36% of the total annual precipitation, with the bulk of the remainder falling as rain between May and October. The net spring input in 2008 was 34 mm less than 2007 for a total of 130 mm with a rain component of 17 mm and a SWE of 113 mm (Table 1). As in 2007, the majority (>50%) of the precipitation fell between May and August (Figure 7b). Seven daily precipitation values exceeded the leaf interception storage (Figure 7c).

3.2 Root Zone Water Content

Water content in the root zone under uncut conditions on the reference SFS showed a consistent pattern with (1) a maximum value during the Early Green period, followed by (2) depletion during the Green period continued with (3) further depletion or slight increase during the Senescence period (Figure 8 a, b and c). It is assumed that the snowmelt and rainfall that occurred in April of each year accounted for the high soil water content during the Early Green period. The water content in the root zone during the Early Green period is comparable between the years despite considerable difference in spring-melt input suggesting that these sites reached field capacity.

During the Green period, the root zone water content decreased by 21 mm in 2007 and 4 mm the following year suggesting that trees satisfied their water demand from soil storage in the root zone under uncut conditions on the reference SFS. The water content remained higher in 2008 because several daily precipitation events exceeded the leaf interception storage replenishing the soil storage (Table 4). The water content during the Senescence period increased by 4 mm in 2007 but decreased by 4 mm in 2008 contradicting the precipitation inputs during each year. The net change in root zone water content was negative, decreasing by 17 mm in 2007 and 8 mm in 2008 under uncut conditions on the reference SFS during the measurement period. Similarly, the net change in root zone water content was negative decreasing by 41 mm on the uncut experimental NFS in 2007 and by 17 mm on the reference NFS in 2008 (Table 4).

During the measurement period of the first-year of regeneration, the water content in the root zone decreased by 2 mm during the Green period and increased by 4 mm during the Senescence period, resulting in a net increase of 2 mm on the SFS in 2007 (Figure 8d). This net increase resulted in an accumulation of 19 mm more than uncut conditions of similar aspect (Table 4). During the first-year of regeneration the following year, no net increase was observed on the NFS with minimal changes during the growing season. The absence of changes in soil water content on the NFS resulted in an accumulation of 17 mm more than uncut conditions of similar aspect (Figure 8c).

The water content in the root zone during the second-year of regeneration, on the SFS in 2008, showed a net decrease of 2 mm, with a trend comparable to uncut conditions with (1) a maximum value during the Early Green period, (2) a decrease during the growing season, and (3) a slight increase during the Senescence period (Figure 8d). The decrease in soil water content during the Green period was comparable in magnitude to that under uncut conditions of similar aspect, suggesting a recovery of transpiration processes by the second-year of regeneration (Table 4).

3.3 Unsaturated Hydraulic Gradients

The unsaturated hydraulic head gradient between the roots (25 cm) and below the roots (75 cm) under uncut conditions was characterized by (1) potential water table recharge during the Early Green period, (2) upflux conditions interrupted by potential water table recharge events during the Green period and (3) potential recharge into the deeper unsaturated zone during the Senescence period in both 2007 and 2008 (Figure 9a and b). In 2008, the mean hydraulic gradient on the reference SFS was 1.87, with individual values ranging from 0.39 to 2.84 throughout the Early Green period, sustaining potential water table recharge. During the Green period of the same year, the hydraulic gradient ranged from -10.63 to 5.89, where negative values support upflux and positive values support potential recharge into the deeper unsaturated zone. By the Senescence period, the mean unsaturated hydraulic head of 2.15 supported continuous potential recharge, into the deeper unsaturated zone, with individual values ranging from -1.51 to 6.51 (Figure 9b). The hydraulic gradient magnitude was comparable in 2007 despite the lower frequency in measurements. The reference NFS showed a comparable trend with more recharge events and weaker upflux gradients, suggesting that the SFS had greater water use potential (Figure 9a).

Unsaturated hydraulic head results during the first-year regeneration on the SFS in 2007 showed sustained potential water table recharge throughout the field season (Figure 9d). The mean unsaturated hydraulic gradient was 0.81 (site 602), with individual values ranging from -1.45 to 2.84, with three upflux instances observed in late August (data not shown). Similarly, results during the first-year of regeneration on the NFS the following year showed sustained potential recharge into the deeper unsaturated zone with a mean gradient of 1.06, with individual values ranging from 0.10 to 2.09, with no instances of upflux for the entire field season (Figure 9c). The constant recharge potential into the deeper unsaturated zone during the first year of regeneration suggests strong potential for water table impacts.

The unsaturated hydraulic head gradients recovered to a magnitude and trend comparable to those under uncut conditions by the second-year of regeneration in 2008 (Figure 9d). The trend recovered to (1) recharge potential throughout the Early Green period, (2) upflux interrupted with potential water table recharge events during the Green period followed by (3) constant potential for potential recharge into the deeper unsaturated zone during the Senescence period (Figure 9d). The unsaturated hydraulic head averaged 2.77, with individual values ranging from 1.88 to 4.93 during the Early Green period. Throughout the Green period, unsaturated hydraulic gradients ranged from -9.54 to 6.24. Potential recharge into the deeper unsaturated zone dominated the response despite a recovery of upflux conditions. The mean unsaturated hydraulic head increased to 6.45, with individual values ranging from 0.86 to 9.24 by the Senescence period. The quick recovery of upflux conditions reduces the opportunity to observe substantial water table impacts during the second year of regeneration following clear-cutting.

3.4 Water Table Impacts

The hydrograph of uncut sites where the water table is less than 600 cm below the ground surface was characterized by an obvious spring-melt peak suggesting that the soil storage was recharged to field capacity above this depth (Figure 10a and b). The spring-melt peak was followed by a recession trend, where the timing coincides with the period of vegetation growth and thus water demand (Figure 11a). The recession trend was attributed in part to the onset of vegetation water demand as inferred by the timing of upflux conditions (Figure 11b). Sites with more than 600 cm of storage responded minimally if at all to spring-melt or summer rain inputs, suggesting that water exchanges with the atmosphere occurred to and from the unsaturated zone only.

The hydrograph of first-year regeneration sites where the water table is less than 600 cm below the ground surface experienced a large increase in water level compared to sites under uncut conditions in both 2007 and 2008. The greater increase in water table level on the cutblocks, compared to that under uncut conditions, was attributed to enhanced water table recharge inferred by the positive unsaturated hydraulic gradients throughout the first-year of regeneration in both years of study. The dominance of potential water table recharge during the first-year of regeneration could sustain rising water table levels on both the SFS (Figure 10c) and NFS (Figure 10b) cutblocks, in response to spring-melt and summer rain inputs during the growing season, unlike that under uncut conditions (Figure 10a and b).

The hydrograph of all clear-cut sites responded to spring-melt with a peak in water table level during the second-year of regeneration on the SFS cutblock in 2008. Sites with a water table less than 400 cm below the ground surface began to show a water table recession trend comparable to range observed under uncut conditions (Figure 10c). Sites with a water table more than 500 cm below the ground surface continued to generate more water than similar sites under uncut conditions, with a slight water table recession compared to the first-year of regeneration. Sites with a water table more than 750 cm below the ground surface responded to clear-cutting during the second year of regeneration. The large increase in water table level during the second year of regeneration at sites with a water table deep below the ground surface suggests a delay in the hydrologic response to clear-cutting due to the size of the unsaturated zone.

3.5 Groundwater Linkages to Adjacent Pond-Peatland Complexes

Under uncut conditions, the water table elevation at sites with a smaller unsaturated zone above the water table, such as the sites located on the mid- or toe-slope, showed gradient reversals between the peak spring-melt and the end of the fall in 2007 and 2008 (Figure 12a, b and c). During peak spring-melt, the lateral gradients were positive, ranging from 0.002 to 0.02, supporting a maximum recharge to the pond-peatland complex from the uplands. By the end of the fall, the lateral gradients were negative, ranging from -0.02 to -0.01 suggesting that the uplands behaved as hydrological sinks for water from the adjacent pond-peatland complex (Table 5a). The gradient results on the reference SFS upland suggest that the slope area was linked to the adjacent pond-peatland complex via groundwater for 104 days in 2007 and 58 days in 2008. The gradient results on the reference NFS upland suggest that the slope area was linked the to the adjacent pond-peatland complex for 22 days in 2007 and 14 days in 2008.

Unlike the mid- and toe-slope areas, all uncut upland crest water table elevations remained below their respective pond-peatland complexes during the measurement period, despite the small increase during peak spring-melt (Figure 12a, b and c). The lateral gradients ranged from -0.03 to < -0.001, suggesting that the uncut crest areas acted as sinks for water from adjacent pond-peatland complexes under uncut conditions throughout the measurement period (Table 5b). The gradient results suggest that the crest areas accommodated water from the adjacent pond-peatland complex for the duration of the study under uncut conditions.

The absence of a strong vegetation influence during the first-year of regeneration, on the SFS cutblock in 2007, favoured recharge conditions resulting in a continued increase in water level following spring-melt (Figure 12c and d). The increase in water level sustained positive lateral gradients to the adjacent pond-peatland complex from the upland slope (Table 5a) and crest position (Table 5b), with values ranging from 0.01 to 0.03 respectively by the end of the fall.

Similarly, under first-year regeneration conditions on the NFS cutblock in 2008, the increase in water level following spring-melt and during the summer rains (Figure 12c) sustained positive lateral gradients ranging from 0.002 to 0.004 from the upland crest (Table 5b) and slope (Table 5a) areas respectively by the end of the fall. The groundwater gradients suggest that upland areas became sources of water to adjacent pond-peatland complexes by the end of the first-year of regeneration following clear-cutting. The absence of a strong recession trend during the first year of regeneration resulted in a groundwater linkage from the slope area to the adjacent pond-peatland complex for more than 175 days in 2008 compared to 73 under uncut conditions the previous year.

By the second-year of regeneration, the upland slope and crest position had the largest positive lateral gradients compared to uncut and first-year regeneration despite the recovery of the water table recession trend (Figure 12d). The positive lateral gradients ranged from 0.03 to 0.038 for slope (Table 5a) and crest (Table 5b) areas respectively during peak spring-melt favouring the recharge of the adjacent pond-peatland complex. Lateral gradients decreased to 0.02 on the slope and 0.03 on the crest position by the end of the fall. Despite the small decrease in the fall, the positive lateral gradients during the first- and second-year of regeneration resulted in groundwater linkages lasting more than 535 days between the slope and adjacent pond-peatland complex on the experimental SFS for the duration of the study.

3.6 Lateral Hydraulic Head Gradients from Perched Peatland

The water table elevation in the perched peatland located at the top of the experimental SFS hummock remained above the water table elevation of the upland slope and crest area (Figure 13a). The high water table elevation suggests that the perched peatland may have been a source of water to the cutblock during the study period. Having a source of water in close proximity may have enhanced the clear-cutting impacts on the experimental SFS cutblock.

The lateral hydraulic head gradients from the perched peatland to the crest and slope area of the experimental cutblock remained positive and slightly greater than those observed across the hillslope to the pond-peatland complex despite rising water table levels (Table 6). The gradients from the perched peatland to the experimental SFS cutblock ranged from 0.06 to 0.17 in 2007 and 0.03 to 0.08. These values suggest that the perched peatland on the experimental SFS had a slightly greater potential to provide water to the cutblock than did the cutblock to the adjacent pond-peatland complex.

3.7 Vertical Hydraulic Head Gradients

Unlike the lateral gradients, the vertical gradients between the higher-permeability oxidized layer and the lower-permeability anoxic layer at the upland crest positions showed large values, ranging from 0.13 to 0.58 under uncut conditions (Table 7). The large vertical gradients were 1 to 3 orders of magnitude greater than lateral gradients.

During the first year of regeneration, vertical gradients between the higher-permeability oxidized layer and the lower-permeability anoxic layer at the crest position were about 2 to 10 times greater than lateral gradients. On the SFS in 2007, the vertical gradient was 0.11 during peak spring-melt and decreased to 0.06 by the end of the fall. On the NFS in 2008, vertical gradients reached 0.57 by the end of the fall (Table 7).

Vertical gradients in the upland crests were comparable in magnitude to lateral gradients into the adjacent pond-peatland complexes by the second-year of regeneration. The vertical gradients ranged from 0.05 at peak spring-melt to 0.02 by the end of the fall (Table 7). The positive vertical gradients throughout the measurement period suggest that the study site functions as a recharge area.

Chapter 4: Discussion

4.1 Unsaturated Zone Storage and Movement

The water content in the root zone during the first-year of regeneration, in both 2007 and 2008, was not considerably higher than the water content under uncut conditions, as expected based on the findings of Elliott *et al*., (1998), who detected wetter soils in cut areas on the northern Saskatchewan Boreal Plain. In our study, a net increase in water content of 2 mm in the root zone of the SFS was observed, which resulted in an accumulation of 19 mm more than under uncut conditions of similar aspect during the first-year of regeneration in 2007. Similarly, the NFS accumulated 17 mm more than under uncut conditions of similar aspect during the first-year of regeneration in 2008.

While the net changes in root zone water content are positive compared to those found under uncut conditions for the respective years, these values are low compared to the expected increase in net precipitation input due to a reduction in leaf interception and transpiration after clear-cutting (Buttle *et al*., 2000). The lack of substantial difference between cut and uncut in our study was attributed to the large variability in soil texture across the different soil moisture sites, which averaged out the response to clear-cutting. For example, on the experimental NFS in 2008, the water content at some sites went up and others went down, while some did not change averaging the central tendency to a no-change response. Whitson *et al*., (2005) and Macrae *et al*., (2005) also found no considerable difference in the root zone water content between cut and uncut uplands. The absence of considerable difference in root zone water content between cut and uncut conditions was attributed to the rapid regeneration of aspen suckers, which restored the soil microclimate in cut areas to near pre-cut levels, and/or the drought conditions observed during the study period.

While the relative net change in root zone water content under cut conditions is more or less comparable between years, there is considerable difference in the absolute water content between the different cut uplands. The discrepancy in the absolute value of root zone water content between the years can be explained by differences in water-holding capacity of the different upland soils (Fernandez-Illesca *et al*., 2001). Site-specific finger rub analyses show that more sites selected on the experimental NFS have higher clay content, while more sites selected on the experimental SFS have higher sand content in the top 50 cm. The texture differences imply that the NFS had the potential to accommodate more water in the unsaturated zone. Considerable variability in soil water content within sites was also observed by Elliott *et al*., (1998) and was attributed to the influence of differences in canopy structure and density on precipitation inputs. The variability in soil water content observed between the different cutblocks emphasizes the need for accurate characterization of site-specific soil properties and canopy structure and density to predict difference in soil water content between sites.

The unsaturated hydraulic gradients support a potential to fill the deeper unsaturated zone during the first year of regeneration following clear-cutting. The positive unsaturated hydraulic gradients suggest that the addition of water in the root zone of some clear-cut sites, due to a reduction in leaf interception storage and evapotranspiration, had the potential to displace water already held in storage via a process called piston flow. The new water entering the unsaturated zone at the ground surface can push water already held in storage in a downward direction, filling up the deeper unsaturated zone during the first-year of regeneration (Redding, 2009).

Similar to the soil water content, the unsaturated hydraulic gradients showed considerable variability between sites, suggesting that the magnitude of vertical flow will vary from one site to another. The variability between the sites is attributed in part to spatial differences in soil texture across the sites selected for analysis due to the glacial nature of the sediments. Aspect introduces further variability due to the uneven distribution of energy between north-facing and south-facing slopes. For example, sites located on south-facing aspects receive more solar energy resulting in higher rates of evapotranspiration compared to north-facing slopes (Brown *et al.*, 2010). The uneven distribution of solar energy between the different slopes is apparent during the growing season where south-facing conditions experienced more instances of upflux than the north-facing conditions.

Studies have shown that the mechanical disturbance of soils during clear-cutting activities reduces soil storage and infiltration capacities, especially in fine textured soils (Whitson *et al*., 2003). The degree of disturbance is influenced by the timing of clear-cutting, where winter clear-cutting on frozen ground has been shown to minimize soil disturbance (Startsev and McNabb 2000). Startsev and McNabb (2000) showed that infiltration rates were still above the typical precipitation intensities found in the Boreal Plain, despite a slight reduction due to clear-cutting disturbances. These infiltration studies imply a dominance of vertical flow in the sub-humid Boreal Plain despite winter clear-cutting disturbances.

The unsaturated hydraulic gradient trend was comparable to uncut conditions by the second-year of regeneration suggesting recovering evapotranspiration processes despite the spatial variability in geology inherent to glacial sediments. Upflux was not the dominating process, as observed under uncut conditions of similar aspect, because more instances of recharge conditions were observed during this time. The greater instances of recharge into the deeper unsaturated zone suggest that the hydraulic gradient magnitude was still in process of recovery.

The trend recovery of unsaturated hydraulic gradients by the second-year of regeneration agrees with studies that highlight the quick aspen re-growth after clear-cutting. Winter logging usually promotes abundant suckering and growth compared to spring or summer clear-cut (Frey *et al*., 2003). Furthermore, clear-cutting is the recommended silvicultural system for aspen, because it stimulates suckering on the greatest amount of clonal roots and minimizes shading from residual vegetation (Bates *et al*., 1993). Injured aspen roots have also been shown to produce more suckers per root, with taller saplings having greater leaf area compared to uninjured roots (Fraser *et al*., 2004). My findings suggest a narrow window of opportunity to observe considerable water table impacts via recharge through the unsaturated zone. Water table impacts due to clear-cutting appear to be limited to the first-year of regeneration when vegetation influence is at a minimum.

4.2 Unsaturated Zone Influence on the Water Table

The soil water content and unsaturated hydraulic gradients suggest that the bulk of hydrological impacts due to clear-cutting likely occurred during the first-year of regeneration. Despite the natural wetting trend during the years of study, clear-cutting resulted in a greater increase in water table level during the first-year of regeneration, than under uncut conditions, on both cutblocks at water table levels below the ground surface ranging from 200-600 cm in 2007 and 2008.

The comparable water table response between both years of study was not expected because the soil texture of the SFS has a higher clay content, suggesting that the soil above the water table could accommodate more water, which could limit the impacts on the water table. However, clear-cutting of the SFS in 2007 coincided with a wet year that was characterized by a large SWE and higher total precipitation, suggesting that the climate may have exacerbated the impacts of clear-cutting, resulting in comparable results between the two cutblocks.

The fast aspen regeneration resulted in the recovery of a water table recession trend at sites where the water table was less than 600 cm below the ground surface by the second-year of regeneration. The recession trend recovery resulted in a hydrograph comparable to that under uncut conditions at sites where the water table was less than 400 cm below the ground surface, suggesting a hydrologic recovery at shallower depths by the second-year of regeneration.

Unlike shallower depths, the water table level at sites where the depth to the water table was 400-600 cm below the ground surface went up more than uncut conditions, despite the recovery of a recession trend. However, the magnitude of increase was slightly less than the first-year of regeneration. Interestingly, sites with a water table more than 750 cm below the ground surface wet up during the second spring-melt following clear-cutting. The delayed response at these sites suggests a 1 to 1.5 year delay for hydrological impacts due to the depth of the water table. The smaller snowpack in 2008 may have encouraged the quick recovery of the water table trends by forcing the regenerating vegetation to acquire water held in storage from the previous year to sustain the water demand (Rodriguez-Iturbe 2000).

4.3 Groundwater Linkages to the Adjacent Pond-Peatland Complex

The increase in water table level sustained positive lateral gradients from the uplands to the adjacent pond-peatland complex during both the first-year of regeneration on the experimental NFS cutblock as we as the first- and second-year of regeneration on the experimental SFS cutblock. The positive lateral gradients show that upland areas became sources of water to the adjacent pond-peatland complex for a longer period of time when compared to uncut conditions. Positive lateral gradients were also observed from the perched peatland at the top of the experimental SFS hummock and remained higher than those from the uplands to the adjacent pond-peatland complex. Having a source of water in close proximity may have enhanced the clear-cutting impacts and climate effects on the experimental SFS cutblock.

The increase in water table level also induced vertical gradients between the water table surface in the oxidized zone and below in the anoxic zone about 2 to 10 times greater than lateral gradients during the first-year of regeneration. The large vertical gradients suggest that vertical recharge controlled the movement of water during the first-year of regeneration. The vertical gradients in the upland crests became comparable to lateral gradients by the second-year of regeneration, suggesting that vertical recharge and lateral flow controlled the movement of water in the uplands by the second year of regeneration.

While the gradients favoured water movement across the uplands to the pond-peatland complexes, groundwater fluxes are likely negligible due to the low permeability of the clay-rich substrate (Winter and Rosenberry, 1995, Rosenberry and Winter, 1997; Ferone and Devito, 2004). However, exact soil characteristics are required to make more accurate estimates of water budget calculations. McEachern *et al*., (2006) also showed that upland-sourced water did not form an important portion of discharge during spring-melt or the growing season. It has also been suggested that the presence of hydraulic depressions at the base of the uplands in this terrain can accommodate potential input of water from adjacent uplands, thus helping mitigate part of the upland water input (Ferone and Devito, 2004, Burt and Haycock, 1996).

Our results concur with the simulations reported by Swanson and Rothwell, (2001) showing that the effects of aspen clear-cuts on water yield can vanish in as little as two years under low precipitation conditions. Similarly, Verry *et al*., (1983) found that aspen recovery returned water yields to pre-disturbance levels after two years in north-central Minnesota, suggesting that large soil storage potential and fast aspen regeneration could mask or reduce clear-cutting impacts. The potential for upland clear-cutting impacts on water yield is low in this environment due to the large soil storage potential relative to the climate water deficit, the low frequency of large storms (>30 mm/day), and the low saturated hydraulic conductivity (Devito *et al*., 2005a, Redding and Devito, 2008).

4.4 Cryptic Reservoirs

Clear-cutting resulted in a dominance of vertical flow in the unsaturated zone during the first year of regeneration. During this time, the water content in the saturated zone increased generating positive gradients towards the adjacent pond-peatland complexes. The low saturated hydraulic conductivity resulted in small lateral and vertical fluxes suggesting that uplands function as an isolated hydrological unit and that the impacts of forest removal are confined to the upland scale (Figure 14).

These observations support the concept of cryptic reservoirs developed by McDonnell (2003) who put forward the notion that a catchment is made up of a series of buckets that have explicit dimensions with coupled saturated and unsaturated zones which are connected vertically and laterally in time and space to adjacent cryptic reservoirs in linear and non-linear ways. This framework has been used to explain the shortfall of the steady state assumption along a hillslope in a Swedish till catchment at Svartberget. Results from Seibert *et al*., (2003) showed that the groundwater in upslope areas could be rising when the riparian groundwater was falling and vice versa on two opposing hillslopes along a stream reach. Ocampo *et al*., (2006) showed that the upland and riparian zone responded to rainfall events almost independently and differently, remaining disconnected from each other for much of the year. Similarly, Ferone and Devito (2004) observed the hydrologic isolation of pond-peatland complexes from adjacent uplands in the sub-humid Boreal Plain despite large gradients due to the low saturated hydraulic conductivity.

Our results provide further support for the prediction that the hydrological regime of pond-peatland complexes in the clay rich till region of the Boreal Plain are not likely to be sensitive to the disturbances taking place on the uplands (Ferone and Devito 2004). Despite the increase in water table and the development of large gradients in response to clear-cutting, the saturated hydraulic conductivity was low enough that a negligible flux of water was transferred across the hillslope during the time period of the study. McDonnell's (2003) systematic way of dividing the catchment into buckets allows for the construction of a reservoir-based conceptual model in which the upland box fills and spills laterally into a shallower box, then cascades into adjacent lowlands and streams. In the sub-humid Boreal Plain the dominant fluxes are vertical and the low permeability of the substrate suggests that the uplands behave as an isolated unit providing negligible water to adjacent lowlands even under clear-cut conditions.

Chapter 5: Conclusions and Management Implications

5.1 Summary of Major Findings

Understanding the controls on upland water movement is essential for the prediction of disturbance impacts on the sustainability of freshwater resources. Results in this study showed slightly greater soil water content in the root zone (0-50 cm) under cut conditions compared to uncut conditions. However, our results were not as high as expected based on the findings of Elliott *et al.*, (1998), who detected wetter soils in cut areas on the Northern Saskatchewan Boreal Plain. Differences in soil water content between my study and the one presented by Elliot *et al.*, (1998) can be attributed to climate variations between years.

Unsaturated hydraulic gradients sustained potential groundwater recharge during the first-year of regeneration. Water table impacts varied with depth to the saturated zone as influenced by soil properties and topographic position. Water table gradients towards adjacent pond-peatland complexes increased in both cut and uncut hillslopes due to high snowfall and summer rainfall. However, soils in cut sites accommodated more water than those under uncut conditions and upland linkages on the cut hillslope persisted for a longer period of time than forested conditions.

The positive gradients that developed in the uplands suggest that these cutblocks became potential sources of groundwater flow to adjacent wetland areas. While the gradients favoured water movement down the hillslope, groundwater fluxes are likely negligible due to the low permeability of the clay rich substrate (Winter and Rosenberry, 1995, Rosenberry and Winter, 1997). These results suggest that uplands behave as an isolated hydrological unit and that clear-cutting impacts are confined to the upland scale.

Soil water content, unsaturated hydraulic gradients and estimates of actual evapotranspiration recovered to trends comparable to those under uncut conditions during the second-year of regeneration, suggesting a quick recovery of evapotranspiration processes and implying a narrow window of opportunity to observe substantial hydrological impacts. Interestingly, sites with more than 750 cm of soil storage wet up during the second year of regeneration suggesting a 1 to 1.5 year delay due to the size of the unsaturated zone.

5.3 Management Implications

The results of this study have important implications for runoff generation at the catchment scale. Current hydrological models (e.g. TOP MODEL) assume that the shallow sub-surface flow system is connected up the hillslope and that the hydraulic gradient is similar to and in the same direction as the topographic gradient (Ocampo *et al.*, 2006). This study suggests that these assumptions do not hold true in the sub-humid Boreal Plain. The fact that the water table is not a subdued replica of the surface topography in the upland areas and that upland areas function as an isolated hydrological unit undermines the attractiveness of modeling the groundwater linkages in a catchment using surface topography derived by digital elevation models (Todd *et al.*, 2006). To adequately model the development and persistence of the water table configuration, hydraulic gradients and subsequent fluxes to adjacent water bodies, the upland areas needs to be monitored over time and at different topographic locations (i.e. slope and crest positions) (Winter and Rosenberry, 1997).

Goals for water yield and quality influence the acceptability of various silvicultural practices (Twery and Hornbeck, 2001). Based on the Alberta Timber Harvest

Planning and Operating Ground Rules Framework for Renewal, the predicted average annual water yield increase should not exceed 15% within third order streams (ASRD 2006). To mitigate the impacts of landuse activities (agriculture, clear-cutting, urban development etc.) on water, sediments, contaminants and nutrient fluxes from impacted areas to receiving streams, wetlands and lakes, riparian buffer strips have been reserved at the base of uplands adjacent to water bodies (Buttle, 2002). There is general agreement in the scientific community that riparian zones should be conserved in a natural state with the implicit assumption that water passes through these zones and that the processes going on can provide buffering functions from upland disturbance (Castelle *et al*., 1994, Burt and Haycock, 1996, Devito *et al*., 2000). This assumption does not hold true for every catchment, because uplands are not always hydrologically linked to riparian zones (Burt and Haycock, 1996).

In the case of our study site, the low hydraulic conductivity of the clay till limited flow from the uplands to regional groundwater flow systems. Furthermore, the low hydraulic conductivity also limited considerable lateral flow from the uplands to adjacent pond-peatland complexes. These low hydraulic conductivities set the bounds for the cryptic reservoirs where vertical water flow patterns dominate and water table impacts are a function of storage thresholds defined by the climate variability between years. It is clear from these results that landscape disturbance in these uplands, like clear-cutting, limits the hydrological impacts to the upland scale. Furthermore, the quick aspen regeneration, relative to conifer species, allows the rapid recovery of the transpiration regime suggesting that the hydrologic regime should be relatively quick to recover as well limiting the time for considerable hydrological impact.

5.4 Limitations of the Study

The impacts and recovery of clear-cutting were assessed over a period of two consecutive hydrologic years. In the sub-humid Boreal Plain, soil storage potential is controlled by the climate, which varies greatly from year to year. Althought 2007 and 2008 are characterized by different climates, the wetting and drying cycles can take several years and longer-term sampling is required to tease out these effects. Longer-term monitoring of water table dynamics under different climate regimes has been done and is ongoing at the reference and experimental catchment as well as other sites on different hydrological response units across the Utikuma Region Study Area. Longer-term monitoring of water table dynamics resulting from different combinations of seasonal rainfall and evapotranspiration regimes prior to and after disturbance is necessary to capture the natural range of soil storage potential.

In addition, spatially extensive soil characteristic measures (porosity, specific yield, hydraulic conductivity) have been not been done as part of this research but have been conducted as part of other HEAD 2 projects. Spatially extensive soil characteristic measures are essential to understanding spatial soil storage processes. Assessing the natural variability in soil moisture in the range of soil textures observed at a particular site is essential because of the large control soil texture exerts on the soil water regime in sub-humid climates (Rodriguez-Iturbe, 2000).

The spatial variability in soil water content was limited to the aspen uplands. However the spatial variability in soil water content has been monitored throughout and along numerous catchment length transects spanning the peatlands, riparian zones and uplands throughout the growing season from 2005 to 2009. The measurements of soil water content allow a detailed spatial assessment of the unsaturated zone water content from plan view as well as along a two dimensional transect.

While exact snow measurements were not analyzed during the course of this study, numerous catchment length snow transects were surveyed at least once a year each winter close to the maximum snow accumulation from 1999 to 2009 as part of the larger HEAD 2 project. These measurements assessed snow redistribution and interception by different vegetation cover types.

A serious attempt was made to make the spatial organisation of the different data layers (i.e. soil tension, soil water content, groundwater wells) it easy to understand and what parameter averaging was used in the analysis. However, some limitations arise in the interpretation when data is used from different parts of the catchment that are not spatially connected within local flow paths and could negate the paired-catchment approach. This inconsistency will be overcome with complementary data and/or data from other site locations as part of the final publication of the HEAD 2 project.

Lastly and most importantly, only the hydrometric approach was presented here to address the short-term impacts of clear-cutting and climate variability on upland groundwater recharge. As part of the HEAD 2 project, chemical and isotopic approaches have been used to complement the hydrometric approach presented in this thesis. Given the geochemical and isotopic data collected, end member mixing analyses or similar techniques can be conducted to verify the hydrological processes described in this thesis.

5.5 Future Research Direction

Complementary analyses are imperative to challenge and/or validate our understanding of the relationship between recharge, flow and discharge and to appreciate the disparities between general hydrological models like those observed in eastern Canada with the hydrological reality of the western Boreal Plain. The conceptual model developed from this project needs to be transferred and tested in similar and different environments to develop a more generalizable theory that can be the basis for future predictions. In particular, the role of soil storage controlled by climate variability must be examined under a wide range of climate conditions. A particular aim of future studies should be to develop a better understanding of the hydraulic gradients and water fluxes between adjacent landscape units since this is the least predictable aspect of the results presented here.

Tables

Table 1. Total net precipitation for winter (1Nov-30Apr), summer (1May-31Aug), and fall (1Sep-31Oct). Yearly gross precipitation (mm), runoff (mm), and runoff coefficients (%) are also shown for the Environment Canada meteorological station of Red Earth Creek (619 km^2, 70 km north of the study site) from 1998 to 2008 and the study site for 2007 and 2008. Hydrologic years were defined from November 1 to October 31.

Year	Net winter Precip. (mm)	Summer Precip. (mm)	Net fall Precip. (mm)	Total Gross Precip. (mm)	Runoff (mm); (%)	# of daily events >15 mm
Red Earth Creek						
1998	59	126	20	228	14 (6)	3
1999	**109	253	31	**423	5 (1)	4
2000	*56	246	35	*354	27 (8)	1
2001	*59	209	29	*316	21 (7)	1
2002	**63	132	76	**291	5 (2)	1
2003	75	262	55	425	53 (13)	4
2004	48	182	111	363	16 (5)	2
2005	120	229	20	411	79 (19)	3
2006	78	247	41	388	61 (16)	4
2007	148	175	52	430	90 (21)	2
2008	-	-	-	***389	41 (11)	-
Mean	**82**	**206**	**47**	**365**	**37(10)**	**2.5**
Study Site						
2007	164	273	39	530	-	7
2008	130	242	85	504	-	7

* February data missing and the data used here are based on the average of all other year for that month.
**March data missing and the data used here are based on the average of all other year for that month.
***November data missing and data used here are based on the sum from the study site for that month.
n/a: Precipitation data for Red Earth Creek has not gone through quality control at this time.

Table 2. The HEAD 2 experimental design showing uncut (green) and clear-cut (red) conditions for the reference and experimental catchments considering the different aspects (a), sampling regime for water table (WT) and soil, vegetation and atmosphere (SVAT) measurements (b), and date of various forestry activities during clear-cutting on the SFS in 2007 and NFS in 2008 (c).

(a)

Upland/Aspect	2005	2006	2007	2008	2009
REF./SFS	← - →				
REF./NFS	← - - - limited data - - - → ← - - - - - - - - - - - - - →				
EXP./SFS	← - - - - - - - - - - - - - - - - → ← - - - - - - - - - - - - - - - - →				
EXP./NFS	← - → ← - - - - - - - →				

(b)

Upland/ Aspect	2005	2006	2007	2008	2009
REF./SFS	-Basic WT -Full suit SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT
REF./NFS	-Basic WT -Basic SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT
EXP./SFS	-Full suit WT -Basic SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT	-Full suit WT -Full suit SVAT
EXP./NFS	-Basic WT	-Basic WT	-Full suit WT -Basic/full suit SVAT	-Full suit WT -Basic/full suit SVAT	-Full suit WT -Basic/full suit SVAT

(c)

Forestry Activity	South-facing Cutblock	North-facing Cutblock
Clear-cut date	March 8, 2007	February 8, 2008
Road building, wood cutting, processing and hauling	mid-April 2007 finish	mid-March 2008 finish
Slash piled	July 2007	March 30, 2008
Piles burned	mid-January	January 2009
Small piles left for habitat	Yes	Unknown
Road reclaimed	No	Yes

Table 3. Attribute table for the sites selected for hydrometric analysis for this thesis located on the study catchments at URSA. Sites with a hand gauge (HG) or tipping bucket (TB) were used for the precipitation measurements. Sites with an access tube (ACC) were used for the soil water content measurements. Sites with a tensiometer (TENS) were used for the unsaturated hydraulic head measurements. Sites with a well (W), shallow well (WSh), deep well (WDp) and/or piezometer (PIEZ) were used for the water table and groundwater linkage measurements. Missing information labeled as n/a and estimated values labeled with a star (*). The geographic reference system is WGS84 and location accuracy is ± 10 m.

Upland/ Aspect	Site	Site Easting (m)	Site Northing (m)	Equip. at Site	Equip. Attrib. (cm)	Equip. Install. Date	Top of Casing Elev. (m asl)	Ground Elev. (m asl)	Effective Screen Length (m)	Top Screen BG (m)	Bot. Screen BG (m)	Pipe diam. (cm)
REF./SFS	31	595323	6215381	WDp	250	29-Aug-03	655.29	654.50	1.82	0.61	2.42	*3.81
REF./SFS	31	595323	6215381	PIEZ	1000	n/a	655.20	654.47	4.27	5.15	9.42	*3.81
REF./SFS	33	595320	6215453	PIEZ	1100	n/a	663.69	662.83	4.57	6.65	11.22	*3.81
REF./SFS	86	595048	6215355	WSh	100	>1999	654.77	654.30	1.29	Surf.	1.29	*3.81
REF./SFS	219	595247	6215457	ACC1	110	2005	n/a	657.61	n/a	n/a	n/a	n/a
REF./SFS	220	595242	6215499	PIEZ	650	n/a	661.43	660.98	1.25	5.26	6.51	1.91
REF./SFS	220	595242	6215499	ACC1	110	n/a	n/a	661.14	n/a	n/a	n/a	n/a
REF./SFS	220	595242	6215499	TENS	25	End May08	n/a	661.33	n/a	n/a	n/a	n/a
REF./SFS	220	595242	6215499	TENS	50	End May08	n/a	661.32	n/a	n/a	n/a	n/a
REF./SFS	220	595242	6215499	TENS	75	End May08	n/a	661.33	n/a	n/a	n/a	n/a
REF./SFS	220	595242	6215499	TENS	95	End May08	n/a	661.37	n/a	n/a	n/a	n/a
REF./SFS	222	595239	6215463	ACC1	110	n/a	n/a	658.46	n/a	n/a	n/a	n/a
REF./SFS	223	595243	6215451	WDp	400	n/a	656.54	655.78	4.00	Surf.	4.00	*5.08
REF./SFS	223	595243	6215451	ACC1	110	n/a	n/a	655.67	n/a	n/a	n/a	n/a
REF./SFS	223	595243	6215451	ACC2	110	28-May-07	n/a	656.31	n/a	n/a	n/a	n/a
REF./SFS	223	595243	6215451	TENS	10	End May08	n/a	656.12	n/a	n/a	n/a	n/a

Table 3. Continued

REF./SFS	223	595243	6215451	TENS	50	End May08	n/a	656.17	n/a	n/a	n/a	n/a
REF./SFS	223	595243	6215451	TENS	76	End May08	n/a	656.15	n/a	n/a	n/a	n/a
REF./SFS	228	595233	6215384	WSh	150	25-May-04	654.51	654.13	1.41	Surf.	1.41	5.08
REF./NFS	30	595143	6215308	WDp	400	28-Aug-03	655.55	654.60	3.05	0.70	3.75	*3.81
REF./NFS	30	595143	6215308	PIEZ	600	28-Aug-03	655.28	654.74	1.21	5.15	6.36	*3.81
REF./NFS	30	595143	6215308	PIEZ	1500	28-Aug-03	655.41	654.82	3.73	10.61	14.32	*3.81
REF./NFS	30	595143	6215308	PIEZ	2200	28-Aug-03	655.55	655.00	1.52	20.00	21.52	*3.81
REF./NFS	45	595280	6215239	HG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
REF./NFS	45	595280	6215239	TB	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
REF./NFS	65	595029	6215291	WDp	650	19-Apr-06	656.61	n/a	5.28	1.07	6.35	5.08
REF./NFS	65	595029	6215291	PIEZ	900	19-Apr-06	656.86	n/a	1.96	7.16	9.12	5.08
REF./NFS	65	595029	6215291	ACC1	110	29-May-07	n/a	n/a	n/a	n/a	n/a	n/a
REF./NFS	65	595029	6215291	ACC1	110	June 08	n/a	655.79	n/a	n/a	n/a	n/a
REF./NFS	65	595029	6215291	TENS	25	End May08	n/a	655.95	n/a	n/a	n/a	n/a
REF./NFS	65	595029	6215291	TENS	50	End May08	n/a	655.94	n/a	n/a	n/a	n/a
REF./NFS	65	595029	6215291	TENS	75	End May08	n/a	*655.94	n/a	n/a	n/a	n/a
REF./NFS	65	595029	6215291	TENS	100	End May08	n/a	655.93	n/a	n/a	n/a	n/a
REF./NFS	147	595273	6215269	HG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
REF./NFS	252	595047	6215320	PIEZ	250	26-Jul-07	655.59	654.86	0.60	1.90	2.50	*2.54
REF./NFS	252	595047	6215320	WSh	150	26-Jul-07	655.57	654.79	1.40	0.45	1.85	*3.81
REF./NFS	252	595047	6215320	ACC1	110	Jul-07	n/a	654.92	n/a	n/a	n/a	n/a
REF./NFS	252	595047	6215320	TENS	25	End May08	n/a	654.97	n/a	n/a	n/a	n/a
REF./NFS	252	595047	6215320	TENS	50	End May08	n/a	654.91	n/a	n/a	n/a	n/a
REF./NFS	252	595047	6215320	TENS	75	End May08	n/a	654.98	n/a	n/a	n/a	n/a
EXP./SFS	501	594862	6215427	WDp	150	21-Jun-09	653.55	652.87	1.25	0.39	1.64	3.81

Table 3. Continued

EXP./SFS	501	594862	6215427	WDp	250	n/a	653.54	652.78	1.26	1.18	2.44	3.81
EXP./SFS	509	594872	6215484	W	500	n/a	656.04	654.91	1.80	3.05	4.85	3.81
EXP./SFS	512	594907	6215476	W	400	n/a	656.78	656.03	1.36	2.74	4.10	3.81
EXP./SFS	517	594903	6215547	W	200	2005	658.48	658.02	1.74	0.34	2.08	5.08
EXP./SFS	538	594846	6215419	TP	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
EXP./SFS	538	594846	6215419	HG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
EXP./SFS	564	594933	6215490	WDp	550	n/a	659.02	658.03	n/a	n/a	5.40	5.08
EXP./SFS	566	594840	6215534	TENS	25	End May08	n/a	660.44	n/a	n/a	n/a	n/a
EXP./SFS	566	594840	6215534	TENS	50	End May08	n/a	660.41	n/a	n/a	n/a	n/a
EXP./SFS	566	594840	6215534	TENS	75	End May08	n/a	660.40	n/a	n/a	n/a	n/a
EXP./SFS	566	594840	6215534	TENS	100	End May08	n/a	660.46	n/a	n/a	n/a	n/a
EXP./SFS	566	594840	6215534	WDp	600	17-Apr-06	661.15	660.39	3.26	2.59	5.85	*3.81
EXP./SFS	566	594840	6215534	ACC1	110	n/a	n/a	660.39	n/a	n/a	n/a	n/a
EXP./SFS	566	594840	6215534	ACC2	110	n/a	n/a	660.40	n/a	n/a	n/a	n/a
EXP./SFS	566	594840	6215534	TB	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
EXP./SFS	567	594771	6215581	WDp	750	17-Apr-06	662.04	661.24	3.79	3.66	7.45	*3.81
EXP./SFS	567	594771	6215581	PIEZ	1200	17-Apr-06	662.00	661.26	1.84	9.91	11.75	*3.81
EXP./SFS	567	594771	6215581	ACC1	110	n/a	n/a	661.21	n/a	n/a	n/a	n/a
EXP./SFS	567	594771	6215581	ACC2	110	n/a	n/a	661.18	n/a	n/a	n/a	n/a
EXP./SFS	574	594878	6215492	WDp	400	19-Apr-06	656.36	655.76	2.07	2.03	4.10	5.08
EXP./SFS	574	594878	6215492	PIEZ	900	18Apr-06	656.50	655.80	1.87	7.47	9.34	5.08
EXP./SFS	596	594873	6215495	HG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
EXP./SFS	597	594819	6215506	HG	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
EXP./SFS	602	594892	6215502	TENS	25	End May08	n/a	657.94	n/a	n/a	n/a	n/a
EXP./SFS	602	594892	6215502	TENS	50	End May08	n/a	657.95	n/a	n/a	n/a	n/a

Table 3. Continued

EXP./SFS	602	594892	6215502	TENS	74	End May08	n/a	657.89	n/a	n/a	n/a	n/a
EXP./SFS	602	594892	6215502	TENS	105	End May08	n/a	657.90	n/a	n/a	n/a	n/a
EXP./SFS	602	594892	6215502	ACC1	110	n/a	n/a	657.82	n/a	n/a	n/a	n/a
EXP./SFS	602	594892	6215502	ACC2	110	n/a	n/a	657.36	n/a	n/a	n/a	n/a
EXP./NFS	505	594889	6215322	WDp	250	n/a	653.62	653.12	1.97	0.52	2.49	*5.08
EXP./NFS	510	594950	6215278	W	500	n/a	655.29	n/a	2.80	2.17	4.97	3.81
EXP./NFS	515	594937	6215289	WSh	200	n/a	654.29	n/a	1.39	0.79	2.18	3.81
EXP./NFS	565	594939	6215243	ACC1	110	n/a	n/a	656.96	n/a	n/a	n/a	n/a
EXP./NFS	565	594939	6215243	PIEZ	600	n/a	659.32	658.43	2.74	3.35	6.10	5.08
EXP./NFS	565	594939	6215243	PIEZ	1500	n/a	659.38	658.45	2.13	13.11	15.24	5.08
EXP./NFS	569	594683	6215325	WDp	1000	18-Apr-06	655.87	655.19	2.87	7.32	10.19	*3.81
EXP./NFS	575	594916	6215271	ACC1	110	n/a	n/a	655.10	n/a	n/a	n/a	n/a
EXP./NFS	575	594916	6215271	WDp	750	19-Apr-06	655.23	654.46	1.89	5.49	7.38	5.08
EXP./NFS	576	594907	6215286	WDp	750	19-Apr-06	654.24	653.72	1.73	5.94	7.67	3.81
EXP./NFS	577	594899	6215271	ACC1	110	n/a	n/a	653.91	n/a	n/a	n/a	n/a
EXP./NFS	578	594906	6215259	ACC1	110	n/a	n/a	655.51	n/a	n/a	n/a	n/a
EXP./NFS	579	594906	6215253	ACC1	110	n/a	n/a	657.25	n/a	n/a	n/a	n/a
EXP./NFS	645	594899	6215247	TENS	24	End May08	n/a	657.76	n/a	n/a	n/a	n/a
EXP./NFS	645	594899	6215247	TENS	50	End May08	n/a	657.75	n/a	n/a	n/a	n/a
EXP./NFS	645	594899	6215247	TENS	75	End May08	n/a	657.71	n/a	n/a	n/a	n/a
EXP./NFS	645	594899	6215247	TENS	100	End May08	n/a	657.73	n/a	n/a	n/a	n/a
EXP./NFS	667	594936	6215250	ACC1	110	n/a	n/a	657.45	n/a	n/a	n/a	n/a

Table 4. Net change in upland root zone (0-50 cm) water content under uncut and first- and second-year regeneration conditions in 2007 and 2008. Water content presented here is the median value for the given time period.

		2007		2008	
Upland/ Aspect	Period	Water Content (mm)	Seasonal Change (mm)	Water Content (mm)	Seasonal Change (mm)
		Uncut		**Uncut**	
REF./ SFS	Early Green	59	0	62	0
	Green	38	-21	58	-4
	Shutdown	42	4	54	-4
	Net Change		**-17**		**-8**
				Uncut	
REF./ NFS	Early Green	**Incomplete Data**		93	0
	Green			82	-11
	Shutdown			76	-6
	Net Change				**-17**
		Uncut		**First yr. regen.**	
EXP./ NFS	Early Green	81	0	73	0
	Green	44	-37	71	-2
	Shutdown	40	-4	73	2
	Net Change		**-41**		**0**
		First yr. regen.		**Second yr. regen.**	
EXP./ SFS	Early Green	57	0	58	0
	Green	55	-2	53	-5
	Shutdown	59	4	56	3
	Net Change		**2**		**-2**

Table 5. Lateral gradients (*Δh/Δl*) and number of days of hydrological linkage from the upland slope (a) and crest (b) position of each hummock to the adjacent pond-peatland complex under uncut and first- and second-year regeneration conditions in 2007 and 2008 under peak spring-melt and end of fall conditions.

(a) Slope

		2007		**2008**	
Upland/Aspect (Site)	**Period**	***Δh/Δl***	**Days**	***Δh/Δl***	**Days**
		Uncut		**Uncut**	
REF./SFS (223)	Spring-melt	0.01	104	0.01	58
	End of fall	-0.01		-0.02	
		Uncut		**Uncut**	
REF./NFS (30)	Spring-melt	0.002	22	0.01	14
	End of fall	-0.02		-0.01	
		Uncut		**First yr. regen.**	
EXP./NFS (510)	Spring-melt	0.02	73	0.02	175
	End of fall	-0.01		0.004	
		First yr. regen.		**Second yr. regen.**	
EXP./SFS (574)	Spring-melt	0.001	170	0.03	365
	End of fall	0.01		0.02	

(b) Crest

		2007		**2008**	
Upland/Aspect (Site)	**Period**	***Δh/Δl***	**Days**	***Δh/Δl***	**Days**
		Uncut		**Uncut**	
REF./SFS (33)	Spring-melt	-0.02	0	-0.02	0
	End of fall	-0.02		-0.02	
		Uncut		**Uncut**	
REF./NFS (65)	Spring-melt	-0.002	0	-0.003	0
	End of fall	-0.03		-0.03	
		Uncut		**First yr. regen.**	
EXP./NFS (565)	Spring-melt	-0.002	76	-0.001	180
	End of fall	<-0.001		0.002	
		First yr. regen.		**Second yr. regen.**	
EXP./SFS (566)	Spring-melt	0.03	>163	0.04	365
	End of fall	0.03		0.03	

Table 6. Lateral gradients (*Δh/Δl*) from the perched peatland and the upland slope (a) and crest (b) position on the experimental SFS hummock in 2007 and 2008 under peak spring-melt and end of fall conditions.

(a) Perched Peatland to Upland Slope (574 WDp)

		2007	**2008**
Perched Peatland (Site)	**Period**	***Δh/Δl***	***Δh/Δl***
		First yr. regen.	**Second yr. regen.**
EXP./SFS (564)	Spring-melt	0.17	0.07
	End of fall	0.08	0.07
		First yr. regen.	**Second yr. regen.**
EXP./SFS (517)	Spring-melt	0.09	0.04
	End of fall	0.06	0.06

(b) Perched Peatland to Upland Crest (566 WDp)

		2007	**2008**
Perched Peatland (Site)	**Period**	***Δh/Δl***	***Δh/Δl***
		First yr. regen.	**Second yr. regen.**
EXP./SFS (564)	Spring-melt	n/a	0.08
	End of fall	0.07	0.03
		First yr. regen.	**Second yr. regen.**
EXP./SFS (517)	Spring-melt	n/a	0.04
	End of fall	0.06	0.05

Table 7. Vertical gradient (*Δh/Δz*) between the higher permeability oxidized layer and the anoxic lower permeability layer at the crest position of three upland hummocks for uncut and first- and second-year regeneration conditions in 2007 and 2008 during peak spring-melt and fall conditions. Note that all these values are positive suggesting that the groundwater function of this site is recharge.

Crest

		2007	**2008**
Upland/Aspect (Site)	**Period**	***Δh/Δz***	***Δh/Δz***
		Uncut	**Uncut**
REF./NFS	Spring-melt	0.42	0.29
(65)	End of fall	0.21	0.13
		Uncut	**First yr. regen.**
EXP./NFS	Spring-melt	0.58	0.53
(565)	End of fall	0.53	0.57
		First yr. regen.	**Second yr. regen.**
EXP./SFS	Spring-melt	0.11	0.05
(566)	End of fall	0.06	0.02

Figures

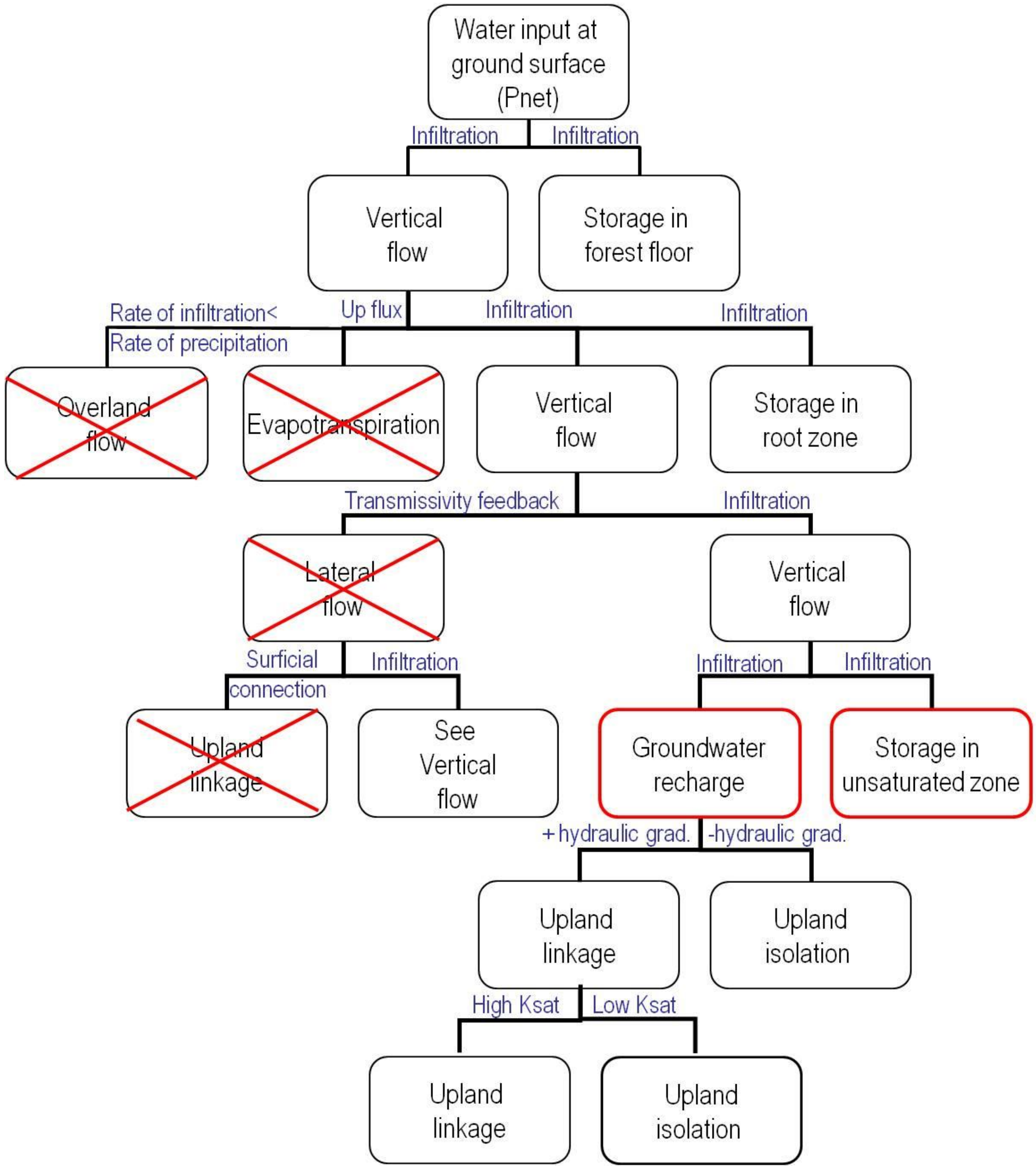


Figure 1. The general upland water movement in the western Boreal Plain depicted by a flow chart. The lines show flow path and the boxes show the underlying hydrological process. Dominating hydrological processes in response to clear-cutting are highlighted in red. Upland clear-cutting is predicted to increase infiltration into the deep unsaturated zone due to a reduction in interception and evapotranspiration. However, it is unclear whether or not the soil storage above the water table will be exceeded and positive saturated hydraulic gradients will be generated due to clear-cutting.

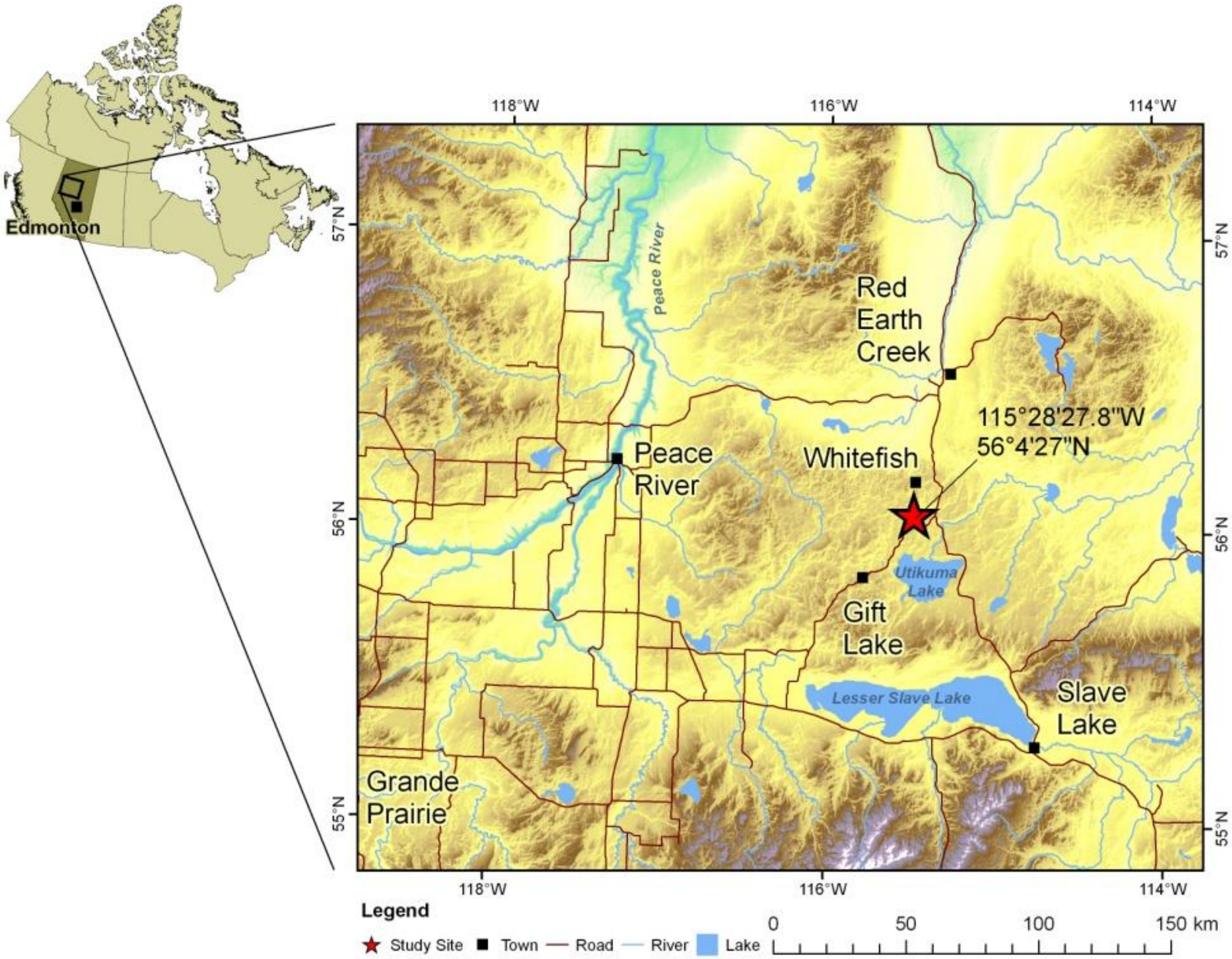


Figure 2. Study site (red star) located north of Utikuma Lake (Lat: 56°04'27 N; Long: 115°28'27 W), 370 km north of Edmonton. Alberta, Canada, in the Boreal Plain ecozone.

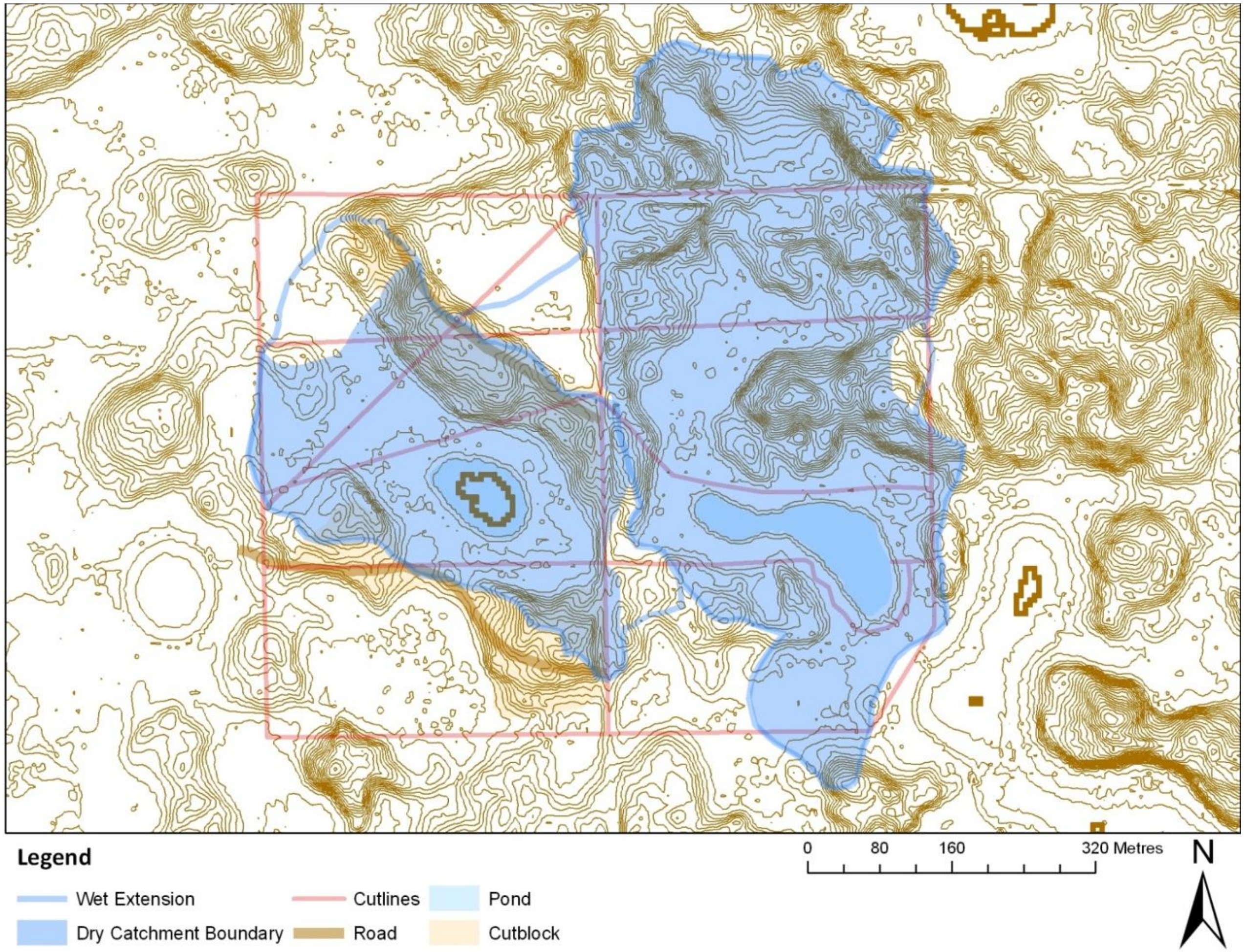


Figure 3. Study site with the experimental catchment on the left and the reference catchment on the right showing the preliminary catchment boundary under dry conditions with the extension due to wet climate conditions. The ground elevation of the lowest pond-peatland complex is approximately 653 m above sea level and rises to about 659 m above sea level in the upland areas. The geographic reference system for this map is WGS84.

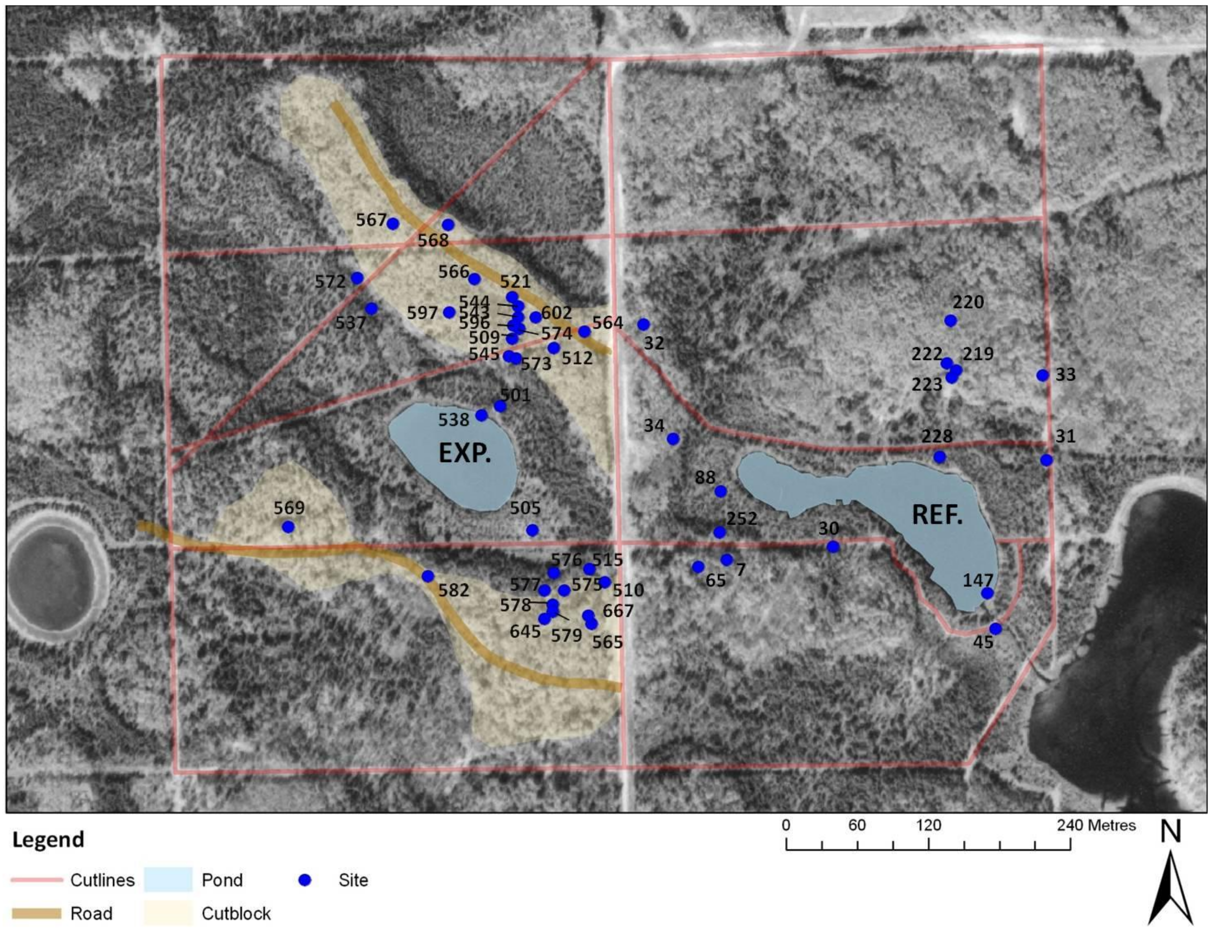
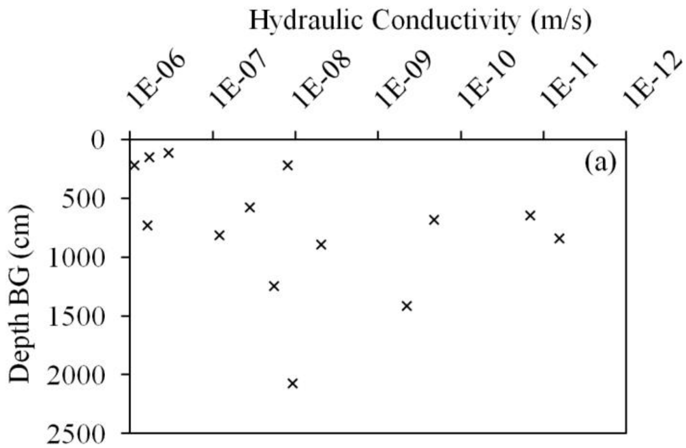


Figure 4. Site locations labeled by number with the experimental catchment on the left and the reference catchment on the right superimposed on an air photo. The lighter shades on the air photo depict aspen in the uplands and the darker shades reflect the conifer trees in the pond-peatland complexes. Date of the air photo goes back to May 29, 2000. The geographic reference system for this map is WGS84. Note that not all sites depicted on this map are addressed in the thesis. Refer to Table 3 for a list of instruments at site locations. Site 517 is located in the middle of the perched wetland at the top of the experimental SFS hummock.



(b) Site data

Site	Equip.	Equip. Attrib.	Depth of Mid-Screen BG (cm)	Ksat at Mid-Screen (m/s)	Soil Description at Mid-Screen
252	PIEZ	250	220	9E-07	Silty till, brown, grey, kimberlite, pebbles, oxidation
252	WSh	150	115	3E-07	Till (silt and sand), light brown, charcoal, pebbles/sand, oxidation
65	PIEZ	900	814	8E-08	Grey, clayey silt, pebbled, till
33	PIEZ	1100	894	5E-09	Silt with sand
30	W	400	222	1E-08	n/a
30	PIEZ	600	576	4E-08	Grey till
30	PIEZ	1500	1248	2E-08	Till with some sand
30	PIEZ	2200	2076	1E-08	Grey till
31	W	250	152	6E-07	n/a
31	PIEZ	1000	729	6E-07	Silt with clay and sand
565	PIEZ	1500	1418	5E-10	Grey clay with pebbles
575	WDp	750	644	1E-11	Blue grey silty till
576	WDp	750	681	2E-10	Blue grey clay rich silt
574	PIEZ	900	841	6E-12	Silty grey till
			Geo. Mean	9E-09	
			Min	6E-12	
			Max	9E-07	

Figure 5. Graphical representation of lateral saturated hydraulic conductivity (m/s) of 14 well/piezometer sites (8 upland and 6 riparian) relative to the depth below the ground (a). The table provides a list of the sites where measurements were made, the depth of the mid-screen point below the ground, site specific lateral hydraulic conductivity (Ksat), and the soil description at the mid-screen location (b). Refer to Figure 4 for site locations on the study catchments.

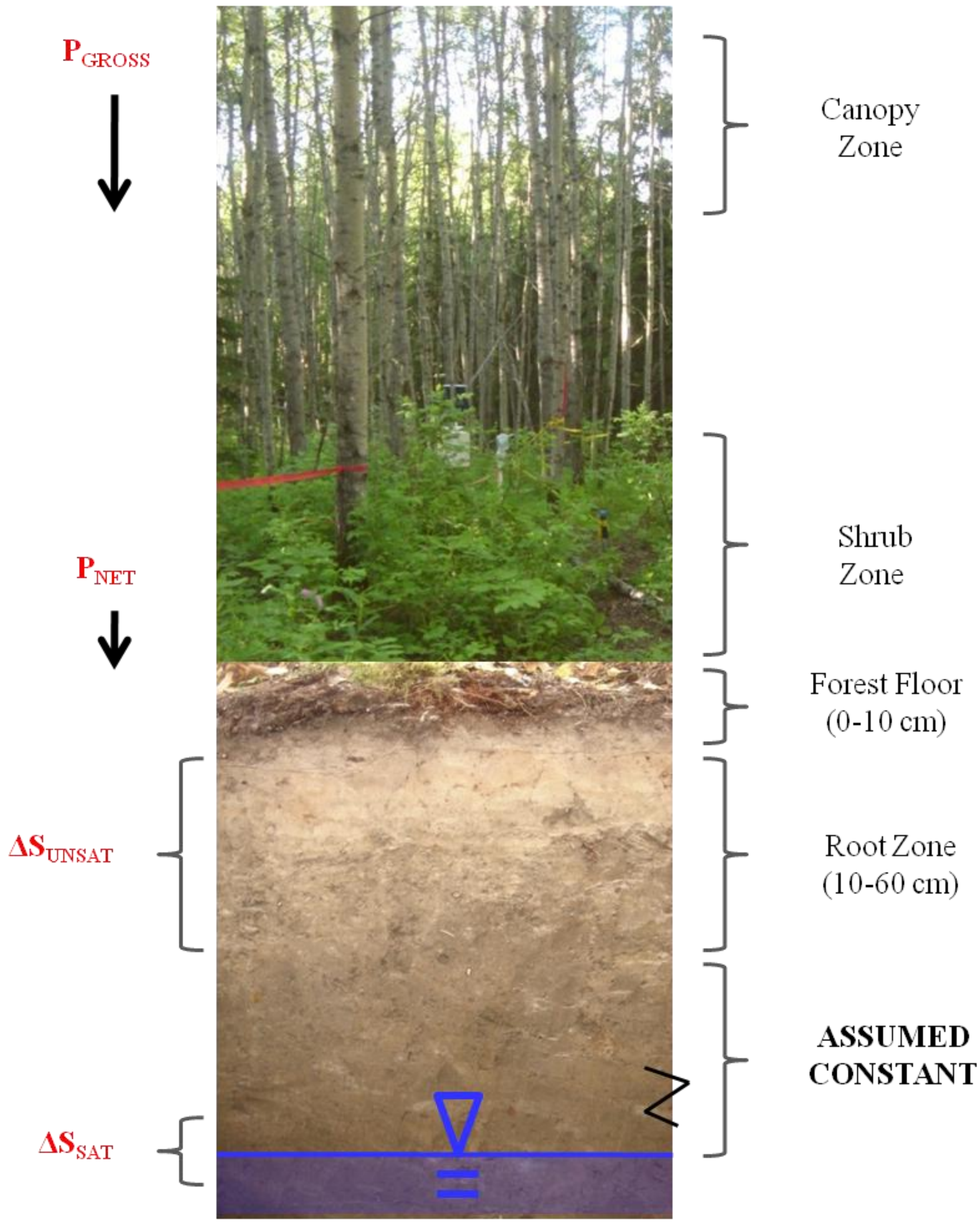


Figure 6. Schematic of hydrometric approach with the assumption that water moves vertically down the soil profile. The hydrometric approach also assumes that the conditions below the bulk of the root zone are constant. The water table is depicted by the blue upside down triangle.

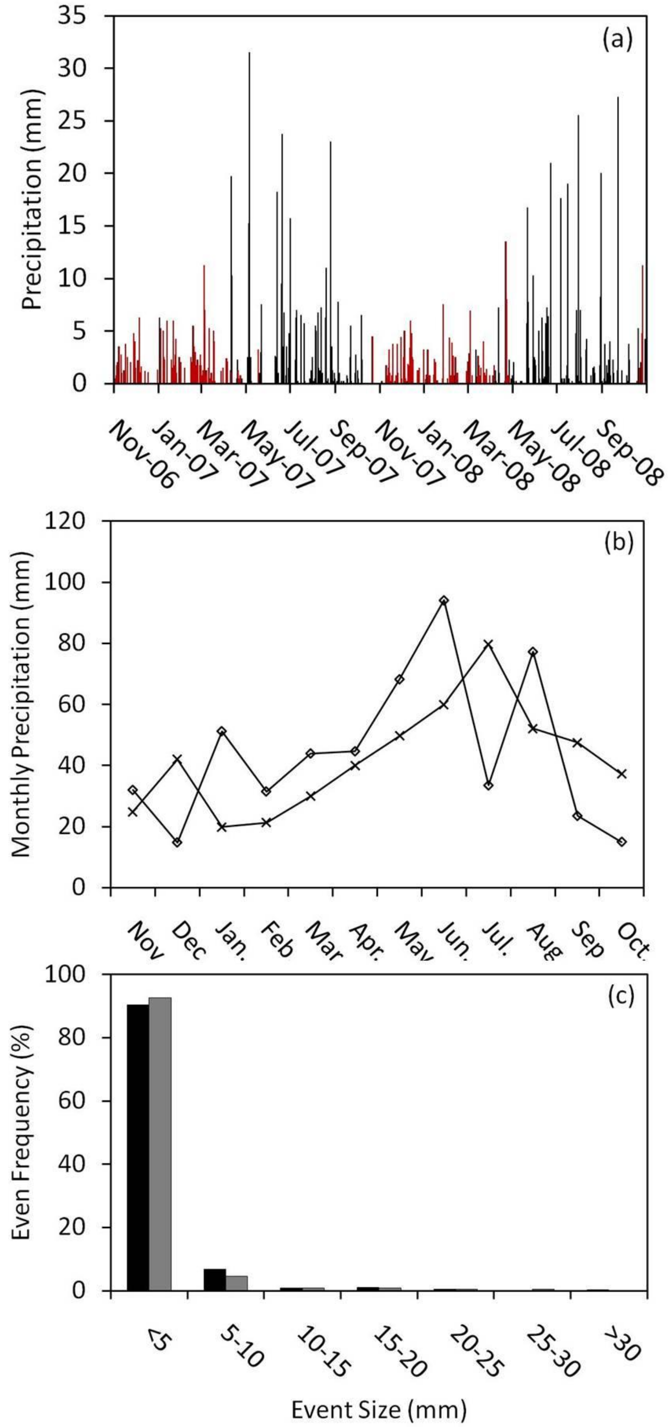


Figure 7. Precipitation (mm) with rain (black) and SWE (red) for the 2007 and 2008 hydrologic years, where the dotted line depicts the integrated (aspen canopy, understory, and forest floor) interception storage of a mature aspen forest estimated at 15 mm (Riddell 2008) (a). Monthly precipitation showing most falling between the months of May and August for 2007 (diamond) and 2008 (x) (b). Precipitation event frequency distribution for 2007 (black) and 2008 (gray) where more than 95% of events are less than the interception storage of a mature aspen forest (c).

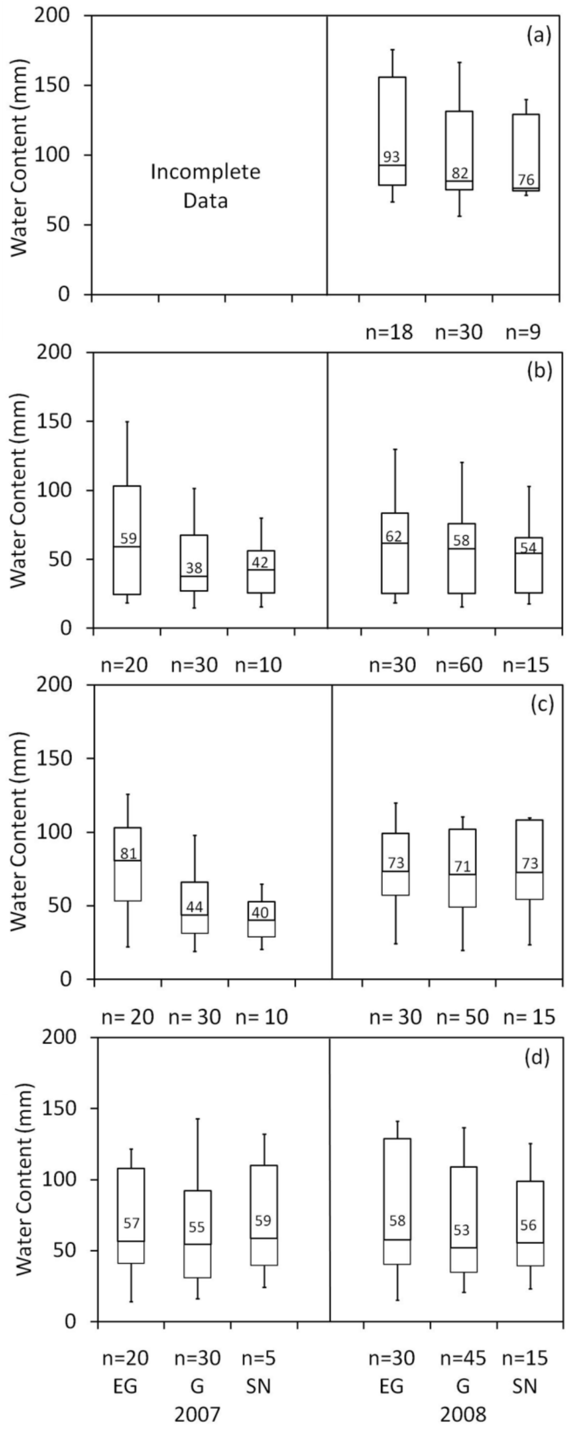


Figure 8. Water content in the root zone under uncut and first- and second-year regeneration conditions during the Early Green (EG), Green (G), and Senescence (SN) period on the reference NFS (a), reference SFS (b), experimental NFS (c), and experimental SFS (d) in 2007 and 2008. Boxes show the 25, 50, and 75 percentile and the minimum and maximum values are represented by the whiskers. Note that the experimental NFS was clear-cut in the winter of 2008 and the experimental SFS was clear-cut in the winter of 2007.

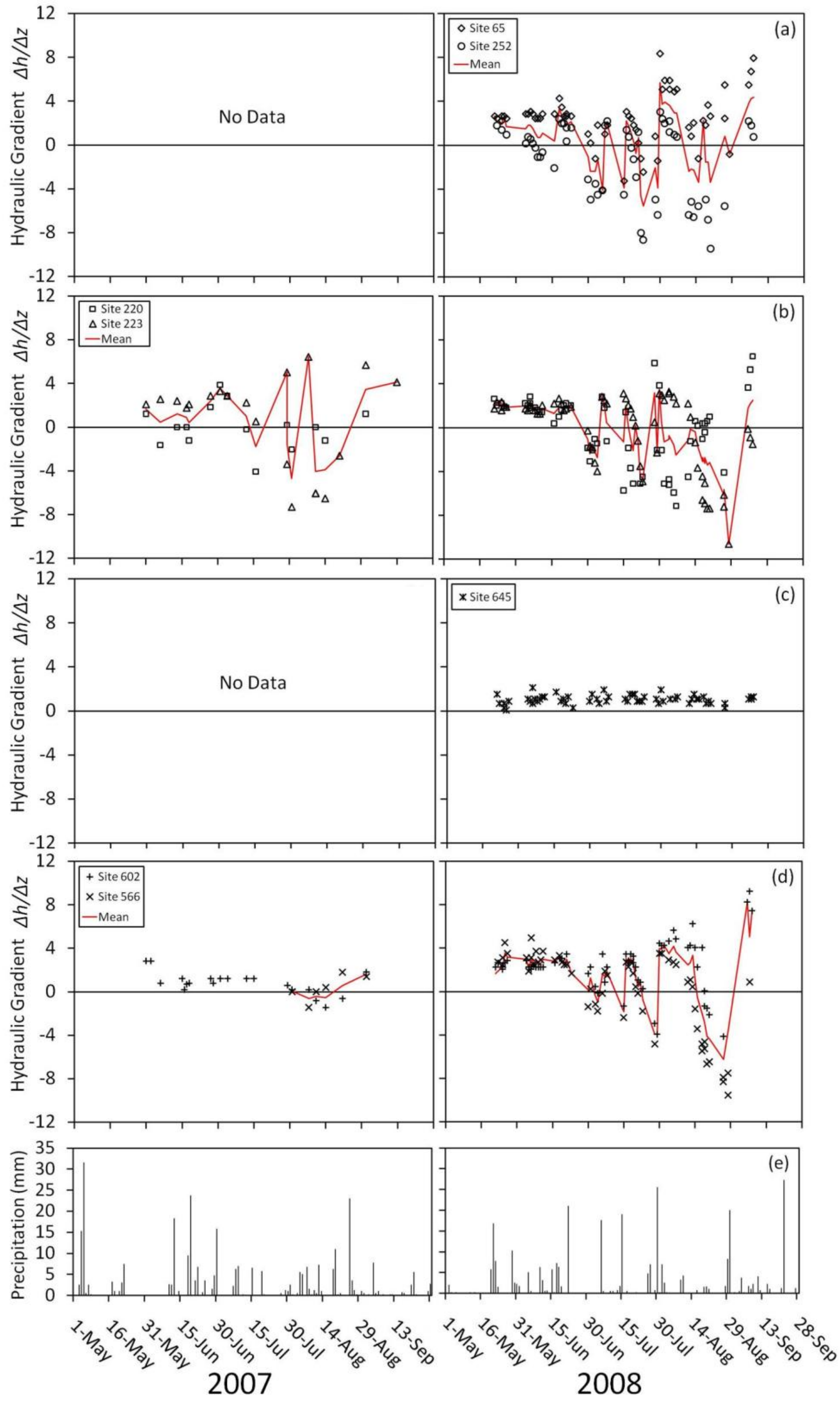


Figure 9. Unsaturated hydraulic gradient (*Δh/Δz*) on the reference NFS (a), reference SFS (b), experimenatal NFS (c), and experimental SFS (d) during the 2007 and 2008 growing season, with precipitation (e) shown by the black bars. The mean hydraulic gradient is depicted by the red line.

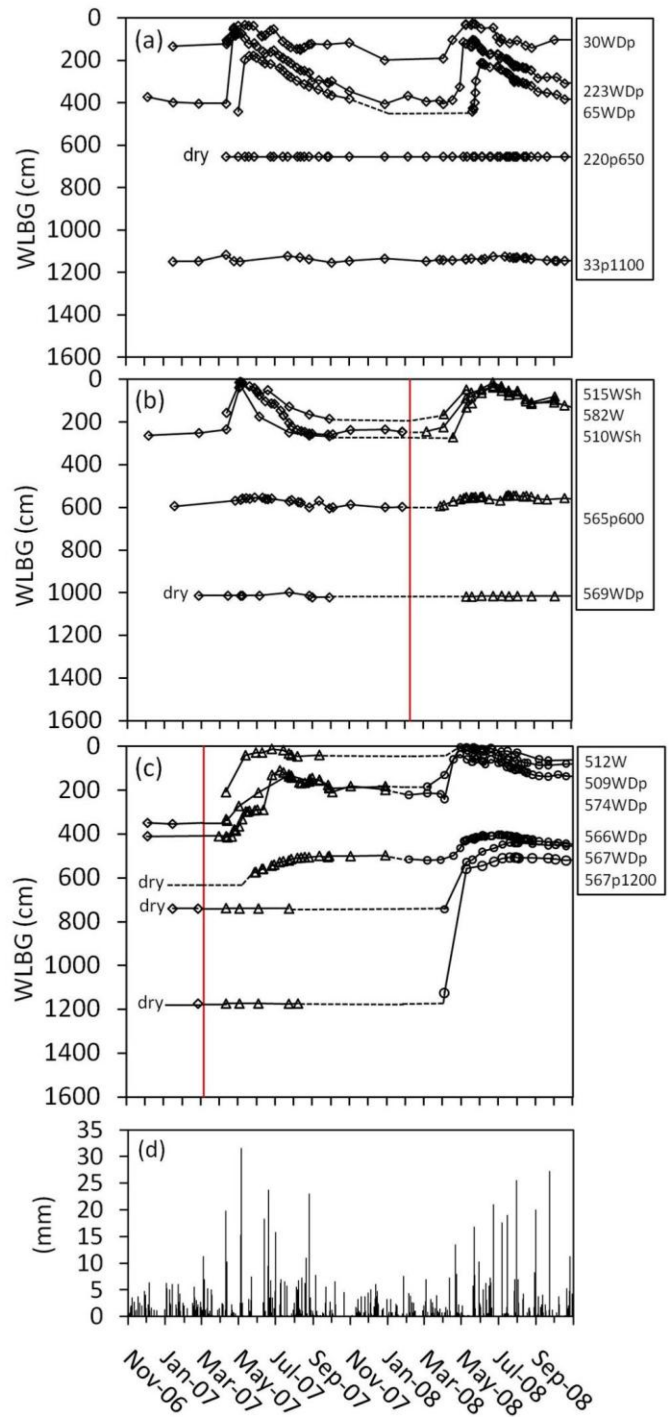


Figure 10. Water table levels below the ground (WLBG) expressed in cm under under uncut (diamond) and first-(triangle) and second-year regeneration (circle) conditions over the 2007 and 2008 hydrologic years on the reference NFS and SFS combined (a), experimental NFS (b), and experimental SFS (c) with precipitation (d) shown by the black bars. The clear-cut date is shown by the bold red line and the dotted lines depict estimates during absence of measurements.

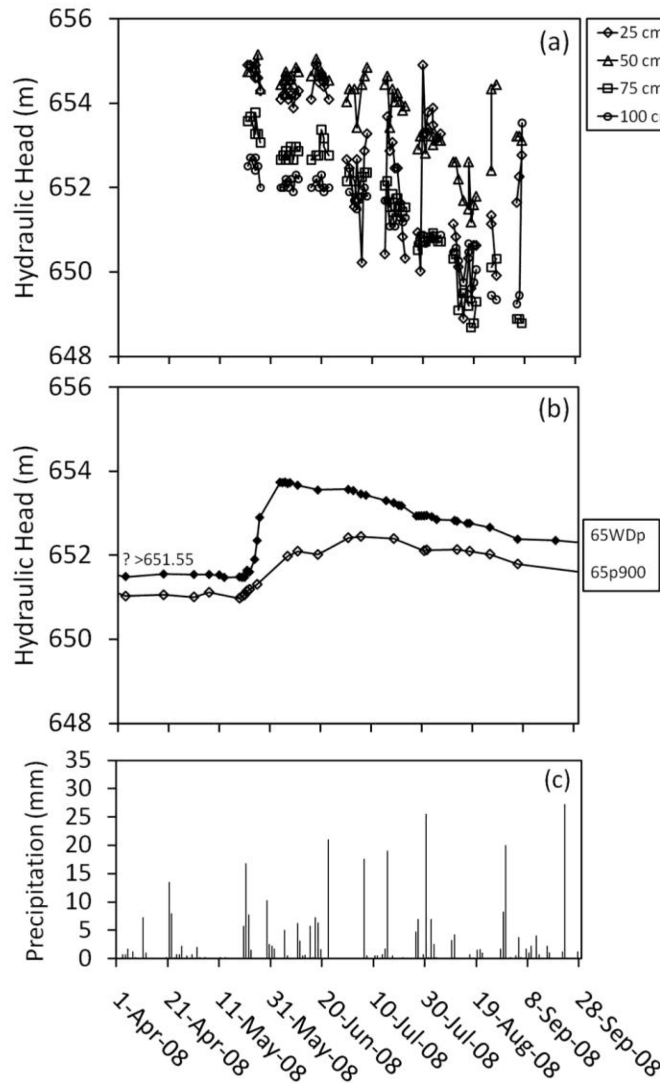


Figure 11. Unsaturated hydraulic head at 25, 50, 75, and 100 cm below the ground surface at the crest position on the reference NFS crest in 2008 (site 65) (a) as well as the water table (full diamond) and piezometric (open diamond) hydraulic head in the deeper anoxic zone (b) with precipitation depicted by the black bars (c).

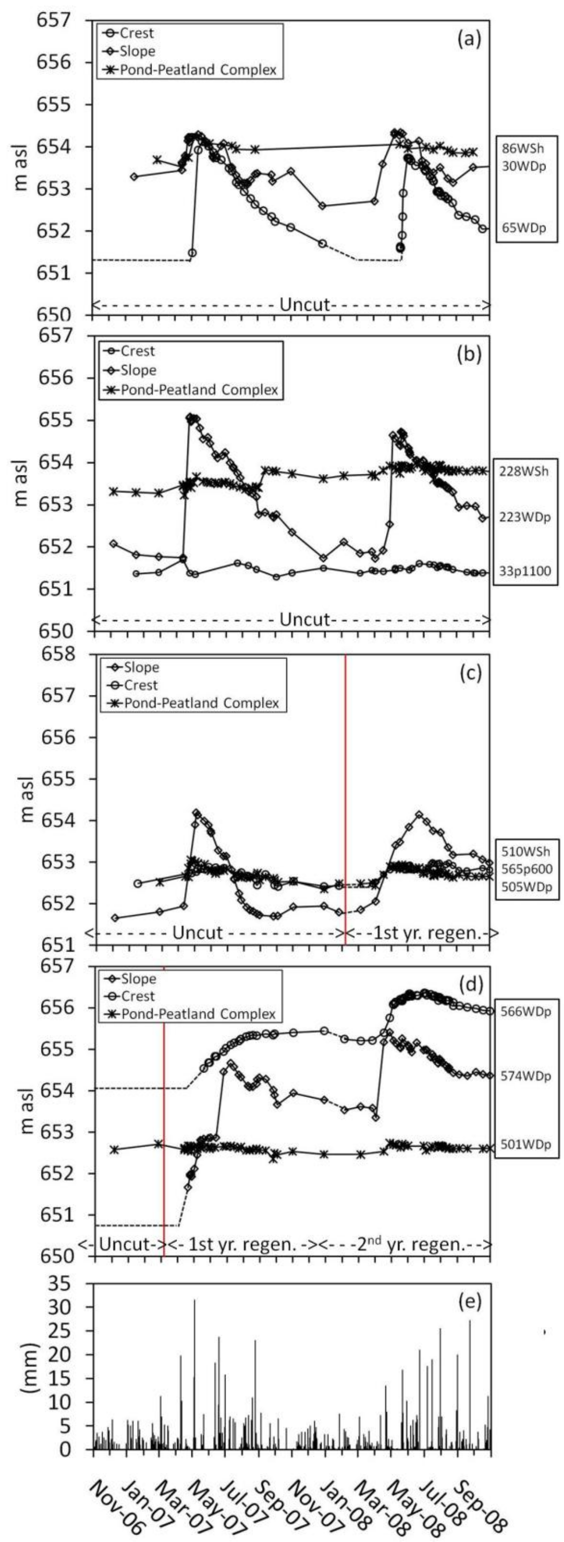


Figure 12. Water table elevation at the crest, slope, and pond-peatland complex position under uncut and first- and second-year regeneration conditions over the 2007 and 2008 hydrologic years on the reference NFS (a), reference SFS (b), experimental NFS (c), and experimental SFS (d) with precipitation shown by the black bars (e).

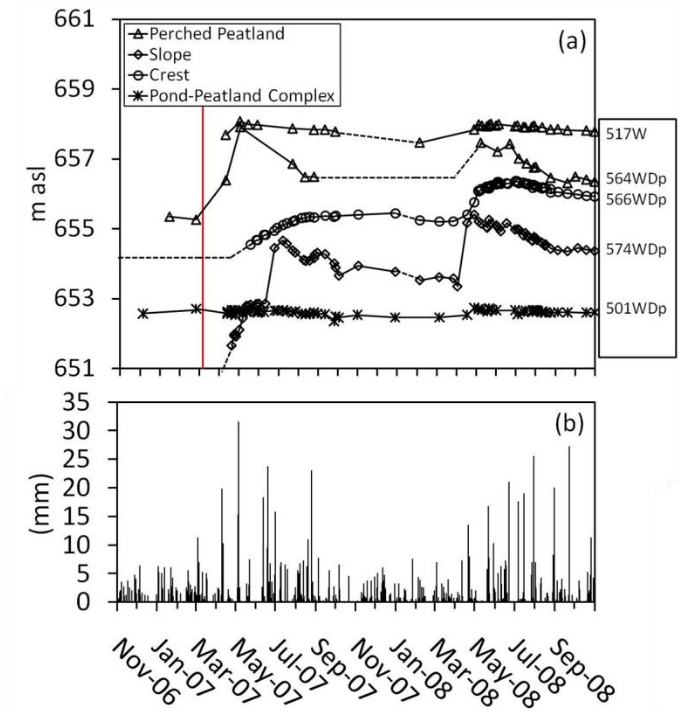


Figure 13. Example of water table elevation at the crest, slope, pond-peatland complex, and perched peatland position on the experiemental SFS (a) with precipitation shown by the black bars (b).

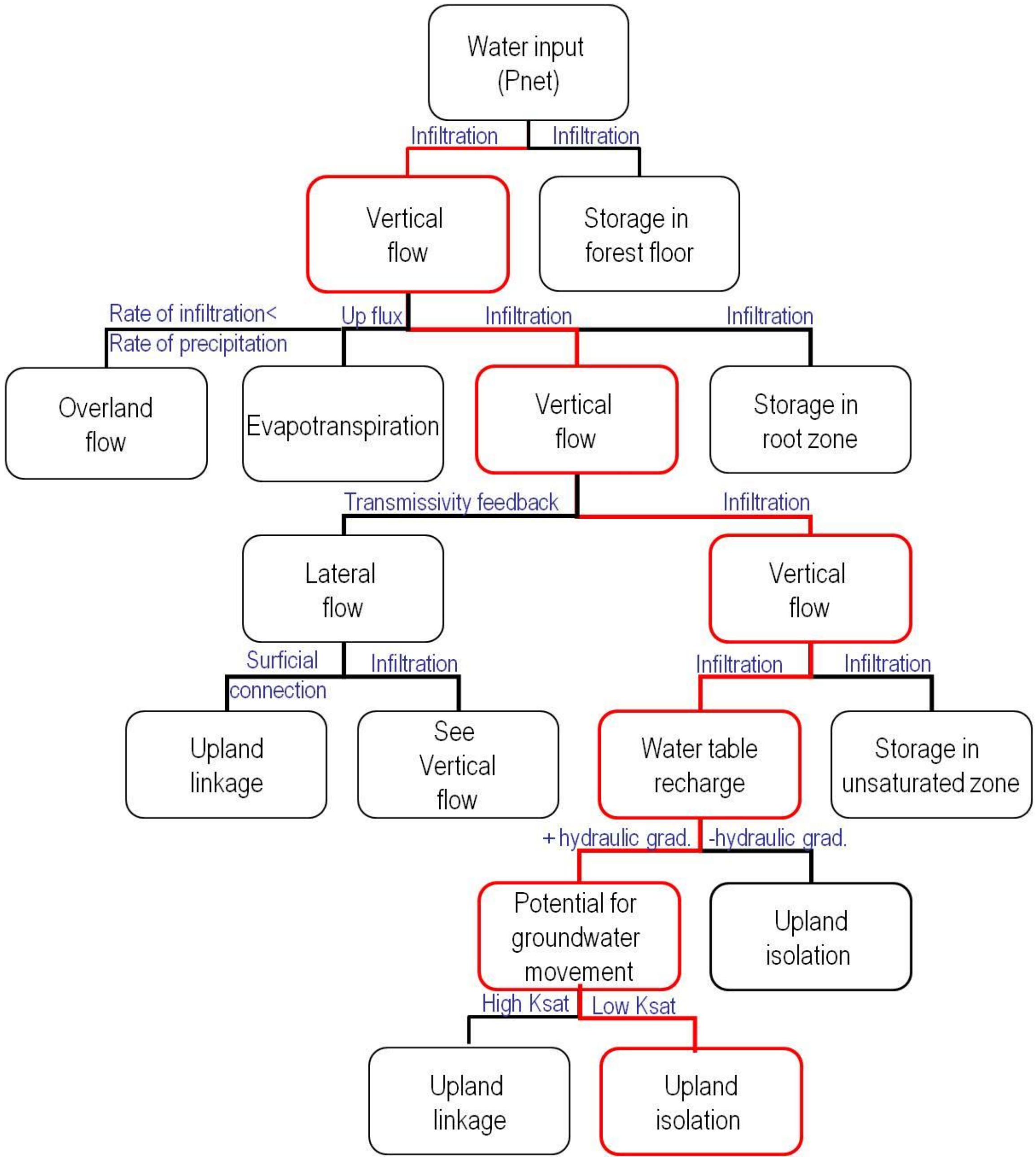


Figure 14. The general upland water movement in the form of a flow chart in the western Boreal Plain. The lines depict flow path and the boxes show the underlying hydrological process. Observed changes in hydrological processes under clear-cut conditions are highlighted in red and support a dominance of vertical flow and negligible lateral flow suggesting that the hydrological impacts of clear-cutting are limited to the upland scale.

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Appendix

Table A.1. The lab calibration equation compares well with the factory calibration equation justifying its use for the soil water content calculations.

Lab Calibration Equations	
PR1	$VMC_{PR1} = (3x10^{-11}mV_{PR1})^4 – (2x10^{-8}mV_{PR1})^3 + (2x10^{-6}mV_{PR1})^2 + (0.001mV_{PR1}) - 0.0945$
R^2	0.93
PR2	$VMC_{PR2} = (9x10^{-12}mV_{PR2})^4 - (2x10^{-8}mV_{PR2})^3 + (2x10^{-5}mV_{PR2})^2 - (0.0065mV_{PR2}) + 0.7561$
R^2	0.97
Factory Calibration Equations	
PR1	$VMC_{PR1} = (8.63x10^{-3}mV_{PR1})^3 - (3.56x10^{-3}mV_{PR1})^2 + (1.62x10^{-3}mV_{PR1}) – 0.113$
R^2	1
PR2	$(1.447x10^{-2}mV_{PR2})^6 - (4.246x10^{-2}mV_{PR2})^5 + (4.923x10^{-2}mV_{PR2})^4 - (2.791x10^{-2}mV_{PR2})^3 + (8x10^{-3}mV_{PR2})^2 - (6.6x10^{-4}mV_{PR2}) - 0.057$
R^2	1

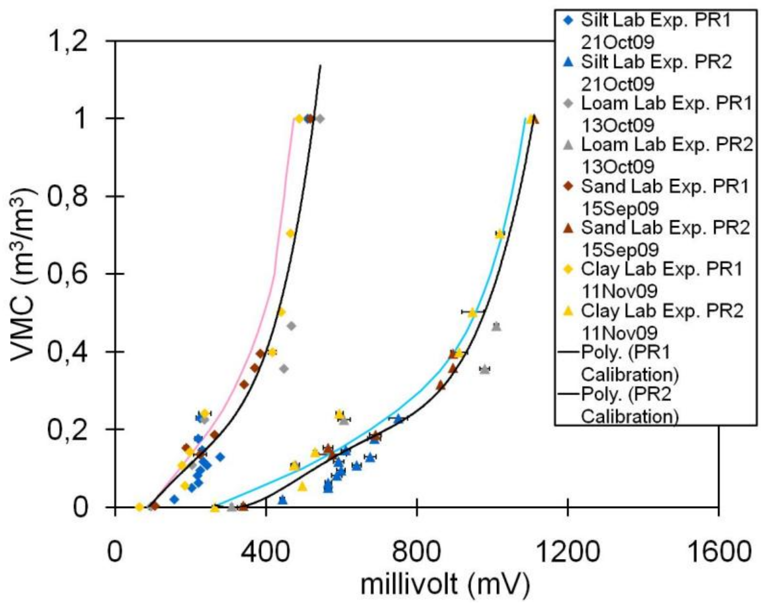

Figure A.1. Calibration comparison between lab measurements and factory values for mineral soil using the PR1 and PR2 instruments. The factory calibration curve for the PR1 (pink) and the PR2 (blue) compare well to the lab calibration curves (black) for a range of soil textures (sand, silt, loam, and clay) suggesting that the instruments may not be sensitive to differences in texture. Refer to Table A.1 for equations.

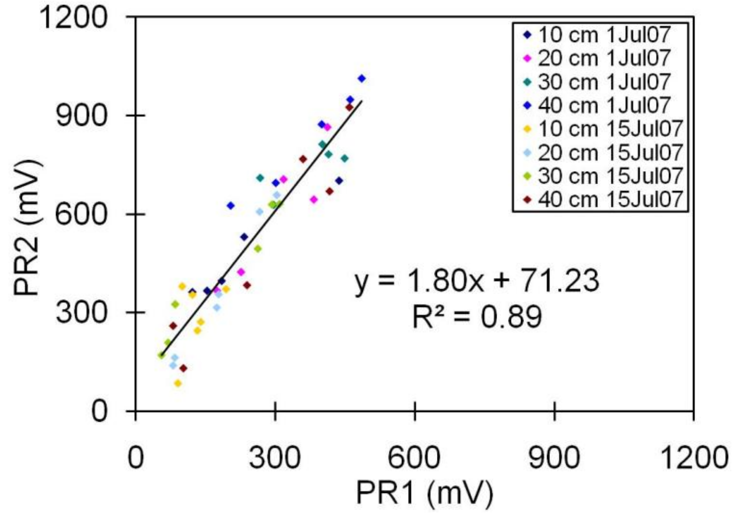

Figure A.2. Linear relationship between measurements collected in millivolt units on July 1 and July 15, 2007 at the 10, 20, 30, and 40 cm sensors using the PR1 and PR2 soil moisture instruments. The linear relationship is expressed as a linear function.

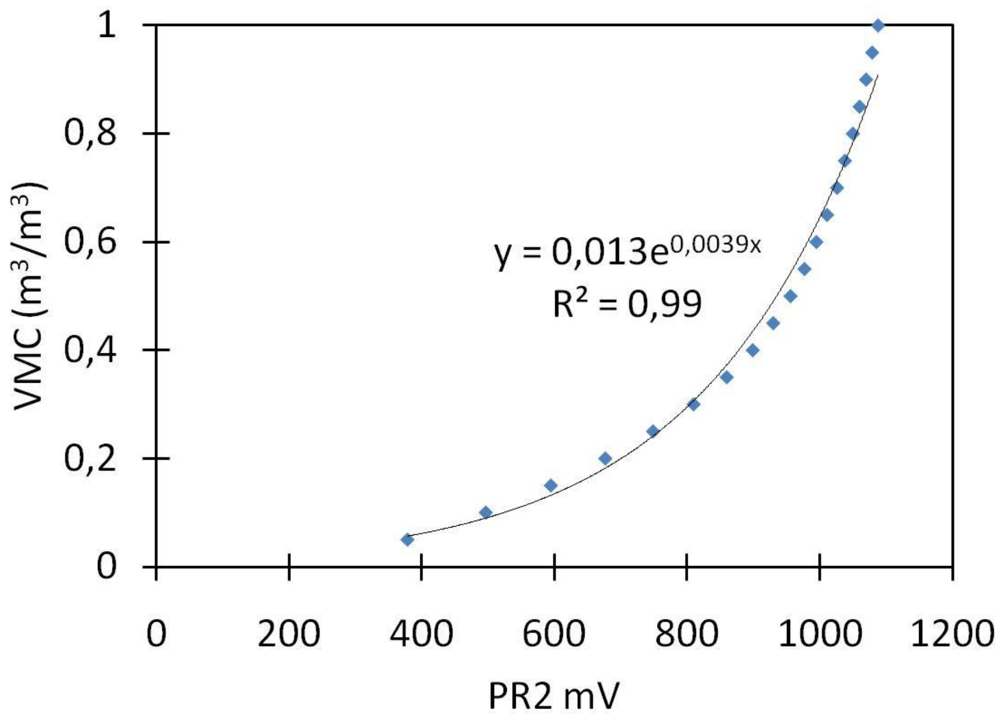

Figure A.3. Exponential relationship between PR2 mV measurements and estimated VMC (R^2 = 0.99) based on the factory calibration values.