CHARACTERIZATION OF REGIONAL AIR TEMPERATURE AND PRECIPITATION AND ITS RELATIONSHIP TO SHALLOW GROUNDWATER RESOURCES IN THE ANCIENT FOREST, BRITISH COLUMBIA

by

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Abstract

In the Inland Temperate Rainforest (ITR) of northeastern British Columbia, nearly 50% of the annual precipitation falls as snow. Persistence of soil moisture has implications for tree species survival and snowmelt is a vital component of the soil moisture regime in the ITR. Presented in this study are hydrometeorological data from 1 November 2011 to 31 August 2012 from two sites, the Ancient Forest and Lunate Creek, 110 km east of Prince George, British Columbia and are compared to the 1981-2010 climate norms at Prince George Airport. Shallow groundwater, surface water, and seasonal precipitation were collected for isotopic analysis to identify moisture sources for shallow groundwater. Soil moisture and shallow groundwater had minimal response to rainfall, but snowmelt comprises 40% of shallow groundwater. With changes in climate indicating a phase shift from snow to rain, the snowmelt contribution to groundwater, and thus available soil moisture, has the potential to diminish.

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1 Introduction

1.1 Motivation

Water has always been an important resource in British Columbia (BC); from water used in industrial activities such as mining and timber processing to agricultural use to habitat for salmon and other fish species, water quantity and quality are essential. The Fraser River is the fifth largest river basin in Canada, encompasses 238,000 km^2 within its basin, and supports one of the largest salmon fisheries in the world. Water for the Fraser River originates in the Rocky Mountains of eastern BC and travels 1400 km to the Salish Sea near Vancouver, BC. The Upper Fraser is one of thirteen major sub-basins of the Fraser River; the Upper Fraser sub-basin drains over 2.8 million hectares (ha) of land in east-central BC (Calbick et al 2004). This sub-basin of the Fraser holds a large swath of the inland temperate rainforest (ITR) and will be the focus region of this research (Figure 1.1).

Automated weather stations are important in the Upper Fraser River basin to aid governmental agencies in determining the flood potential each year. The data provided allow for the BC River Forecast Centre (RFC) to inform citizens of potential flood risk, water availability, and risk of drought conditions. Understanding the benefits and limitations of the automated weather stations allows for the RFC to make more accurate predictions. Given the stations are placed at great distances from each other and are attempting to represent large areas, it is necessary to extrapolate information from these datasets.

The ITR of eastern BC is a unique ecosystem; these forests rely on the precipitation coming from the Pacific to support the large Interior Cedar-Hemlock (ICH) forests that are similar to the Cedar-Hemlock forests located near the coast of the Pacific Ocean; these forests rely on orographic lift of Pacific storm systems over the central interior mountain ranges for their moisture needs. These forests get up to half of their annual precipitation in the form of snow, such that changing air temperature and precipitation patterns have the potential to greatly affect the survival of these forests in their current range. In particular, the Ancient Cedar stands in the vicinity of the Ancient Forest trail (which we will call the Ancient Forest), 110 km east of Prince George, are considered especially vulnerable to any shift in precipitation; many of these trees may be more than 1000 years in age.

Snow acts as a natural reservoir for freshwater and releases it into the groundwater system slowly, allowing for the toeslope trees to receive water even during the drier summer months. Qualitative observations indicate that there is an abundance of moisture present in the soils, even in the driest times of the year, but quantitative results regarding the actual volumes remain unidentified. The evidence of greater amounts of precipitation as snow versus rain indicates that winter precipitation is vital to the persistence of moisture during drier summer months.

The ICH (Figure 1.1) zone is located in an area of interior, continental climate dominated by easterly moving air masses that produce cool, wet winters and warm, dry summers (Ketcheson et al 1991). These forests occupy the wettest areas of the interior province. Mean annual precipitation for the ICH is 500-1200 mm, of which, 25-50% is received as snow (Ketcheson et al 1991); this is significantly lower than the mean annual precipitation seen along the coastal western hemlock zones.

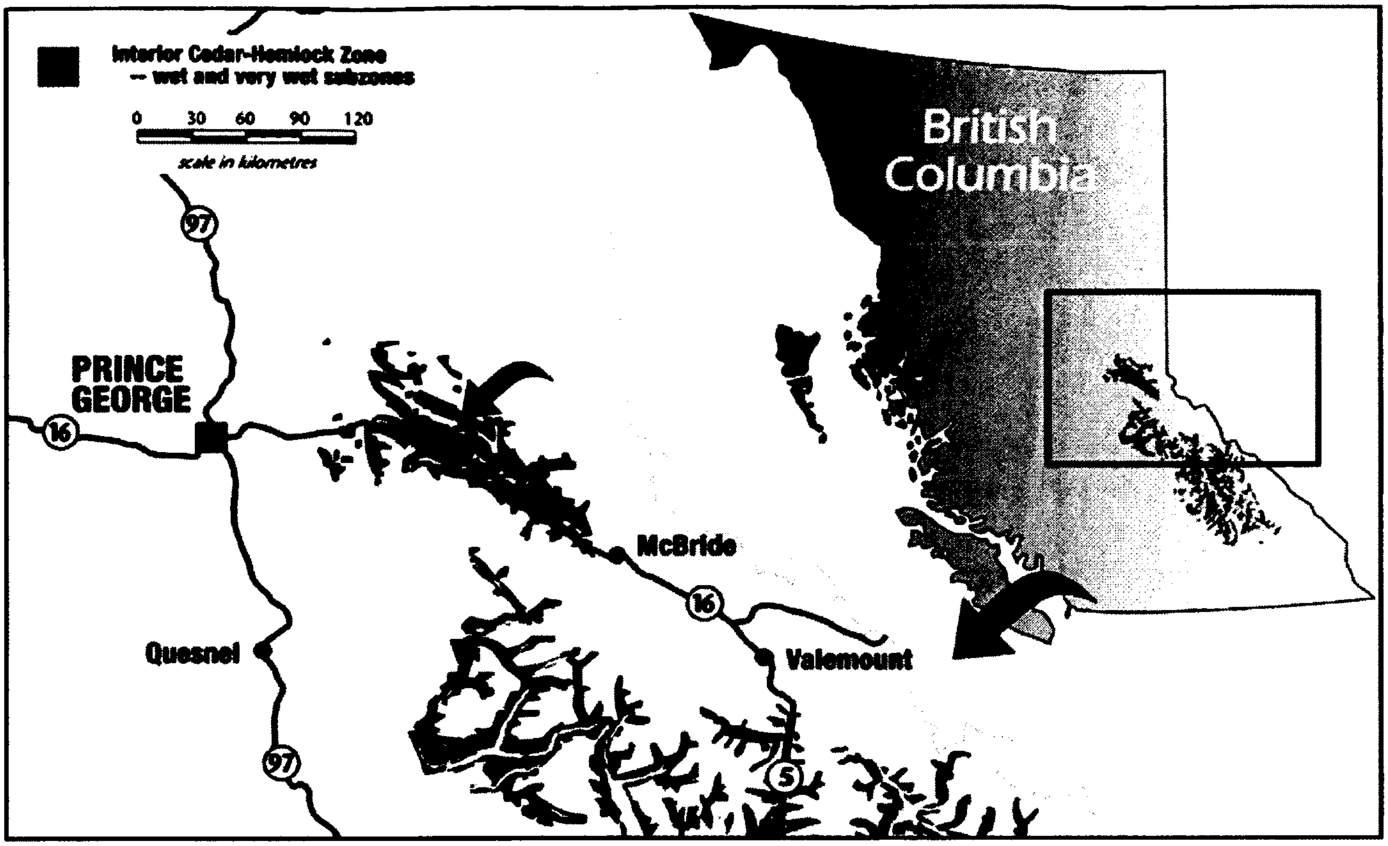

Figure 1.1 Map of British Columbia showing the range of the ITR in black, with the detailed map showing the study area within the outlined box east of Prince George (courtesy of Darwyn Coxson)

Snow is an important feature to this ecosystem, as snowmelt contributes considerably to the hydrologic regime; the slower release of water into the groundwater system minimizes the summer soil moisture deficits (Ketcheson et al 1991). The ICH is most often found at mid-slope in mountainous areas, with few wetlands. The soil types are most often ferro-humic podzols, with soil development reaching one metre in depth.

Snowmelt is an important contributor to both surface and groundwater inputs. Since the Ancient Forest sites are snow dominated systems, looking at the impacts of climate change on groundwater, groundwater and surface water interaction, and groundwater quantity and quality is important, as these impacts are difficult to assess in cold regions where significant changes in snowfall versus rainfall distribution, snow depth and soil frost depth are predicted (Okkonen et al 2010). A change in climate could alter the precipitation regime from snow dominated to rain dominated as the largest changes from a changing climate are predicted for snow dominated basins (Barnett et al 2005). Overall recharge of groundwater resources could increase with a shift from a cold climate to a temperate climate, with more rain occurring in the spring and autumn. Spring melt is predicted to occur about one month earlier by 2050 (Barnett et al 2005) in snow-dominated regions across continents; an earlier spring melt could reduce the ground melt that could allow for decreased infiltration of the meltwater due to still frozen soil (Okkonen et al 2010). Since snow, not manmade reservoirs, is the largest component of water storage in western North America (Mote et al 2005), any alteration to a snow regime could greatly affect the amount of water available to a region. Any determination of snowmelt's role in groundwater recharge will help predict the effects of climate change on the groundwater resources in this area.

1.2 Objectives

The objectives of this study are to:

1. Determine how air temperature and precipitation in the Ancient Forest region compare to that of Prince George, BC. Compare Cariboo Alpine Mesonet results to past and present Prince George weather.
2. Utilize soil moisture probes and shallow groundwater wells to track the change in near surface groundwater and soil moisture values during snowmelt and summer conditions.

3. Evaluate the isotopic composition of surface and groundwater to determine whether snowmelt or rainfall is the dominant component of persistent surface and soil moisture and determine how this distinction could affect the Ancient Forest region.

1.3 Outline

An extensive literature review in Chapter 2 will explore the properties of snow and soils that dictate the relationship between them and local climate. There is a brief review of the climate system including a look at the hydrological cycle and energy balance; these concepts provide the basis of understanding the interactions between snow, soils and climate. Snow and its role in soil moisture production and retention are discussed; these processes are important in understanding the moisture dynamics at the study sites. The principles of isotopic analysis of snow and water are presented with a discussion of fractionation and their use in separation of the hydrograph.

Chapter 3 provides a detailed look at the study sites of the Ancient Forest, Lunate Creek, Prince George, and the River Forecast Centre (RFC) snow pillow sites. This chapter gives a description of the local climate based on data collected from the sites and compared to data from a long term station located at Prince George Airport. Information about the local ecosystem, soils and climate will be included here along with maps, photographs of the stations and soils, and other points of interest.

Data and Methods are discussed in Chapter 4. All field methods are described in detail along with any rationalization for sampling methods. Detailed explanation and description of analyses performed and statistical software used will be given in this chapter.

Results and Discussion (Chapters 5 and 6) will focus on the relationship of different physical and meteorological variables to the propagation of the snowmelt signal. Significant correlations and trends between measured variables are presented and discussed. Isotopic values are compared to global and regional standards. A summary and conclusion will highlight the main findings, offer potential recommendations for management, and suggest avenues for future research.

2 Background

2.1 The Climate System

All components of the environment interact to produce climatic conditions that are unique to different ecosystems. The main components of the climate system are the atmosphere (air, water vapour, trace gases, and aerosols), lithosphere (rocks, soils, and minerals), the hydrosphere (rivers, lakes, and oceans), cryosphere (snow, permafrost, ice, and glaciers), and the biosphere (plants, animals, and humans) (Figure 2.1).

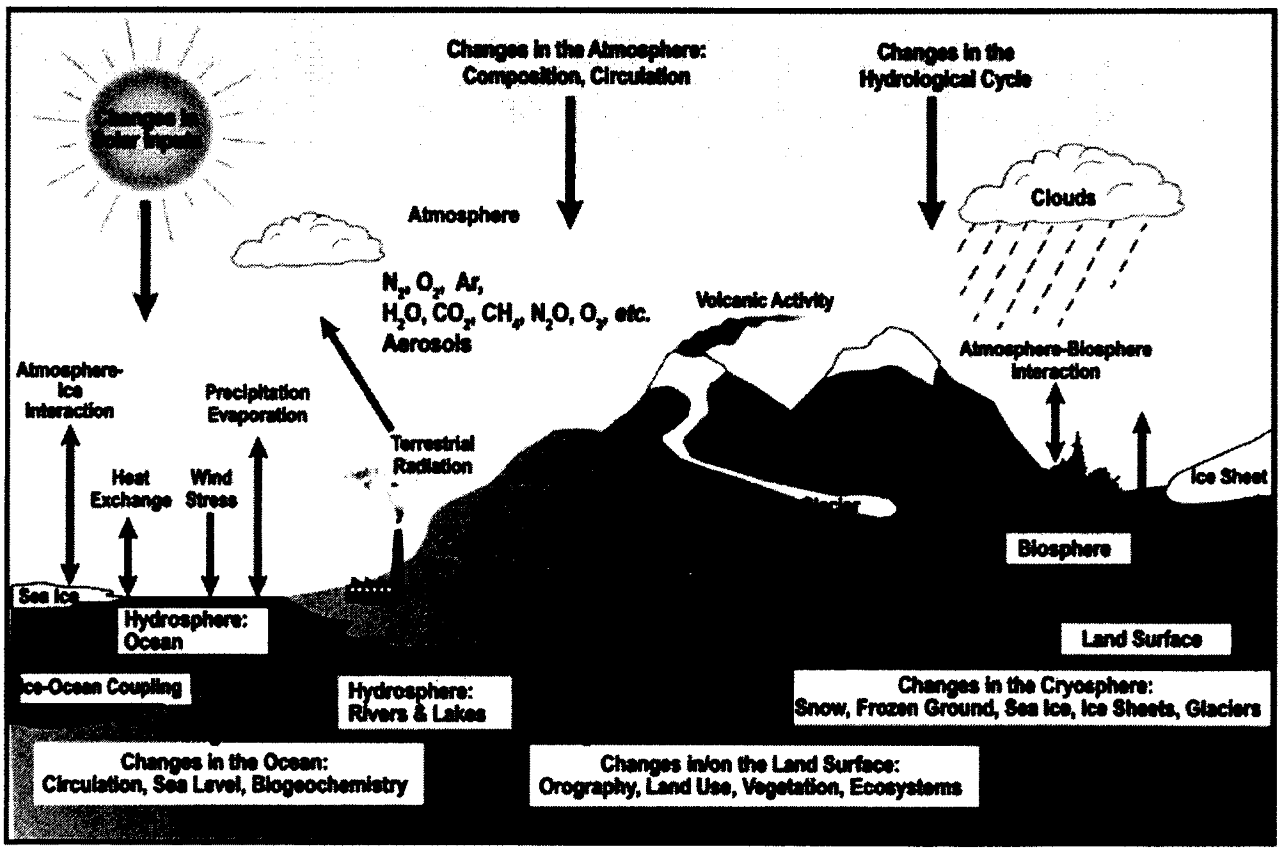

Figure 2.1 Schematic of the Global Climate System (Source: IPCC AR4 2007)

Depending on the environment, different factors will limit precipitation, heat exchange, and the radiation budget. For example, in wet environments, precipitation is likely to be limited by the radiation budget and convective processes. In drier environments, precipitation may be limited by the availability of water from the atmosphere and from the soil. Knowing the relative importance of each climate variable for different ecosystems or regions is important in making informed projections about future weather and climate.

Mid-latitude climates represent a transition zone between tropical environments and polar environments. The climate in mid-latitude regions is largely dependent on the feedback loop of the soil, plants, and the atmosphere (Kim and Wang 2007). Evapotranspiration links these elements and is largely dependent on soil moisture and the energy budget.

Convective processes, dependent on vertical thermal gradients, pull water from the surface to be condensed into clouds and precipitation at higher levels in the atmosphere. It is through these convective processes that soil moisture has the greatest effect on precipitation. The controlling factors for convective processes change depending on the scale to be considered (Anderson et al 2003).

2.2 The Hydrological Cycle and Water Budget

The hydrological cycle accounts for the exchange of water between the atmosphere, the cryosphere, the lithosphere, the biosphere, and the hydrosphere (Figure 2.2). The exchange encompasses both precipitation and energy fluxes, which drive the cycle. The components of soil moisture, snow, and rainfall, along with the energy components, are the important parts of the hydrologic cycle for this study.

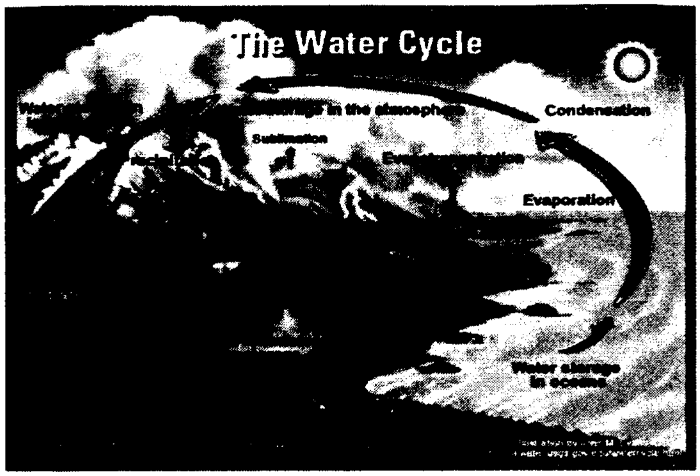

Figure 2.2 The Water Cycle (Source: http://water.usgs.gov/edu/watercycle.html, accessed 29 April 2014)

Excess soil moisture is generally considered to be a contributing factor to groundwater recharge (Rushton et al 2006). Much of our freshwater resources are fed in part by groundwater, such as the contribution of precipitation to soil moisture; subsequently, groundwater recharge is of great interest to many scientists.

The water budget is expressed in the following equation:

$$\Delta S = P + G_{in} - (ET + Q + G_{out}) \tag{1}$$

where P is precipitation, G_{in} is groundwater input, ET is evapotranspiration, Q is streamflow, G_{out} is groundwater output, and ΔS is change in storage. Evapotranspiration is a combination of evaporation, which can occur in snow environments from sublimation and blowing snow, and transpiration, the transfer of water from vegetation to the atmosphere.

The difference between infiltration and evapotranspiration values provides estimates of groundwater recharge; however, due to spatial variability in soil conditions and a host of other factors, these estimates are prone to significant error and are often unreliable. Models must incorporate important processes and take into consideration an element of heterogeneity when computing these values; these factors often differ from region to region making it impossible for any single model to provide a global estimate, let alone an accurate regional estimate. There are many different approaches to rectifying this issue, from methods of estimating recharge to looking at soil moisture memory, i.e. longterm persistence of soil moisture. These concepts are linked due to the consideration of near surface storage of soil water in the processes of infiltration and evapotranspiration.

There have been many approaches to estimating groundwater and soil moisture recharge, and all have their own inherent error. Estimates can be made by monitoring the level of the water table, employing lysimeters, the use of stable isotopes of water (Wang and Yakir 2000), and use of chemical tracers (Murray and Buttle 2005; Rushton et al 2006). Less direct methods include estimating infiltration based on unsaturated flow equations and hydraulic properties and/or storage properties (Vigiak et al 2006). It is also possible to estimate recharge by utilizing the soil moisture balance technique that depends on estimates of evapotranspiration and moisture holding properties of the soil (Rushton et al 2006).

Some studies show evidence of infiltration occurring in frozen soils (Sutinen et al 2008) or during warm periods in the winter. The snow provides an insulating layer keeping the near surface soil from freezing in the winter. Zhang et al (2007) showed that deeper snow cover resulted in a shallower depth of frozen soil, less heat loss from soil, and higher soil temperature. This implies that unfrozen water that percolates to the base of the snow pack has the potential to infiltrate into the soil, contributing to soil water and groundwater recharge even during the winter. Having ground based measurements, such as from small scale, local mesonets, in areas where evapotranspiration contributes significantly to local precipitation will improve weather forecasting in these and adjacent regions as well as provide more certainty with respect to projections of climate change.

With the advent of better remote sensing technology, soil moisture may be estimated using surface radiometric temperature data and other forms of remotely sensed data (Crow et al 2008). Advances were made in the early 2000s relating vegetation cover and surface temperature data to estimate soil moisture content (Vicente-Serrano et al 2004; Wang et al 2007). Wang et al (2007) show that soil moisture can be estimated from a combination of microwave and optical/infrared remote sensing data. Normalized Difference Vegetation Index (NDVI) and land surface temperature data from the Moderate Resolution Imaging Spectroradiometer (MODIS) are used to generate soil moisture estimates at a horizontal resolution of 1 km (Wang et al 2007). These methods are not without their own uncertainties, which are often difficult to resolve due to spatial heterogeneity of land surface features.

Snow is a key component of the hydrologic cycle and is an important freshwater reservoir. This storage is especially important in areas where most annual precipitation occurs during the winter. Snowmelt runoff supplies more than 50% of the annual streamflow in regions above 45°N latitude and supplies an estimated 17% of the global population with water (Barnett et al 2005). Snow cover lasts longest at high elevations and latitudes due to low temperatures. Snow accumulation and distribution patterns are a function of several factors including dominant regional weather, climate conditions during and between snowfalls, frequency of snowfall, physiography, and vegetative cover (McKay and Gray 1981). Land features that affect atmospheric and snow retention processes also control the spatial distribution and characteristics of the seasonal snow pack. During the accumulation period, variations in snow depth can occur due to snow-canopy interactions, snow redistribution by wind, and/or orographic influences on precipitation; local variability in these processes can result in high spatial heterogeneity of snow cover.

Soil moisture is an important component of the hydrological cycle; the moisture in soil can affect local weather through evapotranspiration, acts as a moisture reservoir for drier months, and dictates the vegetation in a region. The terrestrial hydrologic system encompasses precipitation, runoff, infiltration, and evapotranspiration; in many locations, both rain and snow represent precipitation in a region. Snow is the dominant form of precipitation (Kang et al 2014) replenishing soil moisture in mountainous regions. Often these areas rely on stored soil moisture to sustain vegetation during drier months when convective storms are predominantly the source of precipitation. Snow offers a prolonged release of moisture in most locations; melting periods of weeks to months renew or enhance moisture levels in unfrozen soils. Snow offers a layer of insulation to the ground to regulate soil temperatures in winter.

The importance of surface layer soil moisture replenishment is important in areas where lateral flow (flow between upper layers as opposed to flow from the upper layer to a lower layer) occurs. Lateral flow relies on the following conditions: 1) topographic relief of more than a few percent; 2) the presence of an impeding layer in the soil profile that limits the vertical flow of water; and 3) a high soil moisture content to allow for flow (Western et al 2002).

2.3 The Energy Budget

Energy is partitioned on a global scale; the source of energy, the sun, emits shortwave and longwave radiation (Figure 2.3). A portion of this radiation is reflected back to space by clouds, particles in the atmosphere or the surface itself. Some is absorbed to heat the atmosphere, clouds, ocean and land surface. Once absorbed, radiation from the sun can be radiated back to space as longwave radiation as described above. The connection between water and energy via the latent heat flux is accounted for in this budget, with 23% of the incoming solar energy that is absorbed by land and oceans being carried to clouds and atmosphere via latent heat in water vapour; when this vapour condenses, latent heat is released to heat the atmosphere.

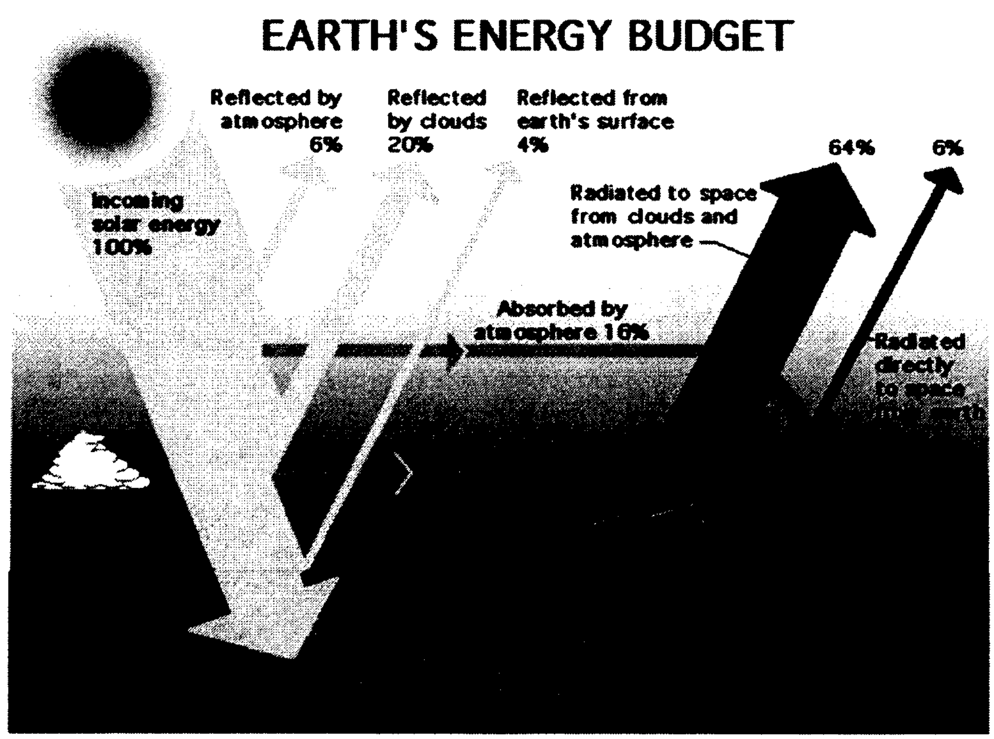

Figure 2.3 Earth's energy budget (Source: http://stelr.org.au)

The energy balance for a surface can be expressed as:

$$Q^{*}=Q_{H}+Q_{E}+Q_{G}+Q_{M}+Q\Delta_{S} \tag{2}$$

where Q^* (W m^{-2}) is the net radiation, Q_H (W m^{-2}) is sensible heat, Q_E (W m^{-2}) is the latent heat flux (evapotranspiration), Q_G (W m^{-2}) is the ground heat flux, Q_M (W m^{-2}) is heat available for snowmelt and $Q\Delta_S$ (W m^{-2}) is the heat stored within the surface, as is the case with a snow-covered surface (Oke 1987). A snow pack at 0°C is said to be "ripe"; the addition of energy to a ripe snow pack will result in snowmelt.

Linking the water and the energy balance is the process of evapotranspiration that releases or stores heat during the change of state between water and vapour. The equation below describes the latent heat flux associated with the change of state of water to vapour via evapotranspiration:

$$Q_{E}=L_{v}\times ET \tag{3}$$

where L_v is the latent heat of vapourization (2.5×10^6 J kg^{-1} at 0°C). Equation 3 describes the energy required to change water to vapour from a surface without snow cover. When snow is present on the surface, the energy requirements to change snow to water vapour (sublimation) are greater because the latent heat of sublimation at 0°C is 2.8×10^6 J kg^{-1}. The difference between the values explains the energy required to melt snow, the latent heat of fusion (L_f), which is 0.3×10^6 J kg^{-1}. While snow cover is present on the surface, cooler air temperatures persist above the snow pack. Once snow cover has melted away, energy that was previously used to melt snow is made available to heat the surface.

A useful value in describing the partitioning of energy into the sensible and latent heat fluxes is the dimensionless Bowen Ratio (β) (Oke 1987):

$$\beta = \frac{Q_H}{Q_E} \tag{4}$$

Values less than unity signify that more energy is being transferred to the atmosphere as latent heat rather than as sensible heat. A value greater than one implies the sensible heat flux is dominant. The Bowen Ratio can be useful in determining the climate of an area based on latent and sensible heat exchange.

2.4 Interactions between Climate, Snow, and Soils

Snowmelt is an important contributor to both surface and groundwater inputs. Since the Ancient Forest sites are snow dominated systems, looking at the impacts of climate change on groundwater, groundwater and surface water interaction, and groundwater quantity and quality is important, as these impacts are difficult to assess in cold regions where significant changes in snowfall versus rainfall distribution, snow depth, and soil frost depth occur (Okkonen et al 2010). A change in climate could alter the precipitation regime from snow dominated to rain dominated as the largest terrestrial changes from a changing climate are predicted for snow dominated basins (Barnett et al 2005).

While it is supposed that groundwater is the major source of water for the Ancient Forest, this hypothesis has yet to be quantified. The potential for winter rainfall to increase and snowfall to decrease could alter the groundwater recharge in the area (Okkonen et al 2010). It was noted in Ketcheson et al (1991) that the ITR received 25-50% of its mean annual precipitation from snowfall; this is also the case in the southwestern United States, where

Earman et al (2006) found that snowmelt may contribute 40-70% of groundwater recharge even when only 25-50% of precipitation falls as snow. Little is known about the mixing of infiltrated meltwater with resident soil water or about its contribution to near-surface groundwater (Maulé et al 1994). Any determination of snowmelt's role in groundwater recharge will aid prediction of the effects of climate change on the groundwater resources in this area.

Snow and soils are intrinsically linked to each other and the climate system. In regions where snow cover exists on a seasonal basis, snow has the potential to prolong cooler air temperatures and recharge soil moisture in the spring.

Snow possesses a number of unique characteristics that collectively makes it an important element of the climate system; fresh snow, for example, has the highest albedo of any natural surface, reflecting up to 95% of incoming solar radiation. Snow is also an efficient emitter of longwave radiation, which results in high rates of radiative cooling from snow-covered areas. Snow is also an excellent insulator and limits the movement of heat between the ground and air; it also keeps snow covered soils warmer than exposed soils and typically much warmer than air temperatures. Finally, the temperature at the snow surface cannot exceed 0°C, which can create large temperature gradients between the snow and the air during the melt period.

2.4.1 Snow and its role in soil moisture

Snowmelt is an important contributor to both surface and groundwater inputs. In snow dominated mountain regions, it has been observed that precipitation does not necessarily enter the soil at the point it falls, but more often where it melts (Williams et al 2009). Seasonal snow cover is in decline in the Northern Hemisphere; there are statistically-significant negative trends in weekly snow cover extent over nearly half the year for the Northern Hemisphere, and only two weeks showing statistically-significant, positive trends (Déry and Brown 2007). A change in climate could alter the precipitation regime from snow dominated to rain dominated. It has been noted that the proportion of precipitation falling and accumulating as snow is highly sensitive to even subtle changes in climate (Edwards et al 2007). Overall recharge of groundwater resources could increase with a shift from a cold to temperate climate. Peak accumulation and the date when 90% melt occurs have also been moving to earlier in the year due to an increase in overall temperature in the western United States (Hamlet et al 2005). An earlier spring melt could increase the ground thaw; this would allow for increased infiltration of the meltwater into the soil (Okkonen et al 2010). In Siberia, Sugimoto et al (2003) found that the amount of snowmelt infiltration was equivalent to about 50% of the season's snow water equivalent (SWE). Since snow, not manmade reservoirs, is the largest component of water storage in western North America (Mote et al 2005), any alteration to a snow regime could greatly affect the amount of water available to a region.

MacDonald (1987) noticed a rapid groundwater response when simulating snowmelt on forested hillslopes. A change from snow to rain could cause more overland flow and increased storage in surface water bodies (Okkonen et al 2010); increased surface storage in combination with warmer temperatures could result in larger losses to evaporation, meaning less long-term storage. Snowmelt is also vital in plant physiology; budding plants take up water with low oxygen-18 ($\delta^{18}O$) during leaf unfolding (Sugimoto et al 2003). Snowmelt is depleted in $\delta^{18}O$ due to snow falling through the atmosphere in a frozen state; it is unable to equalize the depleted values as it falls through the air column (Gat 1996).

The potential for winter rainfall to increase and snowfall to decrease could change the groundwater recharge in the area (Okkonen et al 2010), but the snow pack has other properties that make it important in the ecosystem. Seasonal snow cover insulates the ground and allows for higher soil temperatures during winter (Zhang 2005). Snow is also one of the most important environmental variables for the occurrence of specific vegetation and the spatial distribution of vegetation types (Löffler 2007). Little is known about the mixing of infiltrated meltwater with resident soil water or about its contribution to near-surface groundwater (Maulé et al 1994).

It was observed by Flerchinger et al (1992) that in early spring, snow cover is widespread and recharge of the groundwater occurs over most of the monitored area (Upper Sheep Creek Watershed, Idaho); this is referred to as general snowmelt. Once the general melt is over, recharge of groundwater is localized to the areas of greater snow accumulation. Snow cover also acts as an insulating layer for the soil and can decouple soil temperature from air temperature with as little as 30 cm of snow. Hamlet et al (2006) found that variability in interannual soil moisture values is closely related to variability in snow accumulation in their western United States datasets. In alpine and arctic regions, where permafrost plays a dominant role in soil moisture regimes, snow also acts as groundwater recharge but is not as large of a factor. Melting of the active layer in permafrost contributes to the groundwater from the late melt of the frozen soil, but much of the snowmelt is lost to runoff due to the soils being frozen in early melt (Löffler 2007).

Surface soil layers get replenished by precipitation as rainfall during warmer summer months. He et al (2012) determined that soil moisture replenishment only occurs when there are large rainfall events (>20 mm); they observed soil moisture values in the 20-60 cm soil layer after small events, and, even when the small events were frequent, there was not the same recharge of soil moisture as during large rainfall events. An increase in greenhouse gases can change rainfall regimes and the hydrologic cycle, and these gases are projected to increase further in the future (Porporato et al 2004). Whether precipitation trends change and a higher fraction of precipitation is expected to fall as rain or the amount of total rainfall remains the same, soil drought may occur if there is a decrease in large rainfall events (He et al 2012). In contrast, a positive soil moisture anomaly owing to above-normal snowfall may also pose a problem. Small (2001) found that above-normal snow pack in the North American Monsoon System (NAMS) increases soil moisture, which in turn disrupts the NAMS. The cooling effect on surface temperatures that increased soil moisture may disrupt the ocean-land temperature gradient that drives the monsoon system (Small 2001).

Soil moisture determines vegetation and influences local weather. In drier areas such as the regions affected by the NAMS, southwestern United States and northwestern Mexico, soil moisture has an effect on the amount of precipitation recorded between the months of July and September. Small (2001) determined a positive soil moisture-rainfall feedback; this supports the hypothesis that land-atmosphere interactions, as moderated by soil moisture anomalies, influence annual variability of the NAMS.

Vegetation can also act as a buffer; the organic layer of soil tempers the heat and water transfer between the atmosphere and mineral soil (Kane and Stein 1983) and acts as insulation for the soil and protects against high radiation inputs and soil heat fluxes (Löffler 2007).

2.4.2 Snow and soil temperature

Along with the insulating effect of snow cover during the winter, soil moisture plays a large role regulating soil temperatures. This tempering of soil temperatures is mainly due to the latent heat and sensible heat fluxes in the soil (Löffler 2007; Sugimoto et al 2003; Western et al 2002; Kane and Stein 1983); this cycle of precipitation and evapotranspiration accounts for much of the energy (as latent heat) exchange between the land surface and the atmosphere (Wang and Yakir 2000). Soils with high moisture contents encounter less pronounced diurnal temperature fluctuations than dry soils (Löffler 2007). For many areas, the dry period is defined as the situation when evapotranspiration exceeds precipitation and soil moisture in deeper layers of the soil profile is greater than near the surface (Sugimoto et al 2003). During dry periods, capillary rise from shallow groundwater stores can replenish near-surface soil moisture (Western et al 2002). Dry conditions in late spring can precipitate drought, either by making conditions favourable for drought to develop or persist and become perpetuated (Vörösmarty et al 2001). Soil moisture, along with atmospheric processes, regulates ET and the partitioning of incoming solar radiation and longwave radiation into latent and sensible heat fluxes (Western et al 2002). When there is a large amount of moisture in the soil, latent heat gets released during soil freezing (Sugimoto et al 2003); this latent heat release slows or prohibits the advancing freezing front (Kane and Stein 1983). Wet soil also increases the evaporation rate, causing the surface temperatures to stay cooler than normal in the summer months; this cooling is due to the increased evaporation rate increasing the "thermal inertia" (Small 2001) of the surface soil. Evapotranspiration returns much of the water in soil to the atmosphere, which can influence regional precipitation patterns (Wang and Yakir 2000).

Although snowmelt is an important component to the soil moisture regime, persistence of soil moisture throughout the drier summer months remains important as well. Near surface soil layers have more variable soil moisture levels than deeper layers; factors such as soil type and texture, organic content, and precipitation patterns all play a role in the persistence of soil moisture. This upper soil layer is also where the rooting zone for plants occurs; if the soil moisture means change then there is the possibility of a species shift occurring (He et al 2012). A contradiction to this was found by Penna et al (2009); at their site in alpine terrain of Italy, they showed that the surface layers (0-6 cm) showed less variation than deeper soil layers. The supposed difference at this site was the presence of dew on many of the days of sampling that was thought to temper drying episodes; Penna et al (2009) saw dew deposit totals of up to 1.8 mm day^{-1}.

Soil moisture anomalies persist for longer periods in northerly latitudes due to decoupling of the surface from the atmosphere by snow cover during winter (Barnett et al 1989; Delworth and Manabe 1989; Yeh et al 1984). The snow cover prevents the loss of soil moisture through evaporation and increases the albedo of the surface, so the land surface absorbs little, if any, energy from incoming solar radiation (Barnett et al 1989). Evaporation is limited by the thermal gradient and moisture holding capacity of the atmosphere (Yeh et al 1984); in colder months, evaporation does not contribute substantially to precipitation. When the snow melts, wetter soils regulate above ground temperatures inducing near surface atmospheric cooling (Barnett et al 1989). Wet soil moisture anomalies correspond to cooler air temperatures and often persist due to a reduction in evaporation just as dry soil anomalies persist when less moisture is available at the surface. In these conditions, the surface warms to greater temperatures and the soil moisture evaporates more efficiently.

Snow greatly impacts the thermal conditions of the ground beneath it, as well as above surface air temperatures. The high albedo of snow implies that a greater portion of incoming shortwave radiation is reflected back to space than is absorbed by the snow pack (Oke 1987; Stieglitz et al 2003; Zhang 2005). Having a low thermal conductivity, the snow pack reduces heat loss from the soil surface so that the soil is generally warmer than the air temperature during winter, depending on snow pack depth (Zhang 2005). The snow pack will act as a heat sink because it requires so much energy for a change of phase to occur (Oke 1987; Zhang 2005). When the snow pack melts, this sink is lost and shortwave radiation heats the ground or enables ET instead of melting the snow pack. The overall effect of the snow pack on the ground thermal regime is dependent on the timing, duration, density and thickness of the snow pack as well as local weather conditions, topography and vegetation (Zhang 2005).

Of interest to this study are characteristics of the snowmelt period and how the snowmelt is retained in the soil. With projected changes in the climate, precipitation regime and land use in the area, knowing how the soil responds to precipitation and snowmelt inputs might help with forest management and in identifying the viability of the ICH in its current range.

2.5 Stable Isotopes of Water and Water Partitioning

2.5.1 Principles of Stable Isotopes

Work on identifying stable isotope signatures in groundwater and surface water has been ongoing since the 1970s. Stable isotopes of water oxygen-18 (^{18}O) and deuterium (^{2}H) are most often used because they are incorporated in the water molecule ($H_2\,^{18}O$, $^{1}H\,^{2}H\,^{16}O$) (Birks and Gibson 2009). These molecules undergo measurable and systematic fractionations as they move between phases in the water cycle (Figure 2.4) (Birks and Gibson 2009; Taylor et al 2002; Hammen and Stichler 1981).

Figure 2.4 Schematic drawing of the enrichment and depletion of water for a synoptic system (based on: GNIP Brochure, IAEA, 1996)

Figure 2.4 illustrates the various values of isotopes in the environment and their connection to each other. Monteith et al (2006) used stable isotopes to study topographic control on streamflow sources and groundwater residence times during snowmelt with a paired-basin study. Murray and Buttle (2005) looked at snowmelt infiltration and soil water mixing. Studies looking at the isotope fractionation during snowmelt allow for the determination of the differing inputs of ^{18}O and ^{2}H such that a better estimation of the concentration of the isotopes can be made (Stadnyk et al 2005; Laudon et al 2002; Unnikrishna et al 2001).

Stored groundwater has a relatively constant isotope signature; this reflects the long-term precipitation average due to recharge and minimal evaporative influence (Stadnyk et al 2005).

2.5.2 Use in hydrograph separation

Separating the hydrograph to assess whether there is a shift from snowfall to rainfall has aided in identifying the role snowmelt plays in mountain environments. Isotope hydrograph separation isolates the contributions of new water (water from events such as snowmelt or rainfall) and old water (groundwater, soil water and soil pore water) based on the different isotopic signatures of the two sources (Taylor et al 2002). Isotopic composition of the various forms of precipitation depends on the temperature of condensation and evaporation, atmospheric moisture, and origin of air masses (Stichler et al 1981). As temperature of condensation decreases, $\delta^{18}O$ and $\delta^{2}H$ values of the precipitation decrease; winter precipitation is depleted and summer precipitation is enriched.

2.5.3 Fractionation in the snow pack

Usually, snowmelt is more depleted in ^{18}O than groundwater (Figure 2.4) (Taylor et al 2002). By analysing the groundwater for the old and new water signatures, and then further dividing the new water into warm- or cool-season precipitation, the component contributed from snowmelt can be determined.

Isotope content of each different snow layer does not change significantly during accumulation, since evaporation and condensation play only a minor role during accumulation (Stichler et al 1981). However, by not taking into account the temporal differences in the $\delta^{18}O$ of the snow pack during the melt season, a systematic error is introduced (Taylor et al 2002). Multiple measurements of both the snow pack and snowmelt should be taken to determine the changes in isotopic composition over the course of the melt season. Taylor et al (2002) found that initial meltwater is depleted in ^{18}O and then becomes enriched as the snow pack melts; this change is typically 3-5%.

3 Site Description

The sites being investigated are located 110 km east of Prince George, BC along Highway 16. The sites are commonly referred to as the Ancient Forest due to the extremely old (1000 years old or older) Western redcedar (*Thuja plicata*) found in the stands (Stevenson et al 2011). The area falls within the Rocky Mountain Trench, with the Cariboo Mountains to the south and the Rocky Mountains to the north. The sites chosen for the study are all in the Cariboo Mountain range. The sites were selected for their representation of the elevation and harvest differences in the ITR: an old-growth ICH stand and a second growth ICH stand. The Ancient Forest site has one automated weather station in place while the Lunate Creek site has both an upper and a lower station. For descriptive purposes, the Lunate Creek sites are similar and proximal, such that they will be described together.

3.1 CAMnet Weather Stations

3.1.1 Ancient Forest

The Ancient Forest site (53° 46' 21" N, 121° 13' 44" W) is located on the north side of Highway 16, about 100 m from the road. The site has an elevation of 774 m and is relatively flat. The site is in a clearing of an un-harvested old growth Western redcedar- Western hemlock (*Tsuga heterophylla*) stand with an understory of devil's club (*Oplopanax horridus*) and downed, decaying trees. This area is located at the toe of the slope as the area transitions to the Fraser River flood plain.

3.1.2 Lunate Creek – Upper and Lower

The Lunate Creek site (53° 49' 58" N, 121° 27' 32" W) is located approximately 100 km east of Prince George and approximately 6 km up the Hungary Creek Road from Highway 16. The site is a north facing slope at an elevation of 953 m. The lower station sits on a slope of

23% and is positioned midslope in a regenerating cutblock. The upper weather station was on a flat area approximately 100 m above the lower station and 300 m to the south. It was also in a regenerating cutblock, but at the toe of the slope. Regeneration was mainly planted spruce with some naturally regenerating cedar-hemlock. There was considerable competing vegetation of devil's club and other shrubby plants. A schematic drawing of the Lunate Creek site is illustrated in Figure 3.2.

a) b)

Figure 3.1 CAMnet sites at a) the Ancient Forest and b) Lower Lunate Creek

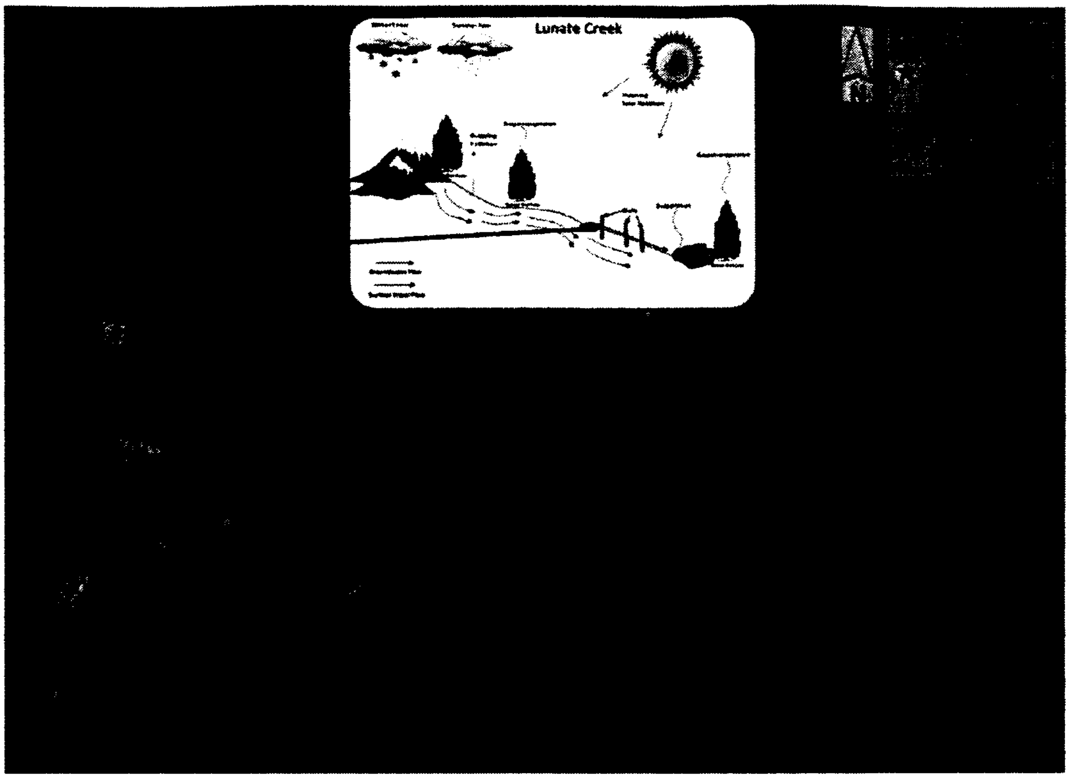

Figure 3.2 Topographic map of the Ancient Forest and Lunate Creek sites with a schematic drawing of the Lunate Creek site energy and water inputs/outputs as inset.

3.2 River Forecast Centre Sites and Prince George Meteorological Station

The RFC operates snow pillow sites that will be used to evaluate higher elevation snow data. Three sites were chosen for their proximity to the research sites; the sites were Hedrick Lake (elev. 1118 m), Revolution Creek (elev. 1676 m) and Dome Mountain (elev. 1768 m) (Figure 3.3).

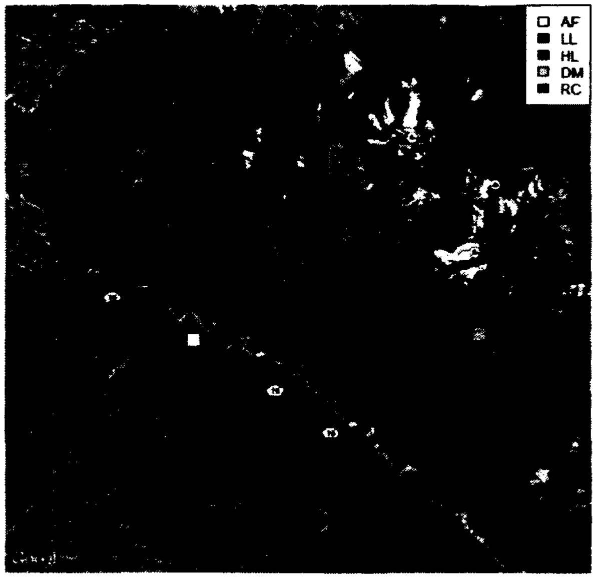

Figure 3.3 Location of RFC sites (Hedrick Lake (HL), Dome Mountain (DM), and Revolution Creek (RC)) with respect to the Ancient Forest (AF) and Lunate Creek (LL).

Each of these sites monitors air temperature, snow depth, and precipitation and utilize snow pillows to determine SWE; the snow pillow measures the water equivalent_of the snow pack based on hydrostatic pressure created by overlying snow. The RFC sites also had monthly snow surveys that were conducted, which will aid in determining spatial variability among the sites.

Prince George was about 110 km northwest of the Ancient Forest/Lunate Creek area where the meteorological stations were located. The Environment Canada station at Prince George Airport (ID: 1096453) was at 680 m in elevation, making it a reasonable station with which to compare our data. Looking at the 30-year climate norms (1981-2010) for Prince George Airport allows us to characterize the 2011-2012 season at both the Ancient Forest and Lunate Creek meteorological stations. It should be noted that data from Prince George Airport were expected to have slightly warmer average air temperatures because it was 94 m lower in elevation than the Ancient Forest and 273 m lower in elevation than Lower Lunate Creek; the station at the airport was also located in an open area that was influenced by wind and an urban area.

Average monthly mean air temperatures at Prince George Airport range from -7.9°C in January to 15.8°C in July for the period from 1981-2010 (see Table 3-1) with an average annual air temperature of 4.3°C. Fall and winter temperatures (November to March) show much greater variation than spring and summer temperatures (April to October) with standard deviations ranging between 3.5°C in November to 4.4°C in January compared to 1.0°C in July and 1.6°C in September.

Table 3-1 Daily maximum, minimum, average, and standard deviation of monthly air temperature (°C) at Prince George Airport, 1981 to 2010, available online at Environment Canada's Climate Archive, Environment Canada (2013)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Daily Avg (°C)	-7.9	-5.0	-0.2	5.0	10.1	13.8	15.8	15.0	10.4	4.5	-2.5	-7.2	4.3
Std. Dev (°C)	4.4	3.8	2.5	1.3	1.6	1.2	1.0	1.1	1.5	1.2	3.5	4.1	0.9
Daily Max (°C)	-4.0	-0.4	5.2	11.2	16.7	20.2	22.4	22	16.7	9.4	1.0	-3.5	9.7
Daily Min (°C)	-11.7	-9.6	-5.6	-1.1	3.4	7.3	9.1	8.0	4.0	-0.5	-5.9	-10.9	-1.1

Table 3-2 presents the average rainfall, average snowfall and average total precipitation for the period of 1981-2010 at the Prince George Airport. Average annual precipitation was about 595 mm; the highest total precipitation falls in June, which averages 65.3 mm and the lowest total precipitation falls in February, which averages 29.5 mm; 423.6 mm falls as rain and 205.1 cm falls as snow (as a depth), on average. January sees the highest average snowfall with 54.6 cm and June sees the highest average rainfall with 72.7 mm. Snowfall totals ranged from a maximum of 54.6 cm in January to a minimum of 1.9 cm falling in May.

Table 3-2 Average rainfall (mm), average snowfall (cm) and average total precipitation (mm), at Prince George Airport, 1981 to 2010, available online at Environment Canada's Climate Archive, Environment Canada (2013)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall (mm)	8.1	6.7	12.0	28.9	47.2	65.3	62.1	51.5	55.9	56.5	23.9	5.6	423.6
Snowfall Depth (cm)	54.6	28.1	20.8	7.4	1.9	0.0	0.0	0.0	0.3	7.9	36.2	47.7	205.1
Precip. (mm)	52.9	29.5	29.7	36.0	49.0	65.3	62.1	51.5	56.3	63.3	55.3	43.9	594.9

3.3 Soil Properties

Soils in the ITR were classified as Luvisols where medium and finer-textured parent material exists (Stevenson et al 2011). The LFH horizon is approximately 15 cm thickness at both sites. The LFH horizon comprises organic litter (L), partially decomposed organic matter (F), and decomposed organic material (H). Beneath this layer was an Ae horizon 6 cm in thickness at Lunate Creek to 25 cm at the Ancient Forest site. The Ae horizon was greyish in colour and wet. The next layer was described as a Bt horizon at the Ancient Forest and a Btg horizon at Lunate Creek; the layer was 20 cm thick at the Ancient Forest and 24 cm thick at Lunate Creek. The Ancient Forest had a Bf layer that was 13 cm thick; this was as deep as the soil pit was dug, so layer thickness and deeper layers are unknown. Below 67 cm at

Lunate Creek, the soil matrix was more rocks and small cobbles than soil, so this was observed as the C layer, the till parent material for soil formation. Clay films and mottles were observed at both sites indicating downward movement of water through the soil. Figure 3.4 illustrates the soil profiles at the Ancient Forest and Lunate Creek. Detailed soil profiles had not been conducted at either site, but doing so would aid in future studies investigating soil moisture properties. Soil moisture probes at Lunate Creek are shown in Figure 3.5.

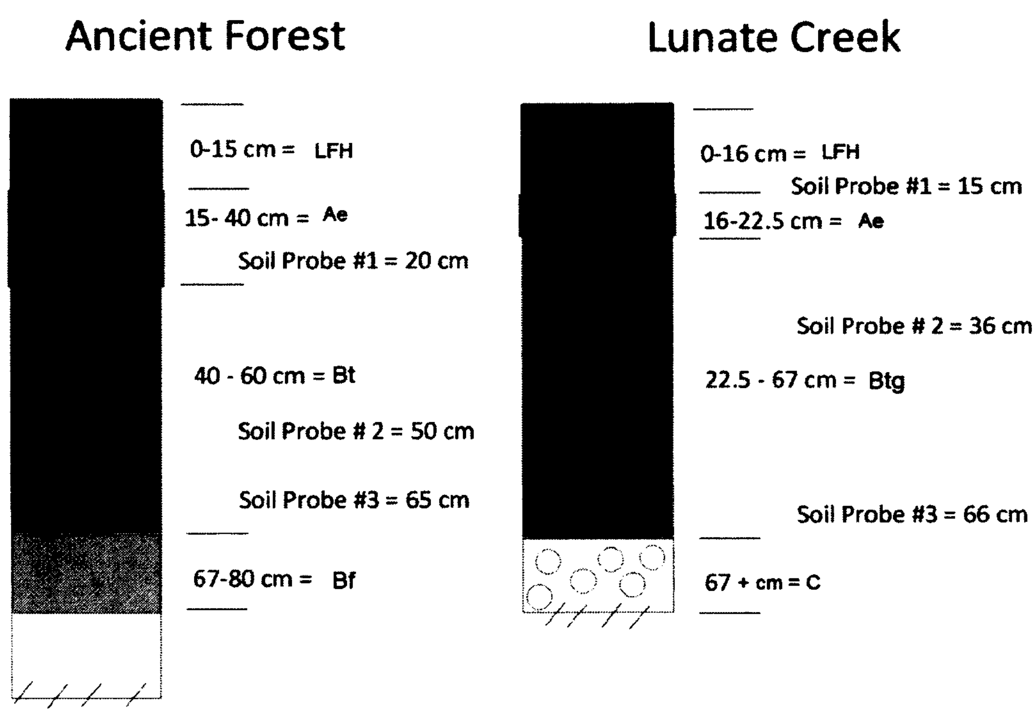

Figure 3.4 Soil profile for Ancient Forest (left) and Lunate Creek (right)

Figure 3.5 CS616 soil moisture probes at Lunate Creek inserted at 15 cm, 36 cm, and 66 cm

4 Data and Methods

4.1 Weather Stations

The meteorological stations at the Ancient Forest and Upper and Lower Lunate Creek support ongoing research by the Northern Hydrometeorology Group (NHG) investigating local hydrological and atmospheric processes. The Ancient Forest station was installed in 2009, while the Lower Lunate Creek station was acquired from the BC Ministry of Forests and Range (now the Ministry of Forests, Lands, and Natural Resource Operations); the Upper Lunate Creek station was set up in the summer of 2011 and dismantled in the fall of 2012. The stations were part of the Cariboo Alpine Mesonet (CAMnet), a network of mesoscale meteorological stations set up by the NHG to monitor the water budget of the Fraser and Quesnel River basins (MacLeod and Déry 2007; Déry et al 2010).

The CAMnet stations at the Ancient Forest and Lunate Creek were equipped with a number of instruments and sensors that monitor meteorological conditions such as wind speed, air temperature and humidity. These instruments were all wired to either a Campbell Scientific CR10X or CR1000 data logger that samples every minute and then averaged for 15 minute periods. Tables 4-1 and 4-2 summarize the instruments present at each site and the towers are shown in Figure 3.1. These data can be downloaded from the station using the Loggernet software, with a connector cable from a portable computer to the data logger. Of particular interest to this study were variables that were known to affect near-surface atmospheric processes: soil moisture, snow depth, precipitation, air temperature and relative humidity. Each of these instruments is described in brief, below.

Table 4-1 Instruments installed at the Ancient Forest

Instrument	Variable	Measured Accuracy
CR10X Data logger	stores measurements	N/A
107B Temperature Probe	soil temperature at 12 cm	± 0.9°C
CS616 Water Content Reflectometer	soil moisture at 20 cm, 50 cm and 60 cm	± 2.5% Volumetric Water Content
SR50A Sonic Ranger	snow depth	± 0.4% of distance to target
RM Young Wind Monitor	wind speed and direction	± 0.3 m s^{-1}
HMP45C212 Temperature and RH probe	temperature and relative humidity	± 0.1°C/ ± 2% (0-90% RH), ± 3% (90-100% RH) at 20°C
TE525WS Tipping Bucket	precipitation	± 1% of precipitation rate up to 2.54 mm hr^{-1}
CMP3 Pyranometer	incoming solar radiation	± 5%

Table 4-2- Instruments installed at Lunate Creek

Instrument	Variable	Measured Accuracy
Lower Lunate Creek		
CR1000 Data logger	stores measurements	N/A
107B Temperature Probe	soil temperature at 12 cm	± 0.9°C
CS616 Water Content Reflectometer	soil moisture at 15 cm, 35 cm and 65 cm	± 2.5% Volumetric Water Content
SR50A Sonic Ranger	snow depth	± 0.4% of distance to target
RM Young Wind Monitor	wind speed and direction	± 0.3 m s^{-1}
HMP45C212 Temperature and RH probe	temperature and relative humidity	± 0.1°C/ ± 2% (0-90% RH), ± 3% (90-100% RH) at 20°C
Upper Lunate Creek		
CR1000 Data logger	stores measurements	N/A
SR50A Sonic Ranger	snow depth	± 0.4% of distance to target
HMP45C212 Temperature and RH probe	temperature and relative humidity	± 0.1°C/ ± 2% (0-90% RH), ± 3% (90-100% RH) at 20°C
TE525WS Tipping Bucket	precipitation	± 1% of precipitation rate up to 2.54 mm hr^{-1}

4.1.1 Soil Moisture

Soil moisture was measured as volumetric water content (VWC) and was expressed as a fraction. VWC (or soil water content) was the volume of pore space within the soil that was occupied by water. The total volume of soil in unsaturated conditions was given by the following equation:

$$V_T = V_w + V_s + V_a \tag{4}$$

where V_w was the volume of space occupied by water, V_s was the volume of soil particles and V_a was the volume of space in the soil occupied by air. The dimensionless volumetric water content (Θ) was then simply:

$$\theta = \frac{V_W}{V_T} \tag{5}$$

The instruments deployed to measure VWC were Campbell Scientific® capacitance devices (CS616). They consist of two steel rods 30 cm long running parallel to each other and an oscillator. The adjacent soil forms the dielectric of the capacitor, which completes the oscillating circuit. Soil dielectric was affected by water content; changes in water content results in a change in the oscillation frequency, which can be related to actual soil water content via a calibration curve. The elapsed travel time and pulse reflection were measured and were used to calculate water content (Campbell Scientific 2006).

Calibration of the soil moisture probes was especially important in soils that contain clays and organic matter as these soil components can alter response of dielectric-dependent methods to water content, often over-recording water content. The probes experience the measurement error when soil bulk density exceeds 1.5 g cm^{-3}. The soils at both the Ancient Forest and Lunate Creek were not analyzed for bulk density nor were the soils' initial moisture content determined; therefore, the values of soil moisture cannot be taken as actual water content but represent the pattern of wetting and drying seen at these sites.

At the Ancient Forest site, the pit was dug to about 70 cm depth and was about 1 m across. The probes were installed at depths of 20 cm, 50 cm and 65 cm in the soil column. Originally, the probes were meant to be spaced approximately 5 cm apart horizontally, and

10 cm apart vertically; rocks in the soil prevented this spacing so they were inserted as close to these depths and spacing as possible. At the Lower Lunate Creek site, the pit depth was approximately 70 cm and 1 m wide. The probes were installed at 15 cm, 36 cm, and 66 cm in the soil column. As with the Ancient Forest site, the presence of rocks and large cobbles prevented the probes from being placed in the suggested manner.

The CS616 probes do not measure frozen water content and hence, frozen water within the soil will not be accounted for until it melts. At both sites, the soil temperature at 12 cm (Ancient Forest) and 17 cm (Lunate Creek) depth did not drop below 0°C for the entire winter season. Since these probes were at 12 cm and 17 cm in depth, respectively, we can assume that the soil water at these depths was not frozen during the winter and hence the sites' measurements represent the true soil water content for the entire period of time that data were collected in the upper probes. Data were sampled every minute and then averaged over 15 minute periods for this study. This interval should capture short-lived precipitation events and allow for a better representation of the temporal variability associated with soil moisture. Hourly and daily averages can be computed from these values. Data were periodically collected from the field using the Loggernet software designed to work with the Campbell Scientific® data loggers.

4.1.2 Snow Depth

Snow depth was measured using the Campbell Scientific® SR50A (Sonic Ranger). This instrument emits an ultrasonic pulse that travels from the sensor to the surface and back. The time it takes to do so was converted into a depth of snow. The measurement must be corrected for the effect of air temperature on the speed of sound in air (Campbell Scientific

2006). The data from the Ancient Forest and both Lunate Creek sites show many inconsistencies and were difficult to filter; the main reason attributed to these inconsistencies was the lush vegetation that was found in the ITR. Often in this case, a fixed target is installed to remove the effect vegetation has on snow depth; this was not done for this study. For this reason, they were supplemented with snowfall data from nearby RFC snow pillow data where snowfall measurements were taken hourly and available in near real-time (RFC 2012); historical climate data were also acquired from Environment Canada (Environment Canada 2012) from the Prince George Airport. These data are reliable and allow for comparison of the 2011-2012 winter/spring seasons with climate norms (1981 to 2010) established at Prince George Airport along with regional comparison to other snow depth measurements from nearby climate stations.

The SR50A only provides a depth to target estimation and hence does not provide information on SWE or snow density; without a snow board, maximum depth would vary due to vegetation death and crushing. Snow surveys as described below were done to obtain estimates of SWE. These values were then used to find the density of the snow through the following equation:

$$\rho_{(snow)} = \frac{SWE}{snowdepth} \times \rho_{(water)} \tag{6}$$

where $\rho_{(snow)}$ was the density of snow (kg m^{-3}), SWE was snow water equivalent (m), snowdepth measured in meters (m), and $\rho_{(water)}$ was the density of water (kg m^{-3}).

Snow density changes over the winter as snow undergoes morphological changes resulting from temperature fluctuations and compaction under its own weight. Sublimation could also contribute to loss of water from the snow pack.

SWE was an important factor in determining the volume of water stored and available from snowmelt. It was determined by either digging a snow pit or by using a Federal snow sampler. Both methods were used during this study.

The snow pit method of SWE measurements involved digging the depth of the snow pack and using a wedge sampler to obtain a measurement every 10 cm. The wedge sampler used was a 100 cc volume and each sample was weighed in a plastic bag to the nearest gram; density was determined using equation (6). There were errors involved in density sampling due to frozen layers in the snow pack, debris from vegetation within the snow pack, and excess snow in the wedge before the next layer.

The Federal snow sampler, an aluminum tube with an interior diameter of 3.8 cm, was graduated by 10 cm increments and was divided into three sections. The sampler and a spring scale, which was calibrated to the sampler, were used to determine the density of a snow core based on weight; depth of snow within the sampling tube indicates millimeters of SWE. The accuracy of the Federal sampler was ±0.5 mm. The tube was inserted and forced through the snow pack. A sample that had not reached the surface of the ground (i.e. there was no soil visible in the bottom of the core) was not acceptable and was resampled. The tube was weighed with the snow inside and values were recorded in a table. SWE was read from the scale on the tube and is determined by subtracting the weight of the tube from the weight of the snow plus the tube. The Federal Sampler does have error associated with the openings on the tube used for reading SWE; the sampler overestimates SWE (except during snowmelt when water can escape through the slats) but is recognized as the standard when measuring official snow courses (Beaumont and Work 1963).

Density measurements using the wedge sampler were conducted at the Ancient Forest site on 13 March 2012; this date corresponded to the average date of peak accumulation at the Ancient Forest, Lunate Creek (both sites), Prince George, and the RFC sites. The Ancient Forest site was chosen for the determination of peak accumulation/peak SWE because it correlates to both the Lunate Creek sites and Prince George. Although the SWE calculations were considerably less than the higher elevation RFC sites, peak accumulation occurred within a week, from about 7 March – 14 March 2012, at all observed locations.

Samples using the Federal sampler were taken on three dates in the spring to represent early, mid-, and late melt periods to determine the average density of the snow pack at these times at Upper and Lower Lunate Creek. Snow depth measurements were taken along with SWE measurements in a transect 50 m long parallel to the slope of the cutblock and 50 m perpendicular to the slope of the cutblock; snow depth was recorded every two meters (n = 50 per site) and a snow core was collected every five meters (n = 20 per site). This process was completed three times on 24 April, 10 May, and 17 May 2012 to establish the evolution of the snow pack with respect to SWE and density during the melt season. The SWE data collected provide an estimate of snow pack conditions for these dates; peak accumulation appeared to have occurred at most locations about a month prior, although a cool spring allowed for the snow pack reducing at a much slower rate than previous spring seasons (RFC 2013).

Snow pillows consist of 3-m diameter bladders containing an antifreeze solution. As snow accumulates on the pillow, the weight of the snow pushes an equal weight of the antifreeze solution from the pillow up a standpipe in the instrument house. This weight of the water content of the snow was converted to SWE. The snow depth sensor was mounted on an arm extending from a 6-m high tower and points toward the ground above the pillow. The ultrasonic sensor measures the distance from the sensor to the surface below it. As the snow depth increases the distance measured decreases (River Forecast Centre, http://bcrfc.env.gov.bc.ca/about/snow-pillow.htm).

4.1.3 Air Temperature and Humidity

The HMP45C212 air temperature and relative humidity probe was housed in a Gill radiation shield to prevent erroneous air temperature measurements. This probe made concurrent measurements of humidity and air temperature at the same temporal resolution as all other variables being monitored.

4.1.4 Precipitation

Measuring precipitation at these remote sites was particularly challenging (especially during winter) and the data collected were not considered reliable. The precipitation gauge at the Ancient Forest was a TE525WS Tipping Bucket Rain Gauge. It measures precipitation in increments of 0.254 mm of water. Every 0.254 mm of water collected by the bucket causes a 'see-saw' device that collects the water to tip. It may take more than one short-lived precipitation event to cause a 'tip'. The problem this poses is that shorter, less intense events may actually not be represented by the gauge until further precipitation causes sufficient accumulation, and, conversely, intense storms may overwhelm the bucket capacity and misrepresent the actual rainfall amount.

There were other problems associated with the precipitation gauge at the Ancient Forest. The gauge was quite small and unshielded such that it was likely affected by wind. Unless the air was very still, it was likely that precipitation accumulation was being underestimated because the precipitation tended to fall sideways as opposed to straight down into the gauge. There were also problems with water freezing in the gauge. Adding antifreeze to the gauge's snowfall adapter in the fall season was meant to prevent freezing of winter precipitation; however, some freezing still occurred and hence, precipitation events were not recorded at the actual time they occur. During heavy snowfall events, the snow would overwhelm the collection capacity of the gauge therefore causing bridging of the snow on top of the gauge; the precipitation gauge was then unable to record the incoming precipitation during these events. Data from the rain gauge at Upper Lunate Creek were used to collect rain samples for isotope analysis and used as a comparison to precipitation data from the Ancient Forest.

4.2 Methods

4.2.1 Data Collection and Quality Control

Data loggers at all sites recorded data for the observation period; these data allowed for a temporal examination of the 2011-2012 fall and winter seasons in these areas. The snow survey at the Ancient Forest captured peak accumulation with the surveys at Lunate Creek capturing the melt season in April and May. These data will allow for an assessment of the representativeness of the depth measurements taken by the SR50A.

4.2.2 Daily Means and Correlations

Descriptive statistics were run on the data from both the regional and local weather stations. SWE data and density were calculated for the Ancient Forest at peak accumulation and Lunate Creek during early, middle, and late melt.

Once sorted and quality controlled, the data were transferred into the R statistical software version 2.11.1 (R Development Core Team, 2008). This program was used to calculate daily averages from the 15 minute data in a sequence loop command. The data presented here were based on daily averages computed from values logged every 15 minutes on the data loggers. Pearson product-moment correlation coefficients, autocorrelation and cross-correlation coefficients at the 95% confidence level were computed in R (R Development Core Team 2008).

Autocorrelation describes persistence in a successive list of values, in this case soil moisture values. The statistical test for autocorrelation in this study assesses the persistence of the soil moisture from snowmelt. Autocorrelation was calculated from daily average soil moisture time series at a lag period of one day up to twenty days. The coefficient of autocorrelation, *r*, with values between -1 and +1 was defined by the following equation:

$$R_{(s,t)} = \frac{E[(X_t - \mu_t)(X_s - \mu_s)]}{\sigma_t \sigma_s} \tag{7}$$

where *R* is autocorrelation between times *s* and *t*, *E* is the expected value, *X* is a repeatable process, μ is the mean, and σ is the variance.

Autocorrelation can be used to assess periodicity in time series data. Positive values of *R* indicate positive correlation in the time series; values near or equal to zero indicate no correlation and values less than zero indicate that values of the time series become less and less related with the passing of time. If values of *r* were consistently close to zero, then there was no periodicity to the data, and they were assumed to be random. Higher or lower values of *r* suggest some trend in the data.

Cross-correlation analyses were performed for the three depths of soil moisture measurements and rainfall at each site; cross correlations were also performed for the relationship between the wells and rainfall at Lunate Creek. Cross-correlation evaluates similarities in the periodicity of two different time series, X_τ and Y_τ. When values were significantly positive or negative then we identify the time lag at which the two series were most highly related. This offers insight into the time lag between the responses of the soil to moisture inputs at one depth compared to the other depths. The cross-correlation was given by the equation:

$$\rho_{xy}(\tau) = \frac{\gamma_{xy}\tau}{\sigma_x \sigma_y} \tag{8}$$

where σ_X and σ_Y were the standard deviations of processes X_τ and Y_τ.

The period of analysis for the autocorrelations of soil moisture response between depths and cross-correlations of soil moisture and rainfall was from 1 November 2011 to 31 August 2012 with lag interval as one day up to twenty. The cross-correlations of rainfall and shallow groundwater were analyzed from 24 May 2012 to 7 August 2012 with lag interval as one day up to twenty days ($p < 0.05$).

4.2.3 Pressure Transducers and Wells

Three wells were constructed from 1-m long PVC piping with a 3.8 cm diameter opening. The wells were screened to 50 cm in 2 cm increments; caps were fitted to the wells to prevent precipitation from augmenting the water in the wells. The wells were dug to a depth of 70 cm; the water table was encountered at this depth, and further digging was prohibited due to large rocks and cobbles. The wells were sand packed to limit sediment infiltration and topped with native soil to mimic natural conditions.

The wells were fitted with Onset® HOBO pressure transducers that were launched in the wells to measure water temperature and absolute pressure. Absolute pressure was converted to water depth utilizing a barometric pressure correction in the HOBOware software provided by Onset; this correction used hourly barometric pressure data obtained from the Prince George Airport weather station. This method was used due to the lack of a barometer at Lower Lunate Creek.

4.2.4 Snow and Water Isotope Analysis

Snow, spring water, and well water samples were collected and stored in sealed containers. Snow samples were collected by the Federal sampler and placed in plastic bags, sealed while removing as much air as possible, and allowed to melt at room temperature in a lidded five gallon bucket. Spring water was collected in 10 ml plastic vials rinsed with deionized water and dipped three times before filling. Well water was extracted via hand pump; water was pumped until well water was clear, allowed to recharge, and then extracted to a 100 ml flask. This water was decanted into plastic vials rinsed with deionized water.

Isotope analysis was conducted at the University of Calgary Stable Isotopes Lab. Water samples were measured using a Los Gatos Research (LGR) "DLT-100" instrument; isotope values were determined via CO_2 equilibration method. Accuracy and precision of δ^2H determinations were generally better than ±1.0‰ (one standard deviation based on n = 50 lab standard); accuracy and precision of $\delta^{18}O$ determinations were generally better than ±0.2‰ (one standard deviation based on n = 50 lab standard). Values were reported in the "per mil" (‰) standard and compared to the Vienna Mean Standard Ocean Water (VMSOW), which was the isotopic standard of fresh water.

4.2.5 Wells and Isotopes

The initial measurements for the wells on 24 May 2012, the day of transducer deployment, are presented in Table 4-3; measurements were made from the top of the well casing.

Table 4-3 Well water measurements on 24 May 2012

Well	Depth to Water	Depth to Bottom of Well	Depth of Water
Upper	1.55 m	1.79 m	0.24 m
Middle	1.31 m	1.71 m	0.40 m
Lower	1.38 m	1.79 m	0.41 m

Results of the stable isotope analysis were plotted against the global mean of stable isotopes to determine where the groundwater, surface water, snow and rainfall compared to this standard. Values were also compared to a longer-term investigation of rain samples in

Vancouver, BC; it was expected that samples from the two sites investigated and the samples from Vancouver would see similar isotope ratios.

A series of equations was used to estimate the amount of water snowmelt contributes to the shallow groundwater of Lunate Creek following Maulé et al (1994); as this study was done in a prairie environment, certain adjustments were made in their methodology to make it applicable to the Lunate Creek site. An assumption was made that the shallow groundwater at Lunate Creek would be similar to the soil water referenced in Maulé et al (1994); their soil water was located from 0-0.9 m below the surface, which corresponds to the depth of the wells and the water contained in them.

Relationships were identified between precipitation waters using the equation:

$$\delta D = m\ (\delta^{18}O) + b \tag{9}$$

that was a variation of the slope-intercept equation; precipitation includes both summer rains and winter snow. The average D and $\delta^{18}O$ concentrations of seasonal winter (D_w, $^{18}O_w$), seasonal rain (D_r, $^{18}O_r$), and shallow groundwater (D_{sw}, $^{18}O_{sw}$) were calculated and from these the point of intersection of the precipitation waters and evaporated shallow groundwater lines were determined (D_i, O_i). Evaporation of water proceeds from this point along the evaporative D - $\delta^{18}O$ relationship and assumes that the intersection of these lines represents the average annual composition of infiltrating precipitation, which may be represented by seasonal compositions of snow and rain. The proportion of snow water (x_{ws}) in soil water was thus the intercept of the shallow groundwater and precipitation lines, shown in the following equation (using ^{18}O as an example):

$$x_{ws} = \left(\frac{^{18}O_i}{^{18}O_w} - \frac{^{18}O_r}{^{18}O_r}\right) \quad (10)$$

This equation gives us the proportion of water that comes from snow that was then multiplied by 100 to get a percentage.

5 Results

This section was organized to facilitate comparison of soil moisture conditions during the spring melt and into summer months to identify relative changes during these seasons. The data from 1 November 2011 to 31 August 2012 were chosen to encompass winter snow cover, spring melt, and early summer conditions.

5.1 Ancient Forest, Lunate Creek and Prince George Weather

The period from 1 November 2011 to 31 August 2012 overall had cooler than average air temperatures at Prince George: 2.7°C for the annual daily average compared to 4.3°C for the 1981-2010 period at Prince George; daily average temperatures were 0.1°C at the Ancient Forest, 0.9°C at Lower Lunate Creek, and 0.3°C at Upper Lunate Creek. The slightly lower temperatures were expected at the Ancient Forest and Lunate Creek since the sites were 94 m and 273 m higher in elevation than Prince George, respectively. The air temperatures were warmer than normal in the fall and early winter with a cooler spring; average monthly air temperatures at Prince George ranged from -6.0°C in January, the coldest month for this year, to just over 1.2°C in December in the 2011-2012 winter season.

Despite this being a particularly warm winter in the earlier months, February to June were slightly cooler than average at Prince George, with monthly mean air temperatures hovering closer to 7°C for most of the summer compared to the warmer climate norms from Prince George over 1981-2010. For the 2011-2012 period of study, air temperatures at Prince George fluctuated higher than average with maximum and minimum daily average air temperatures ranging between -28.7°C in March to 19.8°C in August.

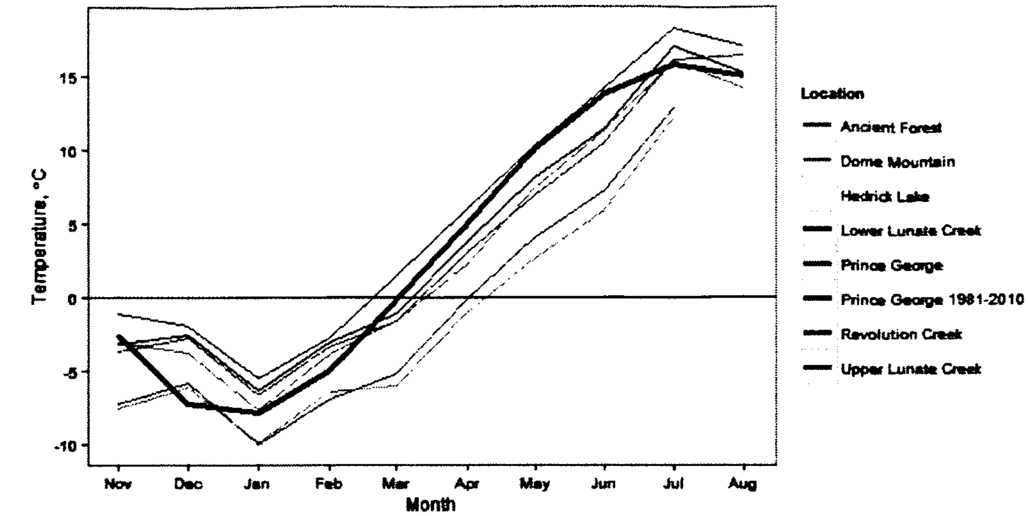

Figure 5.1 Average monthly air temperatures for Dome Mountain, Hedrick Lake, Revolution Creek (November 2011-July 2012 , Ancient Forest, Upper and Lower Lunate Creek, Prince George Airport from November 2011 - August 2012, and Prince George Airport 1981-2010

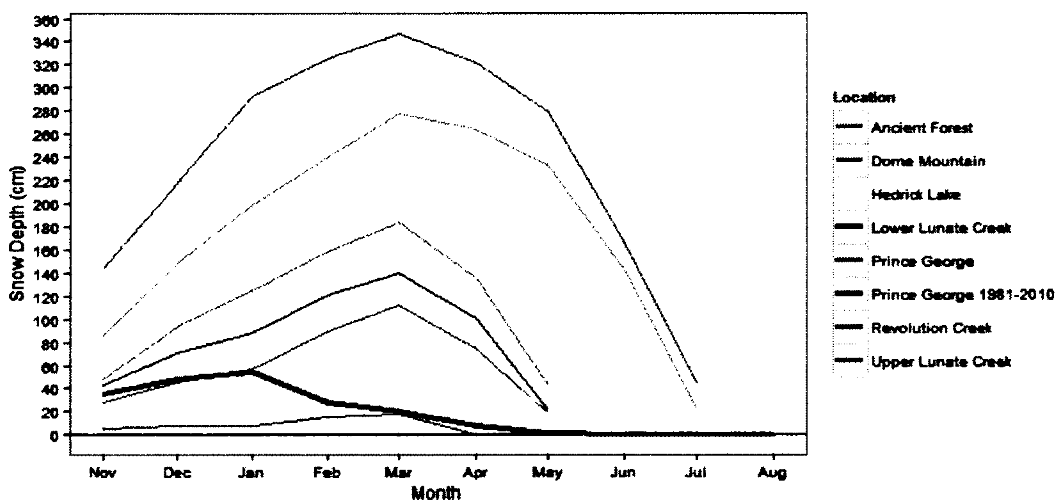

Figure 5.2 Average monthly snow depth for the Ancient Forest, Upper and Lower Lunate Creek, Prince George Airport from 2011-2012, Prince George Airport 1981-2010, Hedrick Lake, Revolution Creek, and Dome Mountain from November 2011-July 2012.

Apart from February, snowfall at Prince George was less than average in every month of the 2011 to 2012 season; RFC sites saw higher than average snowfall for the winter. High snowfall totals may have contributed to lower than average air temperatures in the spring and early summer (see Figure 5.1).

5.2 Ancient Forest and Lunate Creek Data (November 2011 to June 2012)

5.2.1 Air Temperature

Daily average air temperatures from 1 November 2011 to 31 August 2012 reached a maximum of 18.0°C and a minimum of -32.3°C at the Ancient Forest and a maximum of 19.4°C (18.6°C) and a minimum of -29.9°C (-30.5°C) at Upper (Lower) Lunate Creek (Figure 5.3).

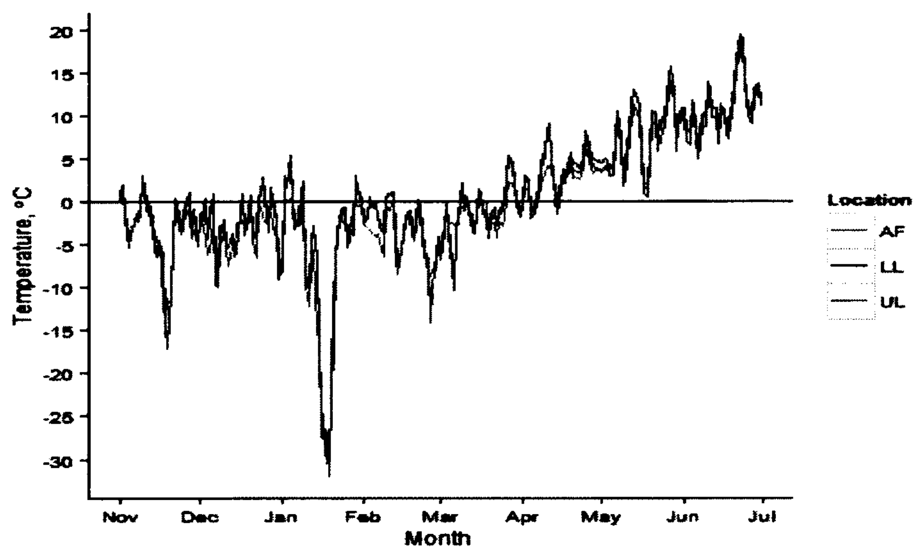

Figure 5.3 Average daily temperatures for the Ancient Forest (AF), Lower Lunate (LL), and Upper Lunate (UL) from 1 November 2011 to 31 July 2012

5.2.2 Soil Temperature

Soil temperature fluctuates throughout the spring and summer when there was no snow cover present (Figure 5.4). From November to mid-January, the soil temperature decreased from 2.5°C to 0.5°C, a difference of only 2°C in a few months; the fact that the soil temperature did not fall below 0.5°C suggests snow cover since soil temperature is decreasing due to decreasing air temperature before this. The sharp increases in soil temperature occur during the spring (late April – May) as the snow pack disappears at the Ancient Forest and Lunate Creek. Once the snow disappears, soil temperature shows a steep rise to higher daily average temperatures, reaching a maximum temperature of over 12°C during the spring and summer months.

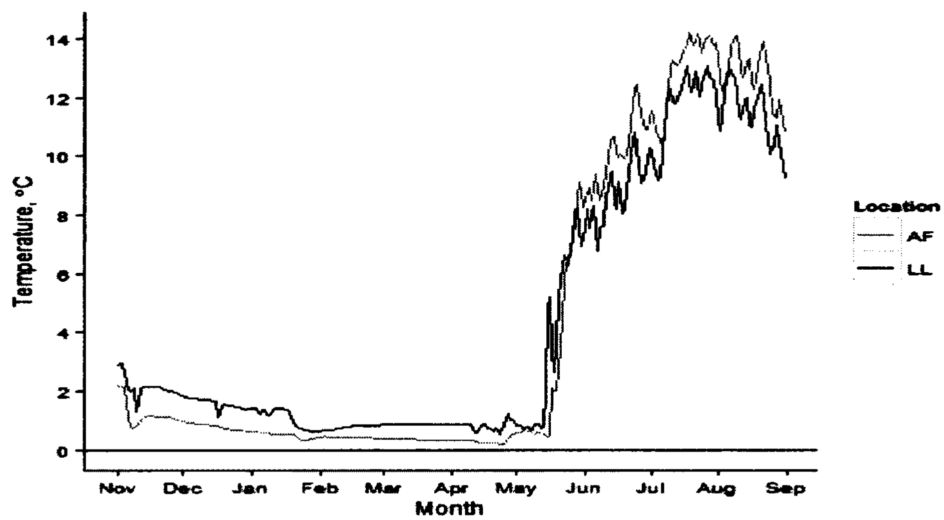

Figure 5.4 Average daily soil temperature at the Ancient Forest (AF) and Lower Lunate (LL) Creek from 1 November 2011 to 31 August 2012.

A steady decrease in soil temperature from late November indicates the area's snow cover was still not sufficiently deep to insulate the soil from fluctuating air temperatures; there were a number of decreases in temperature at Lower Lunate Creek that were not recorded at the Ancient Forest. This indicates that the snow pack was forming more evenly at the flatter Ancient Forest site compared with the steeper Lower Lunate Creek site. By mid-January soil temperatures at both sites remained fairly constant until mid-April; this was due to a sufficiently deep snow pack to insulate the soil from air temperature fluctuations. This was observed in late January when temperatures dropped to below -25°C yet there was no response seen in the soil temperature. Once the snow pack decreased and bare ground was revealed, the soil temperature increased rapidly, increasing from ~1°C in early May to nearly 10°C by the end of June.

5.2.3 Soil Moisture

Soil moisture values were analyzed to determine moisture patterns for the period from November 2011 to August 2012. Since the probes were not specifically calibrated to the soil, the values represent general trends as opposed to absolute values.

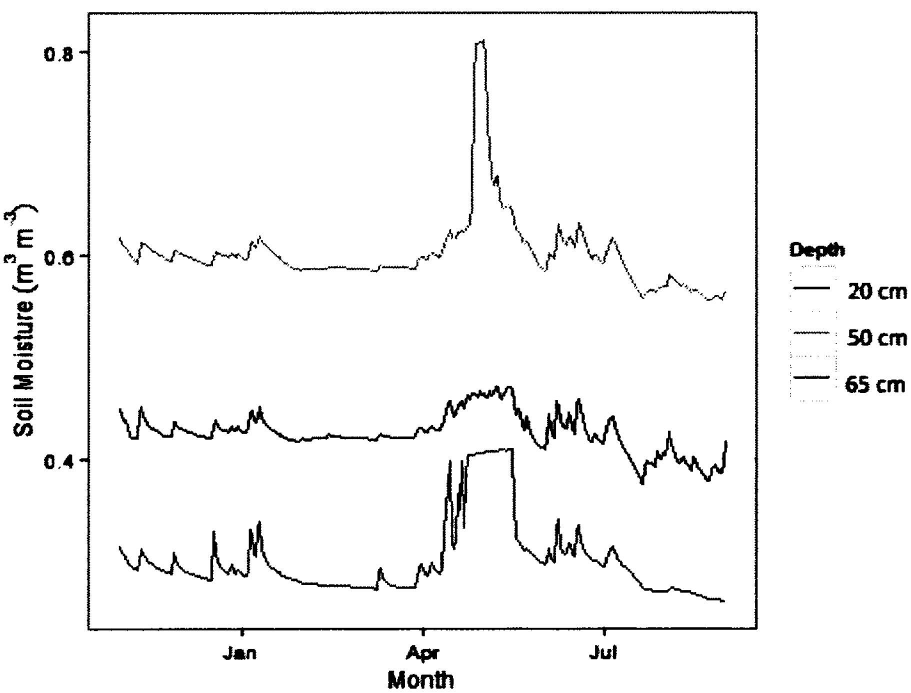

Figure 5.5 Daily mean soil moisture at 20 cm, 50 cm, and 65 cm depth at the Ancient Forest for November 2011- August 2012.

Soil moisture at the Ancient Forest showed minor increases and decreases in soil moisture from November until early January; there appeared to be a pulse in all three layers that indicates the soil was not frozen and was still receiving moisture at this time. Beginning in January, the probes indicated a steady decline in soil moisture; this would indicate that liquid water was unavailable at this time so no moisture was infiltrating the soil. March shows the first indication that soil moisture is starting to change; the 65 cm probe shows spikes in moisture in early March and early April but soil moisture at 20 cm remained lower than deeper layers throughout the study period. Once melt starts to increase, the soil moisture quickly responds, with positive spikes from mid-April to mid-May. The 50 cm and 65 cm probes show larger increases in moisture than the 20 cm layer; this may indicate that the upper layers of soil had better drainage allowing snowmelt to infiltrate to the deeper layers.

The end of snowmelt coincides with soil moisture levels beginning to decrease, starting in mid-May.; once the early summer rains come in June (Figure 5.5), the soil displays increasing and decreasing trends. The rainy season appears to end the beginning of July, when the soil moisture values decrease and stay low until August.

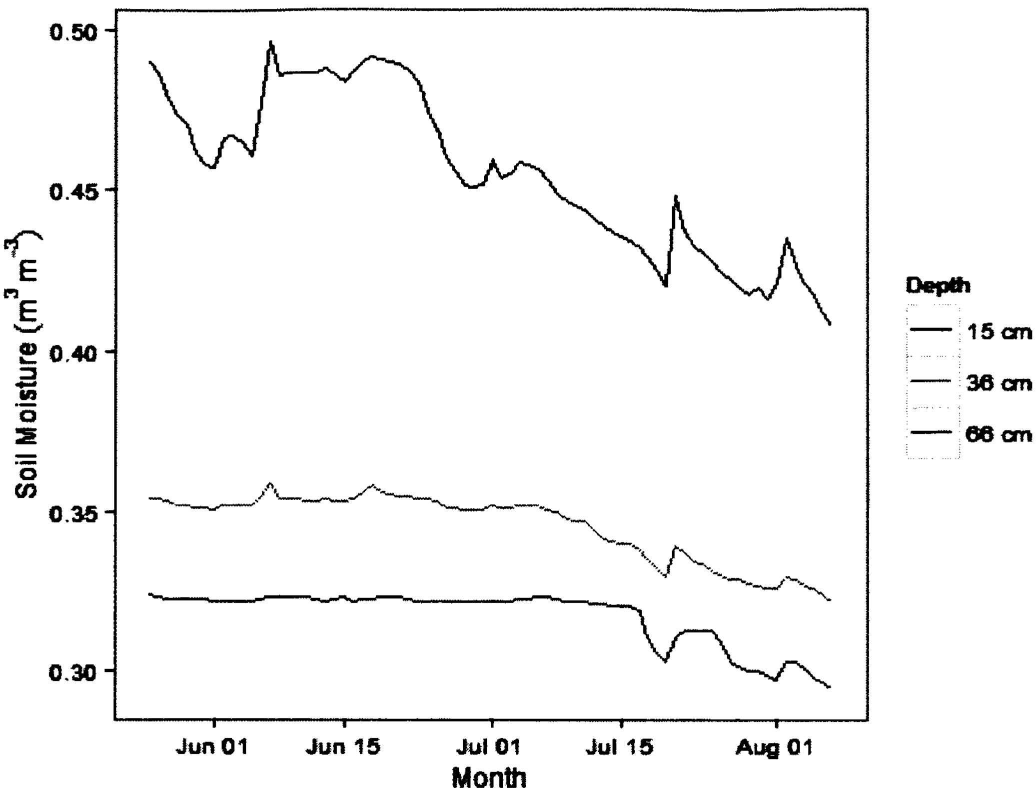

Figure 5.6 Daily mean soil moisture at 15 cm, 36 cm, and 66 cm at Lower Lunate Creek for June 2012 –August 2012.

The soil moisture data during the winter/spring seasons from Lunate Creek (Figure 5.6) show the differences in topography between here and the Ancient Forest. The probes at 36 cm and 66 cm stay fairly constant from November until April; the upper soil probe (15 cm) was the only one that shows any fluctuation. The 15 cm probe indicated slight increases and decreases in moisture from November until mid-January, indicating there was available moisture to wet that layer, but not enough to reach the deeper layers of soil. The upper probe showed the largest depletion of moisture between mid-January and April yet experienced a sharp increase once snowmelt commences in early April. It was worth noting that the upper probe was the only one that observed greatly increased moisture values during snowmelt; the lower probes recorded very little increase at that time indicating limited infiltration. The steep slope at this site may have the biggest influence on the moisture infiltration; although snowmelt infiltrates into the upper layers, the slope allows for lateral flow and prevents the moisture from percolating any further into the soil profile.

Once snowmelt terminates around late May, soil moisture values remain elevated throughout June, similar to the Ancient Forest, before decreasing steadily from July into August. At this time, the upper layer appears to dry more than the lower layers; the large amount of vegetation at this site would contribute to this drying through evapotranspiration. The upper layer does experience spikes in moisture during late July, but the moisture values still remain lower than during spring.

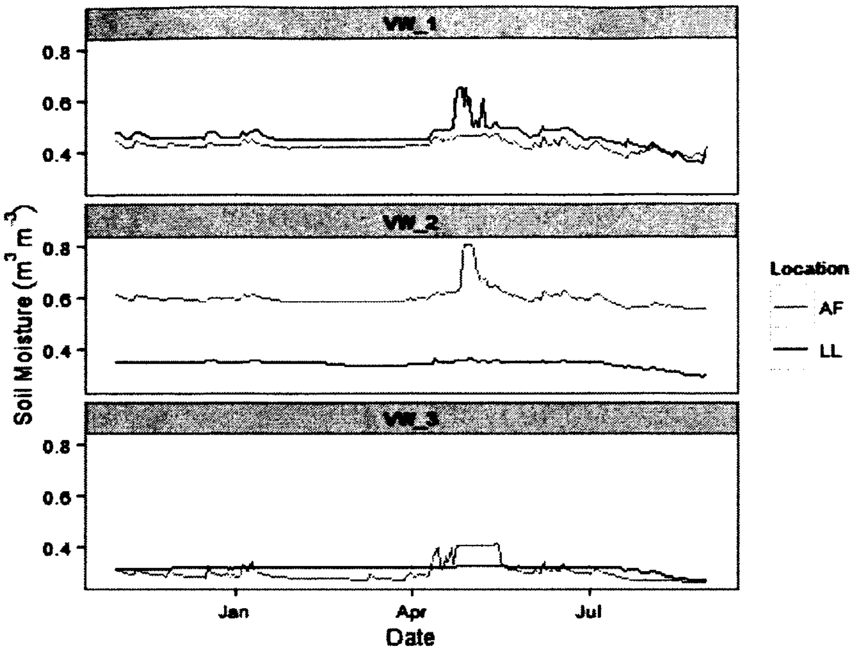

Figure 5.7 Comparison of the daily mean soil moisture between the Ancient Forest (AF) and Lunate Creek (LL) sites from 1 November 2011 – 31 August 2012. VW_1 was 20 cm at AF and 15 cm at LL; VW_2 was 50 cm at AF and 36 cm at LL; VW_3 was 65 cm at AF and 66 cm at LL.

Figure 5.7 gives a direct comparison of the soil moisture deviations for both sites at similar depths. For the shallow probes, Lower Lunate Creek shows the greatest increase in soil moisture during snowmelt, but saw nearly the same pattern in other seasons; Lower Lunate Creek does see more drying in the summer than the Ancient Forest, most likely owing to the difference in slope and density of vegetation between the two sites. At the middle probes, the Ancient Forest site saw the largest increase in soil moisture during snowmelt indicating the soil at the Ancient Forest allows for more infiltration and better drainage than Lunate Creek; soils at the middle depth remained constant at Lower Lunate Creek compared to the Ancient Forest. At the lowest probe, the Ancient Forest site again saw more variation in moisture than

Lunate Creek; the comparison shows that Lower Lunate Creek has a more consistent value, often having less variation than a similar depth at the Ancient Forest. The Ancient Forest did observe a larger increase in soil moisture than the Lower Lunate Creek site during snowmelt, which was consistent with the upper layer.

5.3 Autocorrelation and Cross-Correlation of Soil Moisture

For the study period of 1 November 2011 to 31 August 2012, there was significant correlation (at the 95% significance level) found between daily average soil temperature and air temperature ($r = 0.83$) and between soil moisture at all depths (Table 5-1). Significant negative correlations exist between snow depth and 65 cm soil moisture ($r = -0.40$) and soil temperature and 20 cm and 40 cm soil moisture ($r = -0.58$ and $r = -0.34$).

Table 5-1 Pearson correlation coefficients (upper diagonal) and p-values (lower diagonal) of daily average conditions for the Ancient Forest for the period 1 November 2011 to 31 August 2012; "ns" value indicates the result was not significant.

	Snow	Temp	Rain	Soil Temp	20 cm	40 cm	65 cm
Snow	-	-0.12	0.00	-0.09	-0.29	-0.28	-0.40
Temp	< 0.01	-	0.23	0.83	-0.30	-0.09	0.05
Rain	ns	< 0.01	-	0.33	0.01	-0.05	-0.01
Soil Temp	ns	< 0.01	< 0.01	-	-0.58	-0.34	-0.27
20 cm	< 0.01	< 0.01	ns	< 0.01	-	0.76	0.83
40 cm	< 0.01	ns	ns	< 0.01	< 0.01	-	0.82
65 cm	< 0.01	ns	ns	< 0.01	< 0.01	< 0.01	-

For the study period of 1 November 2011 to 31 August 2012 at Lower Lunate Creek, there was significant correlation (at the 95% significance level) found between daily average soil temperature and air temperature ($r = 0.81$) and between soil moisture at all depths (Table 5-2). Significant negative correlations exist between snow depth and 36 cm soil moisture ($r = -0.42$), air temperature and 36 cm and 66 cm soil moisture ($r = -0.41$ and $r = -0.33$) and soil temperature and soil moisture at all depths.

Table 5-2 Pearson correlation coefficients (upper diagonal) and p-values (lower diagonal) of daily average conditions for Lower Lunate Creek for the period 1 November 2011 to 31 August 2012; "ns" value indicates the result was not significant .

	Snow	Temp	Soil Temp	15 cm	36 cm	66 cm
Snow	-	-0.07	-0.04	-0.41	-0.42	-0.15
Temp	ns	-	0.81	-0.18	-0.41	-0.33
Soil Temp	ns	<0.01	-	-0.43	-0.55	-0.51
15 cm	<0.01	<0.01	<0.01	-	0.77	0.69
36 cm	<0.01	<0.01	<0.01	<0.01	-	0.90
66 cm	0.01	<0.01	<0.01	<0.01	<0.01	-

Figure 5.8 was generated using the autocorrelation function in R. The autocorrelation plots of soil water content at the Ancient Forest (Figure 5.8) show slightly different lag times at each depth, although all depths show a decreasing trend of autocorrelation as lag time increases; all depths had statistically significant autocorrelations although depths 30 cm and 65 cm were stronger and more consistent than the autocorrelations at 15 cm.

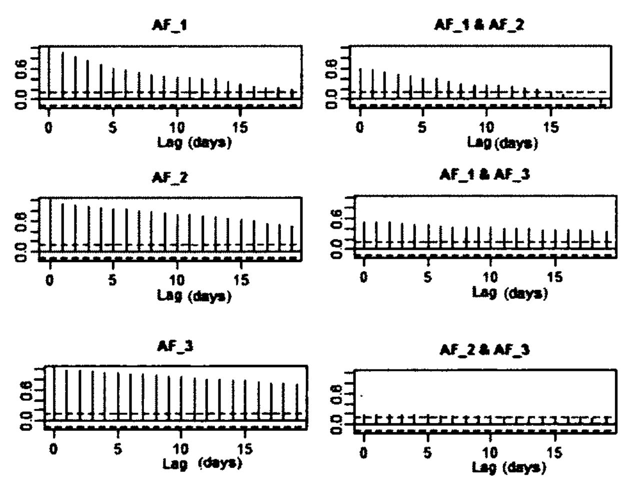

Figure 5.8 Autocorrelation functions of average daily soil moisture at the Ancient Forest 1 November 2011 to 31 August 2012; AF_1 = 15 cm, AF_2 = 30 cm, and AF_3 = 65 cm. Lag time was measured in days with the second value lagging the first; blue dashed lines indicate 95% confidence levels.

Looking at the relationships between the three layers, there was a statistically significant positive relationship between 15 cm and 65 cm; the relationship was also positive between 15 cm and 30 cm, but it was less robust and decreased more rapidly as lag increased. There was a very weak relationship between the probes at 30 cm and 60 cm.

The autocorrelation plots of soil water content at Lower Lunate Creek (Figure 5.9) show similar patterns to those seen at the Ancient Forest, although all depths show a decreasing trend of autocorrelation as lag time increases. All depths had statistically significant autocorrelations although depths 36 cm and 66 cm were stronger and more consistent than the autocorrelations at 15 cm.

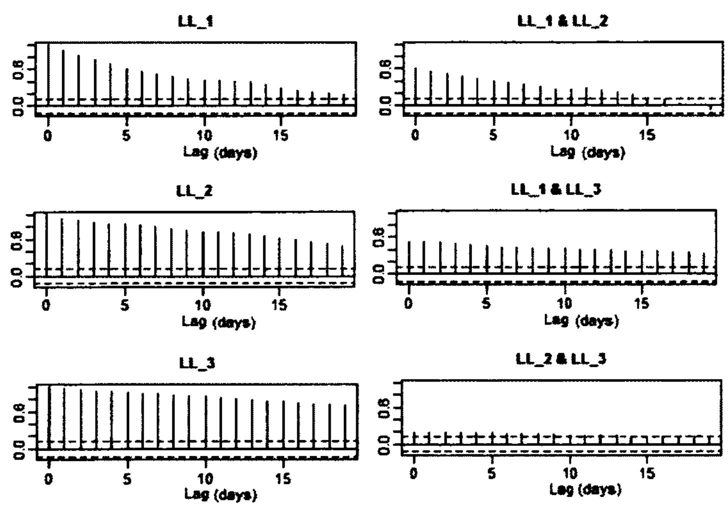

Figure 5.9 Autocorrelation functions of average daily soil moisture at Lower Lunate Creek 1 November 2011 to 31 August 2012; LL_1 = 15 cm, LL_2 = 36 cm, and LL_3 = 66 cm. Lag time was measured in days and the second value lags the first; blue dashed lines indicate 95% confidence levels.

The autocorrelation between depths at Lower Lunate Creek (Figure 5.9) also exhibited similar trends to those at the Ancient Forest. There was strong autocorrelation from days 1-5 between 36 cm and 15 cm and remained statistically significant, although weaker, as lag time increased. The same relationship was observed between 15 cm and 66 cm, which also stayed statistically significant over the lag period. A relatively poor correlation existed between 36 cm and 66 cm with significance observed below the 95% confidence level after seven days.

Cross-correlation functions were also computed in R for the relationship between soil moisture and rain. At the Ancient Forest (Figure 5.10), all three depths showed positive correlations with rain, especially at lag day 2 and 3. There was an apparent cycle of two days decrease followed by two days increase in correlation. All depths showed a negative lag, but none of the correlations were significant. Lag day 2 had nearly the same *r* showing this day was most highly correlated with rain at all depths.

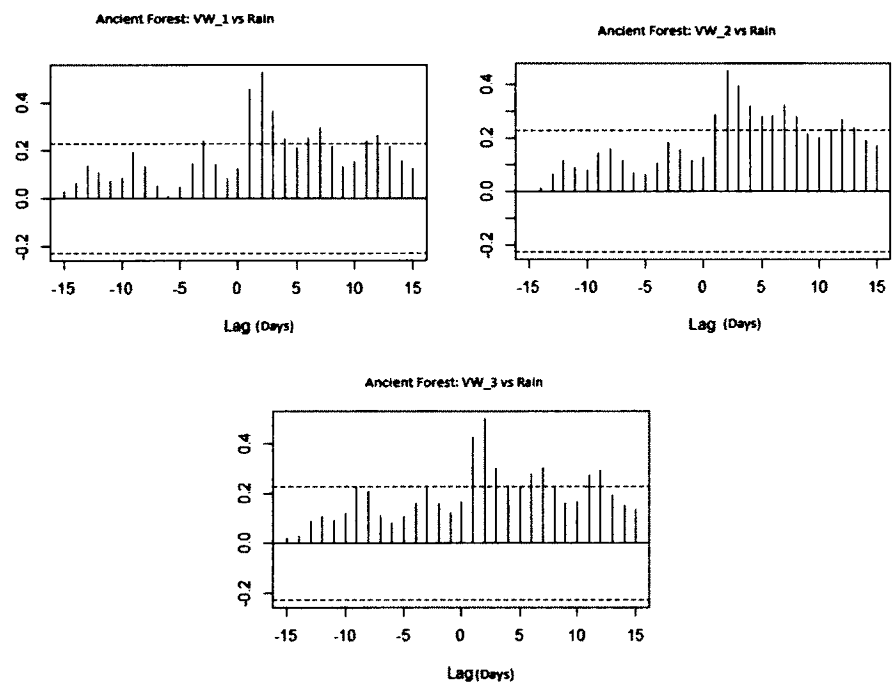

Figure 5.10 Cross-correlation functions between average daily soil moisture (15 cm, 30 cm, and 60 cm) and rainfall at the Ancient Forest from 1 November 2011 to 31 August 2012. Lag time was measured in days; blue dashed lines indicate 95% confidence levels.

Cross-correlations between soil moisture and rainfall at Lunate Creek were shown in Figure 5.11. Probes at depths 15 cm and 66 cm showed a similar pattern with lag day 2 having the highest correlation; the statistically significant correlation persisted until lag day 9. The probe at depth 66 cm did not show any significant correlation to rain; the periodicity at this level appears to be five days, but decreasing in amplitude every period.

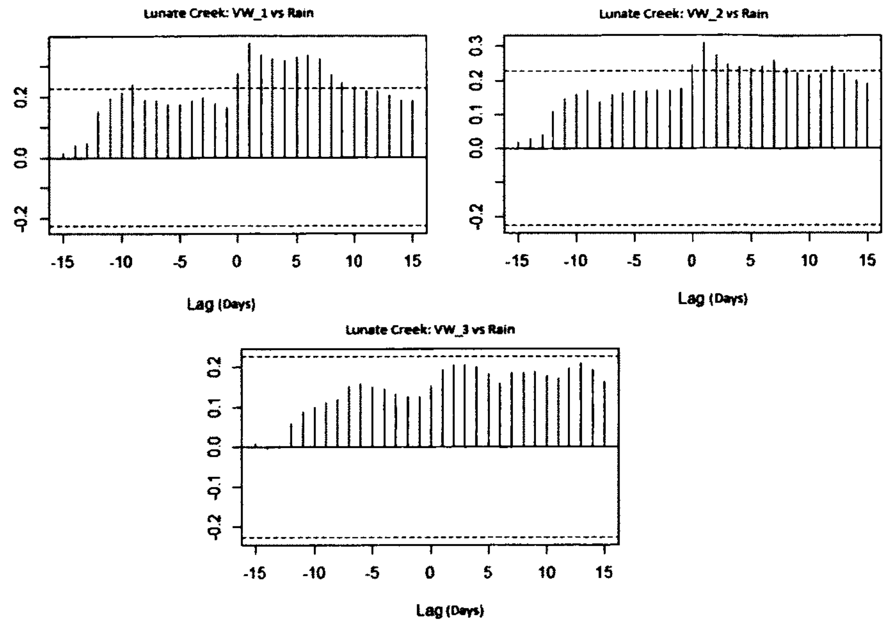

Figure 5.11 Cross-correlation function between average daily soil moisture (15 cm, 36 cm, and 66 cm) and rainfall at Lower Lunate Creek 1 November 2011 to 31 August 2012. Lag time was measured in days; blue dashed lines indicate 95% confidence levels.

5.4 Snow depth, Snow Density and SWE

The snow depth data collected from the Ancient Forest and Upper and Lower Lunate Creek were point measurements, so snow depth data were supplemented with data from snow surveys (Table 5-3). The snow surveys detected the spatial variability of the sites and allowed for a better estimate of the snow pack characteristics at the Ancient Forest and Lunate Creek.

Since the SR50 was located in a cleared area, the snow surveys accounted for the downed vegetation and variability in topography.

Table 5-3 Average depth (cm), coefficient of variation, average density (g cm^{-3}), and average SWE (mm) from snow surveys at the Ancient Forest (AF), Upper Lunate (UL), and Lower Lunate (LL).

	13 Mar 12 AF	14 Apr 12 AF	24 Apr 12 UL	24 Apr 12 LL	10 May 12 UL	10 May 12 LL	17 May 12 UL
Average Snow Depth (cm)	130.0	109.0	113.4	80.7	40.8	4.2	4.9
Coefficient of Variation	NA	0.1	0.1	0.1	0.3	0.4	0.6
Average Density (g cm^{-3})	0.3	NA	0.4	0.4	0.2	0.2	0.2
Average SWE (mm)	310	NA	452	323	82	4	5

Data collected from a snow course survey performed at the Ancient Forest on 13 March 2012 show a SWE of 310 mm of water and an average snow depth of 130 cm near the meteorological tower. This corresponds to a snow density of 0.3 g cm^{-3}, approximately 30% the density of water. The snow depth measured at the Ancient Forest tower for the same day was 189 cm, such that the discrepancy between the sensor and the surrounding conditions was apparent. The maximum snow depth recorded at the Ancient Forest was 192 cm, which occurred on 12 March 2012; this indicates that the survey was conducted at approximately peak accumulation for the site. Another survey was performed at the Ancient Forest on 14 April 2012 with depth measurements but no SWE measurements, which resulted in an average depth of 109 cm; the weather tower recorded an average depth of 135 cm on this date.

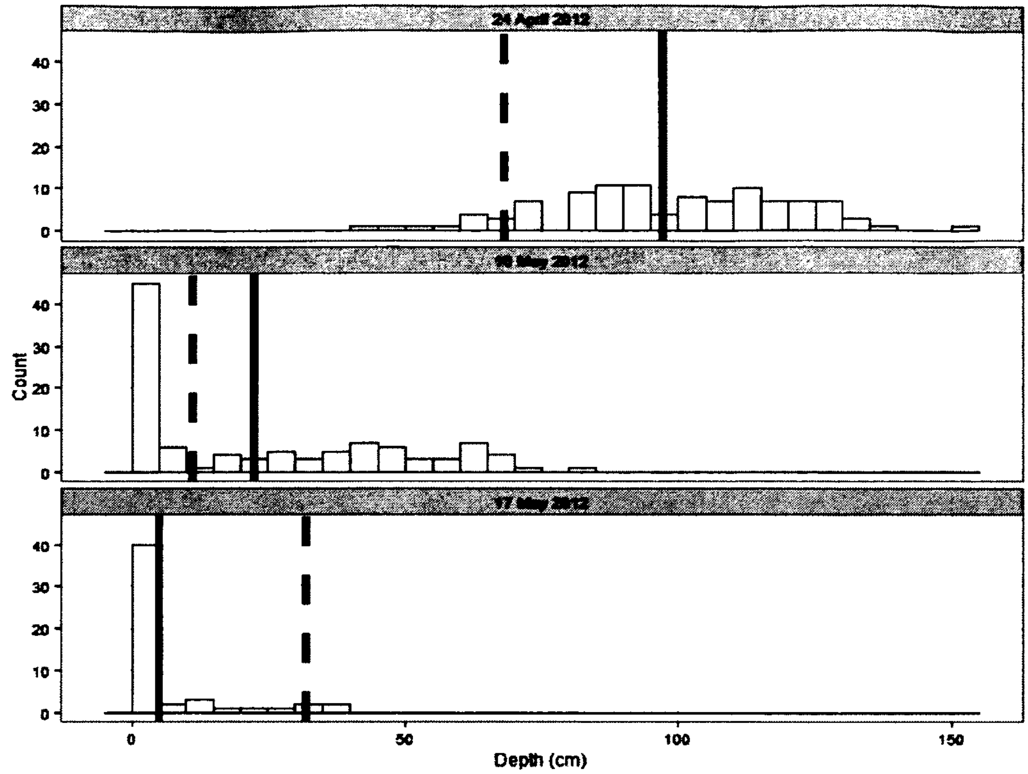

Figure 5.12 Histogram of snow surveys at Lunate Creek. The vertical dashed lines represent the average depth from the acoustic sounder; the vertical solid line represents the average depth from the survey. Bin width was 5 cm.

Data were collected from snow course surveys done at Upper and Lower Lunate Creek on 24 April, 10 May, and 17 May 2012; results for each of the dates are found in Figure 5.12. The survey from 24 April shows a SWE of 452 mm of water at Upper Lunate and 323 mm at Lower Lunate; average snow depth of 113 cm and 84 cm at Upper and Lower Lunate Creek, respectively, was recorded on that date. Snow density at each site was equivalent at 0.4 g cm^{-3}, approximately 40% the density of water.

On the 10 May survey, the snow had depleted significantly with depths of 41 cm at Upper Lunate Creek and only an average of 4 cm at Lower Lunate Creek; these depths were averages of the whole survey, which skew the data as there were areas of deeper snow still present. The survey indicated SWE values of 81 mm and 4 mm of water at the Upper and Lower Lunate Creek sites, respectively; density was 0.2 g cm^{-3} at the Upper site and 0.2 g cm^{-3} the Lower site. The 17 May survey saw very little snow remaining at the site, with only the Upper site having measurable depths. The average depth was only 4.9 cm and the density was less than 0.2 g cm^{-3}, resulting in a SWE value of < 5 mm. The low densities at the end of the season are abnormal as density increases at the end of the season. There may have been measurement errors due to the shallow depth of the snow pack and loss of water through the slats in the sampler.

5.5 Shallow groundwater levels and cross-correlation with rainfall

Figures 5.13-5.14 show depths (m) of water and temperature (°C) in the wells. The upper well had a maximum depth of -1.14 m of water on 5 May 2012; the minimum was -1.24 m recorded on 17 July 2012. The middle well had a maximum depth of - 0.86 m on 24 May 2012 and a minimum depth of -1.03 m on 17 July 2012. The lower well had a maximum depth of -0.94 m on 25 May 2012 and a minimum depth of -1.09 m on 17 July 2012.

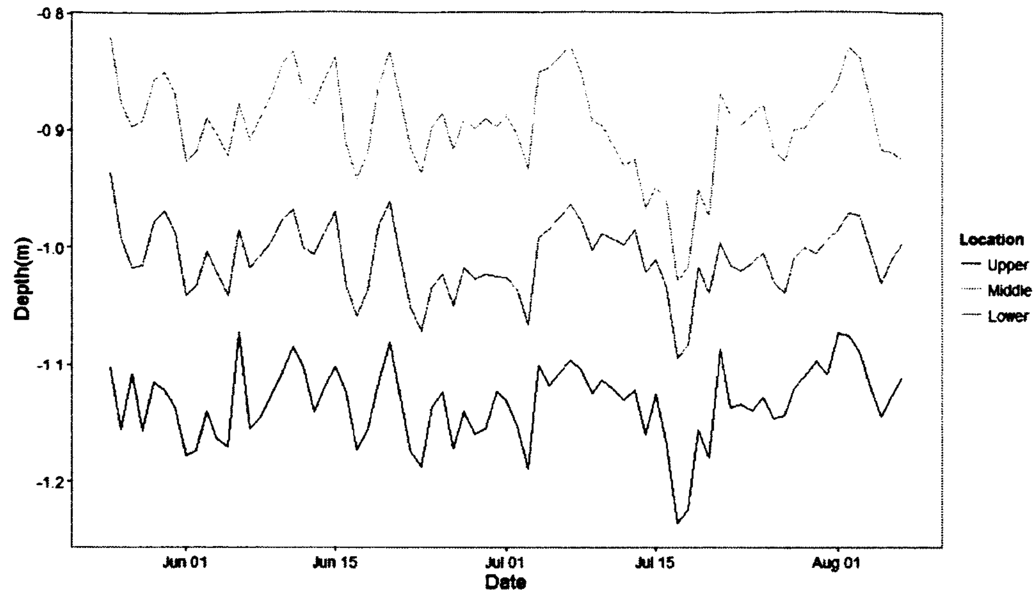

Figure 5.13 Average daily water depth (m) for the upper, middle, and lower well sites from 24 May 2012 to 7 August 2012.

Temperatures in the wells were more closely related at the three well sites, with average temperatures for the upper, middle, and lower wells recorded at 9.9°C, 9.7°C, and 9.6°C, respectively. The maximum recorded average daily temperature for the upper well was 13.3°C, which was the highest average daily temperature for the three wells; the minimum average daily temperature was 6.2°C. The middle well had a maximum average daily temperature of 12.8°C and a minimum average daily temperature of 5.5°C. The lower well had the lowest maximum average daily temperature at 12.7°C and a minimum average daily temperature of 5.7°C.

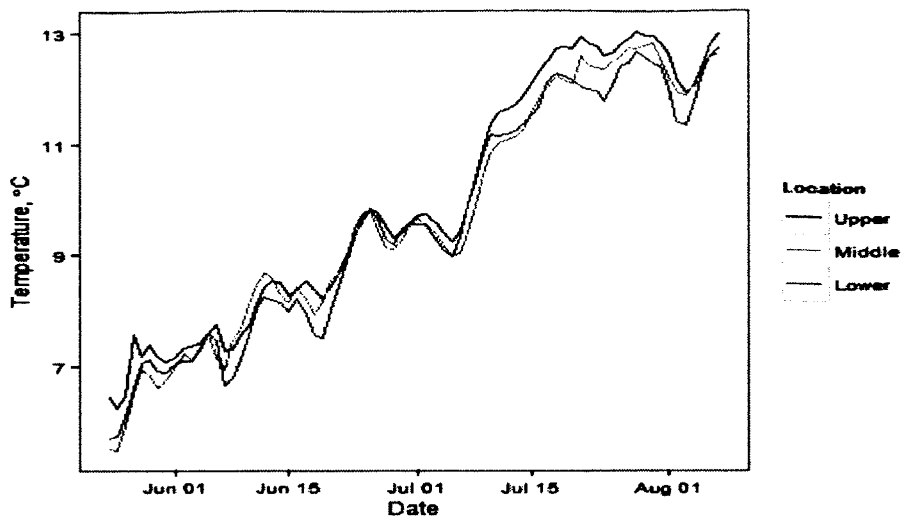

Figure 5.14 Average daily water temperature (°C) for the upper, middle, and lower wells 24 May 2012 to 7 August 2012.

The depth of water in the wells was compared to the rainfall events at Lunate Creek to identify well response to rainfall. Figure 5.15 shows the result of the cross-correlation functions for the upper, middle, and lower wells and rainfall.

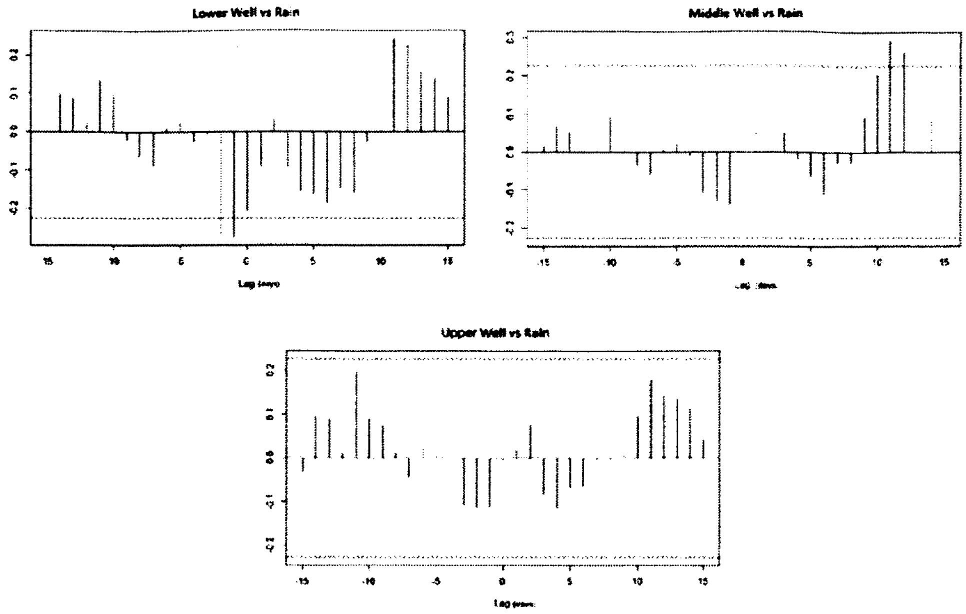

Figure 5.15 Cross-correlations of depth of water in wells and rainfall events from 24 May 2012 to 7 August 2012. Lag time was in days; blue dashed lines indicate 95% confidence levels.

The change in water depth in the wells showed a clear pattern of correlation. The lower and middle well had statistically significant relationships at lags of 11 and 12 days after the event; although it was identified as significant, the *r* value was less than 0.3 indicating only a weak correlation. The upper well also had a statistically significant relationship at one and two days before the event. The wells did seem to individually follow a pattern of positive and negative lags; for the middle well, there appeared to be a four to five day lag pattern, while the lower well had a pattern of five days. Only the upper and middle wells showed a positive response immediately after the event, while the lower well would start showing a positive response at 10 days.

5.6 *Stable Isotopes*

Measured isotope values of precipitation waters for the 2011-12 collection period ranged from a low of -22.5‰ for $\delta^{18}O$ (-173‰ for δD) during the 10 May 2012 survey at Upper Lunate Creek to a high of -8.9‰ for $\delta^{18}O$ (-92‰ for δD), which represents the summer rainfall. The precipitation water line for the 2011-12 data can be described as $\delta D = 6.16\ \delta^{18}O - 31.4$ where $n = 47$ and $r = 0.98$; the groundwater line for Lunate Creek is expressed as $\delta D = 4.07\ \delta^{18}O - 64.4$. The intersection point for the two lines is -15.7‰ $\delta^{18}O$ and -128.7‰ δD.

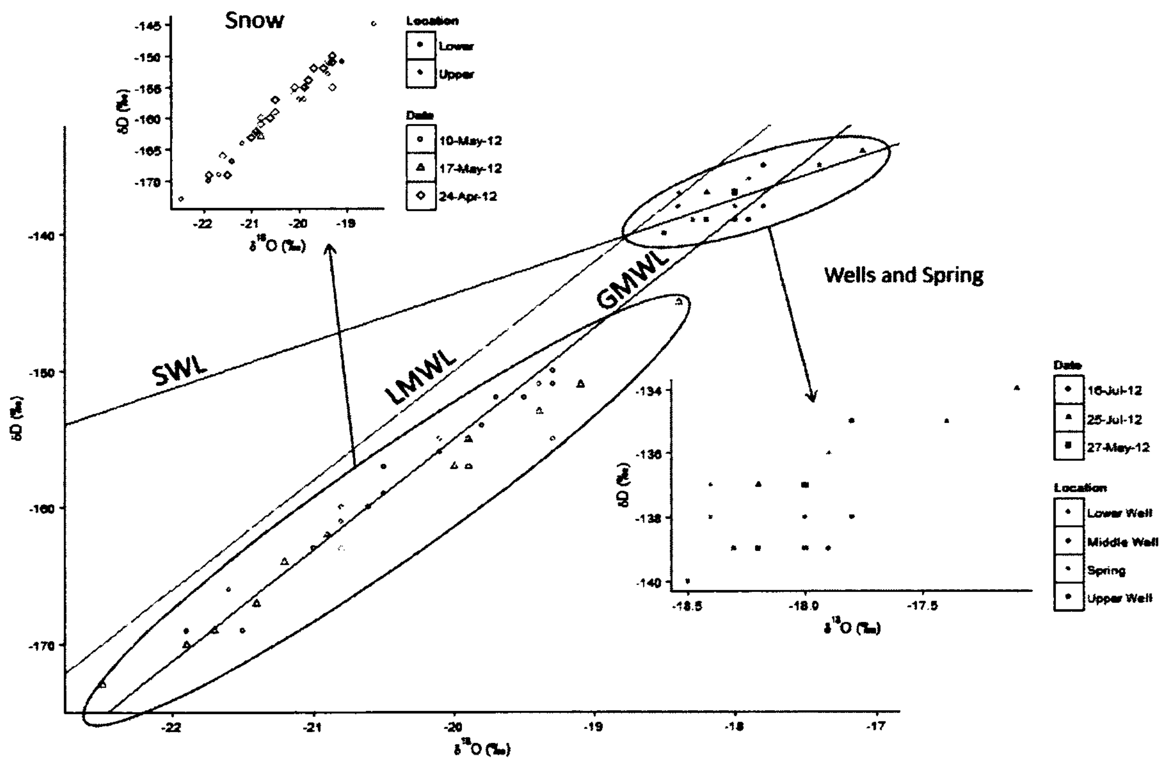

Figure 5.16 Water isotope values for snow sampling dates (24 Apr, 10 May, 17 May), spring and well samples (early, middle, late) from Lunate Creek. Results were reported in δ ‰ (delta per-mil) values compared to the Vienna Standard Mean Ocean Water (VSMOW); Global Meteoric Water Line (GMWL) in red; Local Meteoric Water Line (LMWL) in black; Soil Water Line (SWL) in blue.

A series of equations were used, based on Maulé et al (1994), to estimate the amount of water snowmelt contributes to the shallow groundwater of Lunate Creek (see pages 48-49) ; the results from the equations were presented in Table 5-4. Based on these equations, an estimated 40% of water in the shallow groundwater wells comes from snowmelt waters. Due to lack of long-term weighted means for this site, these results have inherent bias and should not be deemed absolute.

Table 5-4 Values derived from the equations in Maulé et al (1994); values reported in per-mil (‰) compared to the VSMOW

Isotope	Average Summer (r)	Average Winter (w)	Average Shallow Groundwater (sw)	Intercept (i)	Proportion of snow water(x_{was})
D	-92.3	-158.9	-137.0	-119.8	0.4
^{18}O	-9.0	-20.4	-17.8	-13.6	0.4

6 Discussion

6.1 Temperature and Snowfall Relationship between Prince George and the ITR sites

Although the total snowfall in Prince George was less than snowfall at either the Ancient Forest or Lunate Creek, the pattern of accumulation and depletion was similar; an approximation of snowfall events in the Ancient Forest and Lunate Creek can be made by observing snowfall events in Prince George. Figure 6.1 shows the daily means for snow depth, rain, and air temperature; a similar trend and value were shown for each of the sites.

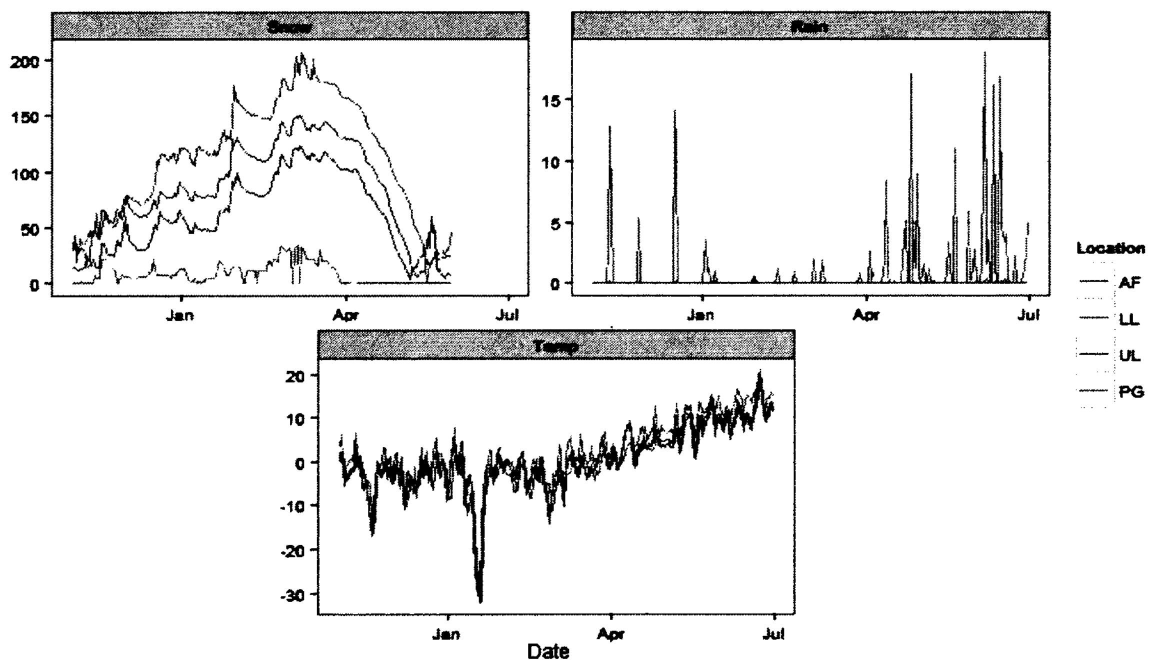

Figure 6.1 Daily means for snow (cm), rain (mm), and temperature (°C). AF - Ancient Forest, LL - Lower Lunate, UL - Upper Lunate, PG - Prince George, November 2011 – July 2012.

While the rain gauge at the Ancient Forest showed rainfall in winter (January through March), these recordings were most likely due to melting snow or accidental bucket tips during routine weather station inspection that were not recorded. That being said, the temperature in early January was well above freezing and rain showers could be the reason for the rainfall recordings.

Snow depth in the ITR sites have a deeper, overall snow pack than Prince George owing in part to the difference in elevation (680 m for Prince George, 774 m for the Ancient Forest, and 950 -1000 m for Lower and Upper Lunate Creek), their topographic variation, and the lack of urban heat island effects. Air temperature was very closely related between sites with very few positive or negative temperature spikes between each location.

6.2 Persistence of Soil Moisture at the Ancient Forest and Lunate Creek

In this study autocorrelation was used to determine persistence of anomalously high or low soil moisture values. Significant autocorrelation in the soil moisture series beyond 3-4 days indicates persistence of anomalously high (low) soil moisture conditions at this site.

There was significant autocorrelation of soil moisture at the Ancient Forest site detected in the autocorrelation analysis of the daily average soil moisture data for up to 14 days at all depths; the significance drops considerably for the upper probe as time moves further away from day 0, but the lower probes show a significantly higher autocorrelation past 15 days. The lack of significant autocorrelation for the time period for the upper probe indicates that it was more susceptible to influence from the atmosphere than the deeper probes.

The melting of the snow pack, which takes place from mid-April to mid-May 2012, causes a significant increase in soil moisture values at both sites, especially in the upper soil layer.

After this date, soil moisture values remain well above average and slowly decline until approximately 1 July 2012. The snow cover at the Ancient Forest had melted by 20 May 2012 so we see that there was some persistence of the snowmelt signal in the soils at this site. Sampling at more depths would allow us to assess whether or not the moisture propagates through the soil column or whether it dissipates at shallow depths. The snow pack delivers a continual supply of water to the soil during the melt period and hence it was this supply that accounts for the persistence observed in the spring melt season, although differences between sites at different depths would most likely be a function of soil properties.

There have been limited studies on soil moisture persistence in mountainous terrain but those that exist highlight the significance of terrain features on spatial variability of soil moisture. One notable study by Williams et al (2009), working out of the Dry Creek Experimental Watershed near Boise, Idaho, attempted to characterize the temporal and spatial variability in a semi-arid mountainous area. The authors show that the amount of snow present on the surface in the spring as well as terrain and soil properties were significantly related to soil moisture in the catchment with wet (dry) areas staying wetter (drier) than average throughout the year.

The work of Williams et al (2009) agrees with a previous effort by Litaor et al (2008) in the high-elevation alpine tundra region of Niwot Ridge, Colorado. Litaor et al (2008) found that soil moisture was significantly correlated ($r^2 = 0.7$ at the 99% significance level) with snow accumulation and terrain factors. The Niwot Ridge study was focused more on the controls of species diversity of herbaceous plants as opposed to soil moisture persistence in particular;

however, soil moisture was a limiting factor of plant growth and hence very important to plant diversity, especially in a changing climate where ecotones were expected to change.

The ICH zone has a high demand for water; the moisture received from higher elevations sustains the water need of the trees in the ICH zone through the spring as there was continual supply of soil moisture from snow and ice melt. Steeper topographic gradients contribute to easy movement of meltwater through the soil and over the surface via gravity, as was indicated by the moisture profile at Lunate Creek.

6.3 Factors Affecting Soil Moisture at the Ancient Forest and Lunate Creek Sites

Slope might affect movement of meltwater into low lying areas so that higher soil moisture values do not necessarily coincide with areas of greater SWE (Williams et al 2009). Steepness of the slope would contribute to redistribution of snow and water during the melt season with a tendency for meltwater to pool in low lying areas (Tong et al 2009; Williams et al 2009). Such was the case at Lunate Creek where waterlogged soils were found in low lying areas, usually at the toe of the slope, and adjacent to the multitude of springs that emerge along the slope.

The lack of persistence in soil moisture in the lower layers of the soil during the summer at Lunate Creek might in part be attributed to the steep gradient of the site. The meteorological station was set mid-way down the cutblock that had a slope of 26°. Even a 1° slope will encourage good drainage (Parent et al 2006). Steep terrain will promote greater surface runoff and drainage through the subsurface via gravity.

Pal and Eltahir (2001) describe the mechanisms for the positive feedback between soil moisture and precipitation. Higher than average soil moisture increases the moist static energy flux, reducing the height of the boundary layer, which in turn increases the moist static energy per unit mass of air. This results in an increase in convective rainfall; it was shown in the summer rainfall and soil moisture data at both the Ancient Forest (Fig 5.5) and Lunate Creek (Fig 5.6) that convective storms often do not produce sufficient rainfall amounts to wet the soils beyond the upper 15-20 cm.

With global climate change, precipitation is expected to fall more often as rain as opposed to snow (Barnett et al 2005). This may have serious implications in snow dominated areas where snow accounts for a significant input of water to the surface. Timing and the form of precipitation could mean less infiltration to soils, as runoff was expected to increase if precipitation occurs more frequently as rain (Barnett et al 2005; 2008). The effect of rain-on-snow through the winter could lead to an earlier snowmelt season. With an earlier melt, we would expect soils to be drier earlier in the spring/summer. There was potential for the feedback to be amplified by the warmer air temperatures projected by climate change models.

Plants and forest litter retain water and shade from trees prevents heating at the surface. Soil moisture measurements taken from the Ancient Forest soil profile were different from the measurements taken at Lunate Creek; the Ancient Forest site was an un-harvested cedar-hemlock forest while harvest had occurred at Lunate Creek and vegetative cover was in seedling stage. Murray and Buttle (2005) report greater infiltration in harvested versus forested slopes. They acknowledge that harvesting of timber contributes to greater runoff to streams and increases erosion.

The frequency of observations along with the spatial distribution of sampling points limits the type of analysis we can do and the objectives we can set for the project. Wu et al (2002) employ a data set of soil moisture from 17 sampling points in Illinois, 11 depths at each site spanning 16 years. These data allow them to characterize the response of soil moisture to precipitation on a long-term basis.

6.4 Soil Moisture and Shallow Groundwater Response to Summer Precipitation

There were a number of substantial (> 5 mm day^{-1}) rain events at the Ancient Forest and Lunate Creek sites during the period of 1 April 2012 to 31 August 2012, which represents the warmer summer months when short-duration (convective) rainfall events occur. Figures 6.2 and 6.3 allow for comparisons of rainfall events and soil moisture deviation from the daily mean at the Ancient Forest and Lunate Creek, respectively. The sharp increases in soil moisture mainly occur from spring snowmelt, but the graph shows a number of days that also experienced soil moisture responses from rain. Rain on snow events may advance snowmelt timing and further impact the amount of snowmelt available for infiltration (Moore and McKendry 1996; Mote 2003; Lundquist et al 2004; Hamlet et al 2005; Déry and Brown 2007). While it was difficult to determine from this study the amount of response from each of the two moisture sources, it appeared that rain affected the soil moisture values after the spring snowmelt was complete, starting late June or early July.

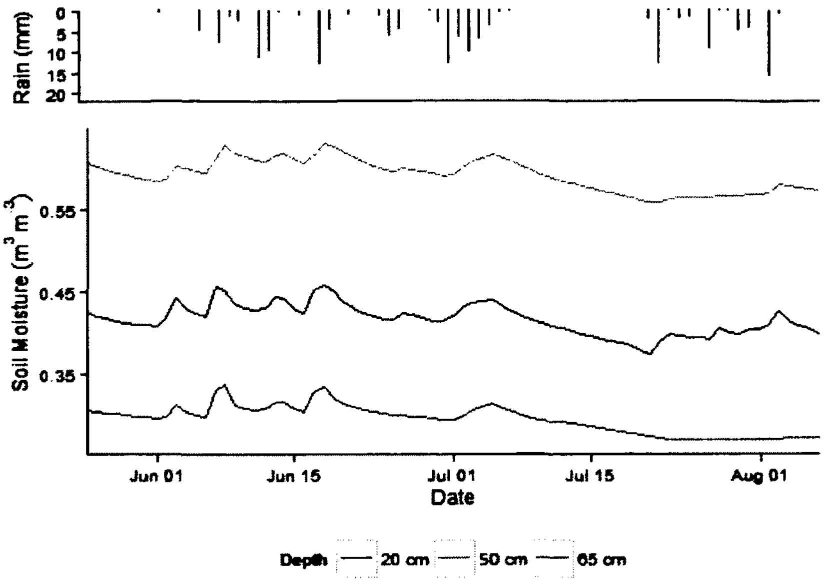

Figure 6.2 Rainfall (top, mm) and daily mean soil moisture (bottom, $m^3\ m^{-3}$) at the Ancient Forest from 1 April 2012 to 31 August 2012.

The soil moisture response to rainfall was evident at both the Ancient Forest and Lower Lunate Creek; rainfall aligns with increases in soil moisture at all depths. The lack of rain from early July until late July is exhibited in the declining soil moisture values; once rainfall occurs, the soil moisture at all depths increases. The upper soil layer at Ancient Forest is drier than the middle layer, possibly indicating that vegetation (both understory and overstory) has an effect on soil moisture persistence after rainfall; this is not the case at Lunate Creek, which has a younger and less dense forest structure. Tree species, understory diversity, and soil characteristics all have an effect on soil moisture uptake; the differences between the two sites (old-growth versus regenerating clear cut) indicate vegetation may have a strong effect on soil water use. Interception from larger trees at the Ancient Forest site also contributes to differences in upper layer soil moisture levels; more snow falls to the ground at Lunate Creek and may have a larger impact on upper soil layer moisture content. With snowmelt timing projected to occur earlier in the spring by 2050 (Barnett et al 2005), a prolonged drying of the soil may occur at these sites; without the sustained soil moisture from snowmelt runoff, the below average soil moisture values could either occur earlier in the summer or persist longer.

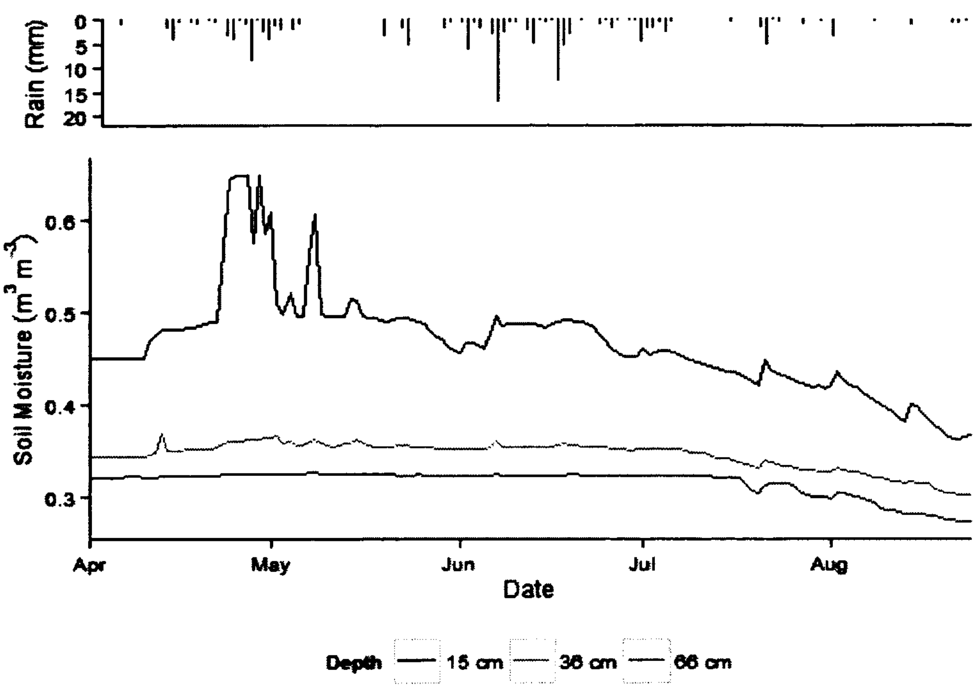

Figure 6.3 Rainfall (top, mm) and relative mean daily soil moisture (bottom, m^3 m^{-3}) from Lower Lunate Creek, 1 April 2012-31 August 2012

If a change in the soil moisture regime was to occur, there could be potential for a change in the convective storm pattern observed in the ITR during the summer. Pal and Eltahir (2000) saw a positive feedback between high soil moisture content and convective summer storms; a decrease in soil moisture in the ITR during the spring and early summer could result in a decreased occurrence of summer storms, thereby producing a negative feedback for soil moisture.

The response of the wells to rainfall events was more evident than the response of soil moisture (Figure 6.4). Well depths show a response to rain events in July, especially on 17 July 2012; there had been almost two weeks since there had been rain and all wells experienced minimum depths on 17 July 2012. Although there was not a significant correlation between rain and water response (see Figure 5.15) in all the wells, the middle well does show a statistically significant correlation at three and four days ($p < 0.05$); the lower well shows a similar response through the observation period, but the middle and upper wells had a greater response to the rain event on 17 July 2012.

The negligible responses of soil water and shallow groundwater show that convective summer storms were not necessarily the source of persistent soil moisture and groundwater; this was apparent at Niwot Ridge, Colorado, where it showed annual precipitation and soil moisture were significantly correlated, indicating precipitation during other times of the year (i.e., winter snow) plays a larger role in soil moisture than summer rainfall (Taylor and Seastedt 1994).

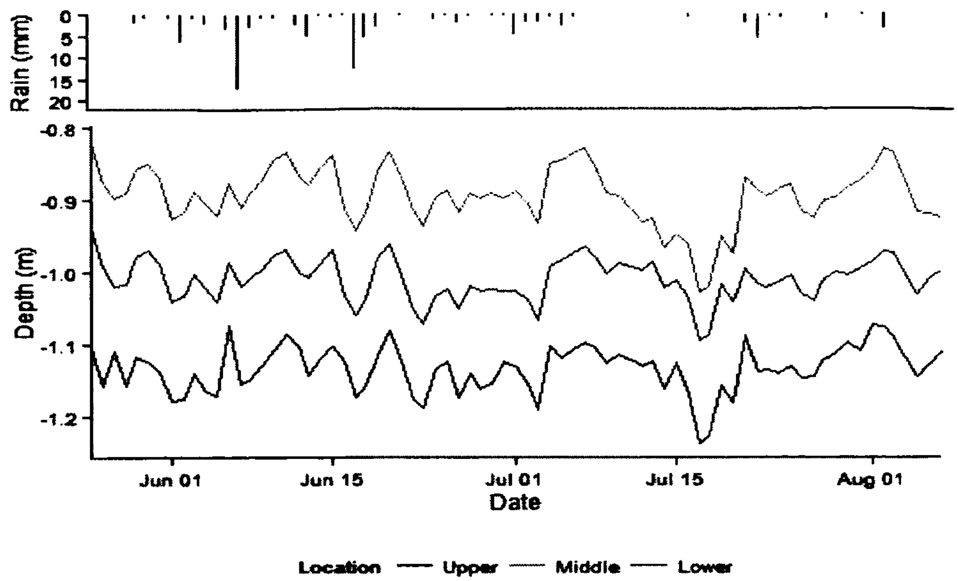

Figure 6.4 Rainfall (top, mm) and well depth (bottom, m) at Lower Lunate Creek, 24 May 2012 to 8 August 2012

Löffler (2007) observed in Norway that occasional rainfall events only have an impact of hours to days on water storage; the persistence of shallow groundwater in the wells throughout the summer indicates that moisture present after the snowmelt period persists in the soil.

The lower well was located at the toe of the slope (see Figure 3.2), which may explain why shallow groundwater was more prevalent here than in the upper and middle wells. Penna et al (2009) investigated the influence of topographic features on soil moisture availability and found that slope was one of the topographic controls best related to average soil moisture; as the middle well was at mid-slope, the influence of upslope shallow groundwater was important but the area also drained to the lower slope. The middle well often shows very low to dry conditions over the summer (see Figure 6.4) while the lower well is consistently higher indicating shallow groundwater from upslope experiences flow to the downslope wells. The upper well was co-located with the emergence of the spring, thus was in an area that experienced wet conditions all summer.

6.5 Quantifying the shallow groundwater components

Isotopic values observed at Lunate Creek indicated the snow pack had values of -22.5‰ for $\delta^{18}O$ (-173‰ for δD) and rainfall values of -8.9‰ for $\delta^{18}O$ (-92‰ for δD). St Amour et al (2005) conducted isotope research in the lower Liard River basin near Fort Simpson, Northwest Territories, Canada, to partition streamflow sources in wetland environments; they observed average snow pack $\delta^{18}O$ values of -29.3‰ (-228‰ for δD) and average rain $\delta^{18}O$ values of -14.6‰ (-127‰ for δD) from 1997-1999. Maulé et al (1994) observed snow pack isotope values near Edmonton, Alberta, Canada, for $\delta^{18}O$ and δD of −25.6‰ and −194‰, respectively; spring through autumn rains had weighted values of −16.2‰ and −125‰, respectively.

The results of the seasonal precipitation equations to determine shallow groundwater composition reveal that it comprises 40% of snowmelt. Maulé et al (1994) determined soil water (0-0.9 m below the surface) was comprised of 27% meltwater and groundwater (2-4 m below the surface) 44% meltwater at a prairie agricultural site. The depths of the shallow groundwater wells at Lower Lunate Creek were all close to 1 m below the surface, so the shallow groundwater in this study was comparable to the soil water in Maulé et al (1994). The higher snow-water content of shallow groundwater at Lunate Creek could be the result of a record maximum snow accumulation for the region, lateral flow from nearby small depressions where snowmelt runoff waters accumulated during spring or cool air temperatures in the spring that allowed a greater opportunity for meltwater to slowly infiltrate the soil. Sugimoto et al (2003) observed that the record high snowfall for a basin in the East Siberian taiga increased the SWE available for runoff and that the infiltration of snowmelt was about 50% of SWE. Lateral flow redistributes moisture when there was topographic relief greater than 2-3% and when there were sufficiently high moisture contents for periods long enough for flow to occur (Western et al 2002). These findings emphasize the importance of the contribution of winter precipitation to groundwater recharge.

Of note with the isotope results, the values from the surface water samples plotted to the left (depleted) side of the LMWL; this was not the case in the Maulé et al (1994) study. Their study showed that the surface water was more enriched than winter precipitation owing to evaporation and therefore enrichment of the water. The results from the Lunate Creek site are similar to the results from Gibson et al (1993) for two boreal lakes in the Northwest Territories (one of which is now in the territory of Nunavut), Canada.

6.6 Limitations of the Study

6.6.1 Length of Time Series

The results presented in this study were based on only one year of data; while soil moisture data were available for longer periods at both the Ancient Forest and Lunate Creek, comparative analysis with the water wells, and thus isotope information, was only conducted for one year. A longer time series of soil moisture would facilitate a more robust analysis of trends and any long-term periodicity in soil moisture. Unfortunately, budget constraints and time limits did not allow for instrumentation of both sites to collect isotope data over multiple field seasons and hence, annual and spatial variability were poorly represented by the results in this study. There were no supplemental soil moisture data available from the RFC weather stations and soil moisture was not typically measured at other meteorological weather stations in the region.

Having only one year's worth of data prevents assessment of long term variability of shallow groundwater inputs. We do not see how anomalously wet or dry years affect moisture contributions and we were unable to assess whether shallow groundwater composition would change. Without a longer series, we were unable to assess how differences in the amount of annual snowfall were manifested in the spring and shallow groundwater composition.

6.6.2 Spatial Variability

Spatial variability of soil moisture can vary considerably within any environment; however, in a mountainous watershed, topography imposes limitations onthe spatial distribution of snow, water, and subsequently soil moisture (Tong et al 2009). Studies in the Dry Creek Experimental Watershed near Boise, Idaho have shown that the spatial distribution of soil moisture was significantly correlated to the spatial distribution of snow, slope, soil texture and soil depth (Williams et al 2009). As soil moisture was a limiting factor for plant growth, any change in its spatial variability was important to ecosystems, having the ability to change vegetation regimes and essentially the soils themselves (Litaor et al 2008). Climate envelope modelling has shown that species will be able to expand their northern range, with the ICH potentially gaining area by 2085 (Hamann and Wang 2006), but this also corresponds to a shift of 300 m in elevation, thus eliminating much of the toeslope, old-growth cedar found along the Highway 16 corridor where the Ancient Forest site was found.

In both the Ancient Forest and Lunate Creek sites, there were only point measurements of hydrometeorological conditions, making it difficult to assess spatial variability in the area. It was also difficult to say that the site chosen was representative of the entire area, as the Ancient Forest was in a small, flat clearing in the dense forest and the Lunate Creek site being set in a clear cut surrounded by other clear and patch cut on varying slopes and aspects. Visual observations confirm that there were more areas with emergent springs and consistently wet soils.

Snow is an important form of precipitation to the Upper Fraser River basin; water stored in the form of snow is vital to the headwaters of the Fraser River for maintaining flows, supporting industry, and enabling agriculture in the Upper Fraser basin. While 2011-2012 was a record year for precipitation in the Upper Fraser, a changing climate has the potential to alter the snow regime in this area. The large amounts of snow (and thus, water) that fell in the Upper Fraser basin caused multiple flooding events and high flows on the Fraser River throughout the summer (RFC 2013). While sufficient water supply was important, high flows were still problematic; high flows throughout the summer can inhibit salmon from efficiently swimming upstream to spawning grounds, cause residential and commercial property destruction through flooding, and saturate soils, hastening agricultural activities. An expanded network of monitoring stations throughout the area at different elevations would allow for some assessment of spatial variability of temperature and snow depth; however, the equipment was costly to purchase and maintain and thus has limitations in implementation. Remote sensing has emerged as a resource to fill these missing data. With further technological advances, more reliable and current data will become available.

6.6.3 *Spatial and Temporal Record*

It was difficult to assess whether or not the data recorded from the CS616 probes were accurate in describing actual soil moisture levels in each horizon, due in part to the issues regarding calibration mentioned in the Methods section (e.g., bulk density of soil). One would expect to see more of a lag in soil moisture with depth and also decreasing soil moisture content with depth; during summer months, the shallow soil probes had a greater deviation from the mean than the deeper probes. At Lunate Creek, the upper soil layer held more moisture steadily the entire study period; the Ancient Forest site saw the middle soil probe with higher moisture levels than the upper layer, further highlighting the spatial variability of soils and forest cover in the ITR. Soil horizons were difficult to distinguish at both sites, and, although there were indications of well-developed horizons, the soil at the Lunate Creek site was disturbed by logging and planting and may not display the same characteristics as would be seen in surrounding soils.

Other studies that utilize ground based data had sampled much greater depths than was possible at the two sites. A study by Wu et al (2002) used soil moisture samples to 2 m in depth from 17 stations around Illinois; the data were taken from 11 layers and span from February 1981 to August 1996. These soils were deeper than would be expected at either site in their study as they were in an agricultural area, but sampling at greater depths was not possible in the glacial-formed soils; heavy cobbling below 1 m hinders excavation and insertion of probes. The results from Wu et al (2002) demonstrate that soil moisture at depth was less variable than near the surface (amplitude damping), which was also observed at Lunate Creek but only the 65 cm layer at Ancient Forest. The study also illustrated the results that can be obtained from a long-term database; patterns and projections were more evident and accurate the longer the time-series.

The shallow groundwater data from Lunate Creek give a limited view of the summer moisture regime; these data may be useful for relating groundwater and soil moisture fluxes to determine how well they were connected. Long term collection of seasonal waters would be needed to assess the contribution of snowmelt and rainfall to groundwater. Flow directions and dynamics would also need to be investigated to see whether there was a causal relationship between soil moisture and groundwater levels and whether lateral flow or surface flow was the prominent flow path for water.

Data from another study set in mountainous terrain employed ground based data taken with Campbell Scientific® Time Domain Reflectometers (TDR) from five depths at 5, 14, 45, 75 and 105 cm (Williams et al 2009). Other measurements were taken with a portable TDR that probes the soil to no more than 30 cm depth to assess spatial variability of soil moisture in the upper soil profile. Parent et al (2006) used similar TDR probes set up at seven sites along a 90 m transect to measure soil moisture at 20 minute intervals at 5-25 cm depth. They used these data to characterize the temporal variability of soil moisture at the surface on short timescales ranging from one hour to two weeks. The increased spatial distribution of instrumentation would allow for investigation of the moisture propagation from upslope to toeslope locations.

A longer record of seasonal isotope measurements would allow for a much stronger indication of the sourcing of shallow groundwater. Although the results indicate 40% of the shallow groundwater was from snowmelt, there were many potential errors in this estimate.

Sampling for isotopes in snow, rain, and groundwater over three or more years could give a mean weighted average and thus be more indicative of the region's isotope signature.

7 Conclusions and Future Directions

Soil is the interface between the land and the atmosphere and processes occurring at this interface link the water and energy budgets, directly affecting local weather and climate. In snow dominated regions, the timing and magnitude of surface water input from snowmelt is of great importance to vegetation and water supplies than summer convective storms. In mountainous terrain, the distribution and amount of snow play a large role in local water budgets. A significant portion of the world population relies on water from mountain streams and rivers fed from snow and ice. As climate change alters precipitation regimes, the input of water from snow will change in many regions. Understanding how these changes influence water availability, agriculture and other land uses was becoming more important as we learn to adapt to climate change.

This study was set in the Inland Temperate Rainforest, 100 km east of Prince George, British Columbia. The Northern Hydrometeorology Group deployed three meteorological stations measuring air temperature, relative humidity, soil temperature at 12 cm depth, snow depth, precipitation, wind speed and direction at the Ancient Forest and Lunate Creek. Soil moisture was measured at 20 cm, 40 cm and 65 cm depths at the Ancient Forest and 15 cm, 36 cm, and 66 cm depths at Lower Lunate Creek. Precipitation and snow depth data from the tower at the Ancient Forest and Lunate Creek sites were supplemented with data from the nearby Environment Canada tower at the Prince George Airport. The data from the SR50A showed similar snowfall patterns at both the Ancient Forest and Lunate Creek sites, but also similar to Prince George Airport. Meteorological data for the Ancient Forest and Lunate Creek sites were obtained from 1 November 2011 to 31 August 2012. Data from the study period at the

Ancient Forest and Upper and Lower Lunate Creek were compared to climate norms (1981 to 2010) from Prince George Airport to characterize the season with respect to average climate in the area.

7.1 Temporal Variability of Soil Moisture at the Ancient Forest and Lunate Creek

The response of the soil to precipitation events during the summer shows that the soils at the Ancient Forest and Lunate Creek were quite different. After a precipitation event, soil moisture at the top depth decreases after approximately 2-3 days. This was likely due to the steepness of the terrain at Lunate Creek, with approximately 26^{o} slopes at the site and the well-drained soils at the Ancient Forest; differences in forest structure also contributed to the differences in soil moisture, as the Ancient Forest site was influenced by larger trees that intercept more precipitation and have increased soil water needs. Water collects in low lying areas and runs off into streams and creeks that drain into the Fraser River.

Soil moisture fluctuates depending on the season at the Ancient Forest and Lunate Creek; a large spike in higher than average moisture values occurs during snowmelt in the spring at all depths, but then declines steadily over the warm summer months in the upper soil layers at both sites. The maximum soil moisture at Lunate Creek was at 15 cm depth, but at the Ancient Forest the 50 cm (middle) depth saw greater values. These maximums were typical during large magnitude rainfall events and during the snowmelt period, times when surface water would have been most abundant. The lowest soil moisture values were typically found in the winter when the soil did not receive inputs from precipitation or during short-lived snowmelt events throughout the winter.

7.2 Soil Moisture at the Ancient Forest and Lunate Creek

Persistence of the moisture signal in soil was detected by calculating autocorrelation functions for the depths of soil moisture probes. Cross-correlation functions were calculated to determine the relationship between soil moisture and major precipitation inputs, snowmelt and rainfall. For this study, this period was chosen to be from 1 November 2011 to 31 August 2012.

We find that during the study period there was persistence of autocorrelation of soil moisture on the order of 16-20 days at the Ancient Forest and 15-20 days at Lower Lunate Creek. This persistence was attributed to the large input of water from snowmelt during the spring, as results of soil moisture values indicate a period during the summer months of continuous low moisture values. The lack of persistence of anomalous soil moisture at other times of the year was likely due to the steepness of the terrain and the soil characteristics at each site. It was also likely that the experimental design and lack of instrumentation prevented proper detection of significant persistence of moisture from snowmelt or high magnitude rainfall events. It was speculated that with increased sampling sites a better idea could be obtained of how soil moisture moves through the soil, vertically and horizontally, to groundwater supplies and how persistence might change with depth. Lateral flow could be observed as well, but further analysis of the soil characteristics and hydraulic conditions of the sites would need to be conducted. Also, monitoring evaporative fluxes would allow for assessment of how soil moisture contributes to the boundary layer moisture and local convection.

7.3 Soil Moisture and Shallow Groundwater Response to Rainfall

Using cross-correlation we find that shallow groundwater in wells responds poorly to summer rainfall events. Analysis of shallow groundwater response to rainfall events shows an autocorrelation at two days, with only one of the sites showing a statistically significant response. Correlation between soil moisture and rainfall showed significant relationships at the Ancient Forest for all probes of 3-8 days; at Lunate Creek, the correlation for the 15 cm and 36 cm probes was significant for 3-8 days.

7.4 Shallow Groundwater Composition

Shallow groundwater showed fluctuations throughout the summer, but this had little relation to the rainfall events. When analyzing the isotopic signature of the shallow groundwater, seasonal precipitation (rain and snow), and surface water, it was determined that the shallow groundwater consisted of 40% snowmelt. This was calculated based on a study conducted by Maulé et al (1994); while this was just one study done over only one year, longer term studies could confirm this value and allow for a further separation of the shallow groundwater into its seasonal components.

7.5 Future Direction and Knowledge Gaps

Future studies on the persistence of snowmelt in the shallow groundwater and soil would be useful to assess surface evaporation. Having measurements for air temperature and humidity at two separate heights above the ground allows for calculations of the moisture bulk fluxes above the surface; use of an eddy covariance system would also enable the direct measurement of evapotranspiration at the site. This would aid in evaluating whether or not evapotranspiration contributes significantly to local precipitation. The Ancient Forest and Lunate Creek were areas that currently receive ~50% of its annual precipitation as snow; however, it was expected this fraction will decrease in a warmer climate. With the surface exposed for a longer period through the year and with a thinner snow cover there was potential for changes in evaporative fluxes and surface water storage.

A larger study to partition water sources in the Fraser River Basin would aid in better understanding the role that snowmelt plays in groundwater recharge and persistence. The installation of wells at multiple sites, in both forests and clear-cuts and on steep and flat areas, would give a better spatial appreciation for snowmelt infiltration at the ICH; a longer term study would also be beneficial as anomalous precipitation years can be averaged to obtain a better estimation of snowmelt in groundwater.

Ideally, there would be a long term soil moisture time series for the ITR that could be used to better assess persistence of anomalous soil moisture and what other meteorological factors might contribute to greater or less persistence. Soil moisture has the greatest effect on local climate where seasonal patterns to precipitation exist. These areas include mid-latitudes and areas where precipitation was non-stationary. The soil moisture probes currently in place will hopefully provide insight in the future to the long-term persistence in soil moisture resources.

Further research in nearby areas would also provide knowledge of spatial variability and differences in surface storage throughout the Upper Fraser River Basin. Having greater representation of soil moisture conditions over the range of ecosystems in this area would facilitate better understanding of how soil moisture limits vegetation and the land-atmosphere interactions that determine ecosystem diversity. With projections of species migration due to changing climate, understanding soil moisture sources and persistence will aid in determining whether migrating species would have the same moisture resources available during the shift. With mountains imposing control on local weather patterns, predicting how climate change will affect soil water budgets was difficult, especially without ground based data to support models.

This study provides some information on the temporal variability of soil moisture and opens a discussion on the source of the persistent moisture found in soils in the ICH. Focusing on the snowmelt season and comparing it with the summer rainfall aids in assessing which precipitation source was the largest contributor to soil moisture resources.

We find that the capacity of the soil to store moisture was limited by a number of factors such as snow accumulation, soil physical properties, and terrain features such as slope. With greater investigation and data that cover a larger spatial extent, it would be possible to isolate the larger impact on soil moisture availability and retention.

We conclude that soil moisture at the site persists for up to 10 days after any given precipitation event throughout the year except during the snowmelt period, during which soil moisture values remain well above average. Analysis of shallow groundwater response to rainfall events shows an autocorrelation at two days, with only one of the sites showing a statistically significant response. Isotope results showed summer precipitation to be more enriched than winter precipitation; groundwater and spring water samples showed more enrichment than winter precipitation, but the values were more closely related to winter precipitation than summer precipitation. Because of this lack of response to summer precipitation, it was inferred that snowmelt was the predominant component of shallow groundwater, which was supported by the calculated value of 40% snowmelt in sampled shallow groundwater. As water was the limiting factor for the ICH forest's survival and persistence, any knowledge gained about the area's water resources was valued.

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