THE EFFECTS OF FOREST STRUCTURE ON
SNOW ACCUMULATION AND MELT
IN SOUTH-CENTRAL BRITISH COLUMBIA

by

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(Department of Forestry)

We accept this thesis as conforming
to the required standard

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THE UNIVERSITY OF BRITISH COLUMBIA

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ABSTRACT

To address gaps in our understanding of the interrelationships between snow accumulation, snowmelt, meteorological conditions, and forest cover, a field investigation was undertaken at Mayson Lake and Upper Penticton Creek, in the south-central interior British Columbia. During 1995, 1996 and 1997, snow water equivalent (SWE) was measured at 576 stations over nine sites including three clearcuts, two mature spruce-fir stands, a mature pine stand, a juvenile pine and a juvenile-thinned pine stand, and a juvenile spruce-fir stand. Stand structure was described in detail at each station. Continuous measurements of meteorological conditions and snowmelt using lysimeters were made at Mayson Lake in 1995.

Peak SWE, taken as that measured on April 1st, was less under forest cover than in the clearcuts, by 32% (at Mayson Lake) and 23% (at Upper Penticton Creek) in the mature spruce-fir, by 14% in the juvenile and juvenile-thinned pine, and by 11% in the mature pine. No difference was found between the juvenile spruce-fir stand and clearcut. At Mayson Lake, average snowmelt rates in the mature spruce-fir, juvenile pine, and juvenile-thinned pine stands were 0.4, 0.8, and 0.9 times those in the clearcut, respectively. At Upper Penticton Creek, average melt rates in the mature spruce-fir and mature pine stands were 0.6 and 0.7 times those in the clearcut, respectively. No differences in melt rate were observed between the juvenile spruce-fir stand and clearcut. Relative to the clearcut, ‘recovery’ in April 1st SWE, defined as the reduction in peak snow accumulation or average melt rate in a juvenile stand from that in the clearcut towards that in the mature stand (B.C. Ministry of Forests 1999), was 43% in both juvenile pine stands and zero in the juvenile spruce-fir stand. Recovery in average snowmelt rate was 13 and 29% in the juvenile-thinned and juvenile pine stand, respectively, and zero in the juvenile spruce-fir stand.

Continuous lysimeter measurements at Mayson Lake showed that maximum daily and average melt rates over the season were similar for the clearcut and both juvenile pine stands. However, on a daily basis, the lysimeters showed a substantially different progression in snowmelt in the juvenile-thinned pine relative to the unthinned stand. Snowmelt began earlier and was more
rapid early in the season in the juvenile-thinned stand than in the clearcut and the juvenile-unthinned stand. Later in the season, melt rates in the clearcut exceeded those in all other stands.

Significant relationships between forest inventory variables and peak SWE and melt were found at the stand rather than plot scale. Standardized ratios of forest to clearcut peak SWE and melt (FOSWE and FOMR) were highly correlated with average stand crown length and basal area, respectively. Crown length explained 73% of the variability in FOSWE among stands and the square root of basal area, 79% of the variability in FOMR. Stand structure also affected below canopy meteorological conditions, particularly wind speed, snow temperature, and air temperature above 0 °C. On average, wind speed was reduced by 30 and 100% relative to the clearcut in the juvenile and mature stands at Mayson Lake, respectively. Prior to the onset of melt, snowpack temperatures in the mature spruce-fir stand were 2 °C colder on average than in the clearcut and juvenile stands. The snowpack became isothermal on the same date at all sites. During the peak melt period of 1995, temperature-index models using daily air temperature above 0 °C and temperature near the base of the snowpack were used to predict daily snowmelt for the stands at Mayson Lake. A radiation budget model, incorporating the FOMR ratios, was used to successfully predict snowmelt measured using lysimeters in these stands.

Incorporating the field data into a temperature-index and radiation budget snowmelt model highlighted the importance of quantifying the relationships between forest structure, meteorological conditions, and snowmelt. Improved understanding of the interrelationships between these variables is necessary to validate and improve the performance of snowmelt models over the broad range of forest types found in south-central B.C.
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And to those who just want the answer - assume it’s “42” - that way we can fix things later.
### SYMBOLS, ABBREVIATIONS AND UNITS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>albedo</td>
<td>decimal fraction; %</td>
</tr>
<tr>
<td>ε</td>
<td>emissivity</td>
<td></td>
</tr>
<tr>
<td>ρ_s</td>
<td>density of snow and ice</td>
<td>kg m^{-3}</td>
</tr>
<tr>
<td>ρ_w</td>
<td>density of liquid water</td>
<td>kg m^{-3}</td>
</tr>
<tr>
<td>ρ_v</td>
<td>density of water vapour</td>
<td>kg m^{-3}</td>
</tr>
<tr>
<td>σ</td>
<td>Stephan-Boltzmann constant</td>
<td>5.67 x 10^{-8} W m^{-2} K^{-4}</td>
</tr>
<tr>
<td>A_c</td>
<td>crown base area</td>
<td>m^2</td>
</tr>
<tr>
<td>B_i</td>
<td>thermal quality of snow</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>canopy cover factor</td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>clearcut</td>
<td></td>
</tr>
<tr>
<td>C_s</td>
<td>specific heat of snow and ice</td>
<td>MJ kg^{-1} °C^{-1}</td>
</tr>
<tr>
<td>C_w</td>
<td>specific heat of liquid water</td>
<td>MJ kg^{-1} °C^{-1}</td>
</tr>
<tr>
<td>C_v</td>
<td>specific heat of water vapour</td>
<td>MJ kg^{-1} °C^{-1}</td>
</tr>
<tr>
<td>dbh</td>
<td>diameter outside bark at breast height measured at 1.3 m above the ground surface</td>
<td>cm</td>
</tr>
<tr>
<td>F</td>
<td>forest</td>
<td></td>
</tr>
<tr>
<td>FOMR</td>
<td>ratio of the average melt rate in the forest to that in the open</td>
<td>cm d^{-1} (cm d^{-1})^{-1}</td>
</tr>
<tr>
<td>FOSWE</td>
<td>ratio of the snow water equivalent in the forest to that in the open</td>
<td>cm cm^{-1}</td>
</tr>
<tr>
<td>H</td>
<td>tree height</td>
<td>m</td>
</tr>
<tr>
<td>J</td>
<td>juvenile</td>
<td></td>
</tr>
<tr>
<td>JT</td>
<td>juvenile-thinned</td>
<td></td>
</tr>
<tr>
<td>L↓</td>
<td>longwave radiation arriving at the surface</td>
<td>MJ m^{-2} d^{-1}; W m^{-2}</td>
</tr>
<tr>
<td>L↑</td>
<td>longwave radiation leaving the surface</td>
<td>MJ m^{-2} d^{-1}; W m^{-2}</td>
</tr>
<tr>
<td>L_c</td>
<td>crown length</td>
<td>m</td>
</tr>
<tr>
<td>L_f</td>
<td>latent heat of fusion</td>
<td>MJ kg^{-1}</td>
</tr>
<tr>
<td>M</td>
<td>snowmelt</td>
<td>cm or mm per unit time</td>
</tr>
<tr>
<td>M_f</td>
<td>snowmelt factor</td>
<td>cm or mm °C^{-1} d^{-1}</td>
</tr>
<tr>
<td>MF</td>
<td>mature forest</td>
<td></td>
</tr>
<tr>
<td>MR</td>
<td>average melt rate</td>
<td>cm d^{-1}</td>
</tr>
<tr>
<td>n</td>
<td>fractional cloud cover</td>
<td>decimal fraction</td>
</tr>
<tr>
<td>O</td>
<td>open (includes clearcuts and natural meadows)</td>
<td></td>
</tr>
<tr>
<td>Q_n</td>
<td>net radiation</td>
<td>MJ m^{-2} d^{-1}; W m^{-2}</td>
</tr>
<tr>
<td>Q_e</td>
<td>latent heat flux density</td>
<td>MJ m^{-2} d^{-1}; W m^{-2}</td>
</tr>
<tr>
<td>Q_h</td>
<td>sensible heat flux density</td>
<td>MJ m^{-2} d^{-1}; W m^{-2}</td>
</tr>
<tr>
<td>Q_g</td>
<td>energy conducted from the ground to the snowpack</td>
<td>MJ m^{-2} d^{-1}; W m^{-2}</td>
</tr>
<tr>
<td>Q_a</td>
<td>energy advected to the snowpack through rain</td>
<td>MJ m^{-2} d^{-1}; W m^{-2}</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Units</td>
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<tr>
<td>--------</td>
<td>------------</td>
<td>-------</td>
</tr>
<tr>
<td>(Q_m)</td>
<td>energy available for snowmelt</td>
<td>MJ m(^{-2}) d(^{-1}); W m(^{-2})</td>
</tr>
<tr>
<td>(S\downarrow)</td>
<td>shortwave radiation arriving at the surface</td>
<td>MJ m(^{-2}) d(^{-1}); W m(^{-2})</td>
</tr>
<tr>
<td>(S\uparrow)</td>
<td>reflected shortwave radiation</td>
<td>MJ m(^{-2}) d(^{-1}); W m(^{-2})</td>
</tr>
<tr>
<td>SRBA</td>
<td>square root of basal area</td>
<td>m</td>
</tr>
<tr>
<td>SWE</td>
<td>snow water equivalent</td>
<td>cm; mm</td>
</tr>
<tr>
<td>(T)</td>
<td>temperature</td>
<td>(^\circ)C; (^\circ)K</td>
</tr>
<tr>
<td>(T_a)</td>
<td>air temperature</td>
<td>(^\circ)C; (^\circ)K</td>
</tr>
<tr>
<td>(T_b)</td>
<td>base temperature at which no snowmelt is observed</td>
<td>(^\circ)C; (^\circ)K</td>
</tr>
<tr>
<td>(T_s)</td>
<td>snow temperature</td>
<td>(^\circ)C; (^\circ)K</td>
</tr>
<tr>
<td>(T_t)</td>
<td>temperature of the trees</td>
<td>(^\circ)C; (^\circ)K</td>
</tr>
<tr>
<td>(V_c)</td>
<td>crown volume</td>
<td>m(^3)</td>
</tr>
<tr>
<td>U</td>
<td>internal energy content of the snowpack</td>
<td>MJ m(^{-2})</td>
</tr>
<tr>
<td>(z_s)</td>
<td>snow depth</td>
<td>m</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Water stored as snow in the headwaters of forested watersheds generates the large spring hydrograph peaks characteristic of most interior streams in British Columbia (B.C.). Historically, detailed investigations of the relationships between forest vegetation, snow accumulation, and snowmelt have focused on improving our ability to forecast floods and water supplies. More recently, work has been undertaken to understand these relationships at a fundamental level and as part of global climate change research (Metcalfe and Buttle 1998; Pomeroy et al. 1998; Woo et al. 2000). However, relatively little information is available to improve operational forest planning at the stand scale, or to model hydrologic change in response to changing forest cover at the watershed scale.

At the watershed scale, the removal of forest cover through logging, fire, insects, or disease has been shown to increase water yield and, in some cases, spring hydrograph peaks (Bosch and Hewlett 1982). These increases are assumed to be directly related to stand scale changes in snow accumulation and melt resulting from changes in forest cover. Increases in the amount of water accumulating as snow have been reported in the range of 10 to 70%, depending on the size and position of the opening (Golding and Swanson 1986; Toews and Gluns 1986; Pomeroy and Gray 1995). Increases in snowmelt rates approaching double the melt per day in forest types similar to those in the southern interior of B.C. have been reported (Skidmore et al. 1994). As new stands grow and re-occupy logged areas, it is assumed that snow accumulation and melt will decrease toward that measured under mature forest cover. Relatively little research has been undertaken that quantifies changes in snow accumulation and melt with forest regrowth. Hardy and Hansen-Bristow (1990) reported 20 to 30% higher snow water equivalents (SWE) and 40 to 70% higher melt rates in a 14 m and a 4 m tall juvenile stand than in a mature forest in Montana. They measured differences in SWE and melt rate between the clearcut and mature forest of approximately 34 and 76%, respectively. Their comparisons
showed only a small effect of the second-growth stand on the snowpack. For 8 m tall coastal Douglas-fir stands, with a canopy closure of 45%, Hudson (2000) predicted a ‘recovery’ in snow accumulation and melt of 75%. The incomplete understanding of the relationships between specific forest cover types, at all stages of stand development, and snow accumulation and melt make it difficult to predict the hydrologic changes expected with logging and stand regrowth.

With few exceptions (Hudson 2000), the relationships between regenerating forest cover and snow have not been quantified in B.C. but nevertheless form the basis of operational watershed management guidelines associated with the Forest Practices Code (B.C. Ministry of Forests 1999). Determinations of acceptable levels of harvest are based on generalised assumptions, extrapolated from research in other provinces and countries, that forest cover removal increases snow accumulation, the rate of melt, and spring peak streamflows, and that forest regrowth moderates these effects. However, with increasing regulatory constraints on timber harvesting and greater concern for water resources, the absence of local knowledge raises questions regarding the validity of regulatory guidelines and in some circumstances ends in unresolvable resource-use conflicts.

The relationships between snow accumulation, snowmelt, forest cover, and meteorological conditions are also key components of hydrologic models. Substantial research effort has been focused on the development of distributed hydrologic models for understanding hydrologic processes and for land-use planning. However, local field data to quantify the relationships between snow and various forest cover types, verify model assumptions, and validate model output are limited (Winkler 1999; Hudson 2000; D. Toews, pers.comm., 2000).

Quantifying the factors affecting snow accumulation and melt and the influence of forest cover on snowpack processes are central to the science of forest hydrology and the practice of watershed management. To better understand forest-related effects on SWE and melt, researchers have suggested work in a broader range of stand types (Moore and McCaughey 1997; Marsh 1999; Hudson 2000), inclusion of weather and energy conditions (Hanley and
Rose 1987; Moore and McCaughey 1997), and field measurements to validate model assumptions and output (Yang 2000). This would allow forest land managers to better predict the effects of vegetation manipulation on snow available for generating runoff, rate of water delivery, and the effects on spring peak flows. These issues are particularly important relative to the economic and environmental implications of land-management guidelines.

The primary objective of this thesis was to quantify relationships between snow, forest structure, and meteorological conditions in clearcut, mature, and juvenile Engelmann spruce (Picea engelmannii Parry), subalpine fir (Abies lasiocarpa (Hook.) Nutt), and lodgepole pine (Pinus contorta Dougl.) stands, forest types common throughout south-central B.C. This research provided a quantitative basis for evaluating the potential effects of forest manipulation in these stand types, as well as an improved understanding of the physical processes necessary for modelling snowmelt. The specific objectives of this work were to:

1) quantify the spatial and temporal variation in peak snow accumulation and melt in clearcut, juvenile, and mature lodgepole pine, Engelmann spruce, and subalpine fir stands;
2) identify stand characteristics, available operationally, that best differentiate between stands where peak snow accumulation and average melt rates differ;
3) quantify the influence of meteorological conditions on snow melt; and
4) investigate methods of predicting relative changes in snowmelt resulting from logging and forest re-growth.

To address these objectives, snow accumulation and melt, stand structure, and meterological data were collected at nine study sites in south-central B.C. Four were located northwest of Kamloops at Mayson Lake and five northeast of Penticton at Upper Penticton Creek. At Mayson Lake, research was conducted in a clearcut, a mature (greater than 100 years old) mixed Engelmann spruce, subalpine fir, and lodgepole pine stand, and two juvenile (12 years old) lodgepole pine stands. One of the juvenile stands was thinned and pruned. At Upper Penticton Creek, a clearcut, a mature lodgepole pine stand, a mature Engelmann spruce, subalpine fir, and lodgepole pine stand, and juvenile Engelmann spruce and subalpine fir stand
were studied. Since many papers in the literature do not provide tree species names but simply state that the stand was ‘spruce-fir’ or ‘pine’, this nomenclature will be retained throughout this thesis for both consistency and brevity. Stands of predominantly Engelmann spruce and subalpine fir will be referred to as spruce-fir and lodgepole pine stands as pine. At each study location, snow accumulation and melt were measured from 1995 through 1997. Detailed forest inventories were also completed at each location. At Mayson Lake, continuous meteorological and snowmelt measurements were made throughout the 1995 melt period.

Each chapter of this thesis describes a specific component of the study and builds on the results described in previous chapters. Therefore, each chapter includes a review of the literature pertinent to the research objectives described in that chapter, as well as sections on methods, results, and conclusions.

Chapter 2, Snow Formation, Accumulation and Melt, provides an overview of the fundamentals of snow formation, accumulation, and melt. The material in Chapter 2 is intended as background for readers not familiar with snow hydrology and is used to infer how the results of the research described in this thesis might be more broadly extrapolated. Chapter 3, The Study Area, provides a description of the study locations and sites. Chapter 4, Snow Accumulation and Melt in Interior Forests, summarizes the results of intensive snow survey measurements and quantifies the differences between the clearcut, mature, and juvenile stands at the two study locations during the three survey years. The snow accumulation and melt measurements provided in Chapter 4 are the foundation of the thesis. Chapter 5, Linking Stand to Snow Characteristics, describes both plot and stand-level relationships between stand structure characteristics as measured during routine forest inventories and snow accumulation and melt. Chapter 6, Detailed Investigation of Snowmelt Dynamics, deals with snowmelt measured using lysimeters and compares daily melt in clearcut, juvenile, and mature stands with the associated meteorological conditions. Chapter 7, Application of Results to Snowmelt Modelling, discusses the inclusion of the field research results in two standard approaches to snowmelt modelling (temperature-index and radiation budget methods). Chapter 8, Conclusions, provides a
summary of the work, a synthesis of the scientific findings, operational interpretations of the results, and recommendations for future research.

This research makes several notable contributions to hydrologic science in snow-dominated forested watersheds. Of particular importance is the inclusion of juvenile forest types, with the entire suite of measurements made in these stands as well as at clearcut and mature sites. The results have increased our understanding of the spatial and temporal variations in snow accumulation and melt in clearcut, mature, and juvenile stands. Stand characteristics and standard meteorological variables more highly correlated with snowpack processes than those used in current forest practices guidelines have been identified. Continuous measurements of snowmelt using lysimeters in association with meteorological measurements have provided insights into stand-level effects on snowmelt processes. Knowledge regarding the interrelationships between stand structure, meteorological conditions, and snowmelt gained through this study have improved our ability to model snowmelt in response to local forest cover manipulation. Operationally, the improved understanding of differences in snow accumulation and melt related to forest cover will contribute to forest watershed management by helping forest planners design cutting strategies that minimize the likelihood of adverse effects on the hydrograph.
CHAPTER 2

SNOW FORMATION, ACCUMULATION AND MELT

2.1 Introduction

Snow accumulation and melt dominate the hydrology of many B.C. watersheds and spring snowmelt produces the hydrograph peaks typical of most interior streams. Above average accumulations of snow followed by rapid melt can result in flooding, channel change, damage to aquatic habitat, and loss of property. Below normal accumulations of snow may result in water shortages for both human consumption and aquatic habitat. An understanding of the factors affecting snow accumulation and melt is central to both the science of forest hydrology and to the practice of watershed management. As background to the research described in this thesis, a summary of snow formation, accumulation, and melt is provided here.

2.2 Snow Formation

Snow is “a solid form of precipitation composed of ice crystals in complex hexagonal form” (Ahrens 1994, p. 576), “ice crystals ... falling to earth in light white flakes” (Barber 1998, p. 1375). “Snowflakes are a non-equilibrium phenomena ... products of imbalance in the flow of energy from one piece of nature to another” … a “blending of symmetry and chance“ (Gleick 1987, pp.309-314).

Snow begins with the formation of small ice crystals in supersaturated air at subzero temperatures. Ice crystals form:

1. through the chance aggregation of water molecules into a droplet of sufficient size to freeze, survive, and grow;
2. when a water droplet containing a particle such as dust or organic matter drops below some particle-specific temperature and freezes;
3. when an airborne particle comes into contact with a water droplet causing the droplet to freeze; or
4. when water vapour in contact with airborne particles turns to ice at low temperatures when the air is supersaturated with respect to ice (Wallace and Hobbs 1977).

The temperature at which water droplets freeze depends on their size, chemical composition, and the ice nucleation mechanism by which they freeze (Wallace and Hobbs 1977; Schemenauer et al. 1981). Water droplets that do not contain foreign particles can freeze only through chance aggregation. This process generally takes place in high clouds at temperatures less than -36 °C (Wallace and Hobbs 1977).

In the presence of particles such as dust, organic matter, or the products of combustion, referred to as ice nuclei, freezing can occur at higher temperatures (Gray and Prowse 1993). For particles to act as ice nuclei, they must be practically insoluble in water and must have a molecular spacing and crystalline arrangement similar to the hexagonal structure of ice. The type of particle influences the temperature at which ice nucleation can occur. Inorganic particles, such as clay, can cause ice nucleation at temperatures above -15 °C, whereas organic material, such as decayed plant leaves, may contain ice nuclei that are active at -4 °C (Wallace and Hobbs 1977). At -10 °C, the number of active ice nuclei per unit volume of air is very small, only about one in ten. However, this number increases by a factor of ten for every 4 °C decrease in temperature between -10 and -30 °C (Schemenauer et al. 1981).

Initially, ice crystals are very small (<75 μm) and have simple shapes. As the ice crystals continue to enlarge, snow crystals with intricate shapes visible to the unaided eye are formed. Their shapes vary from plates to prism-like crystals, to dendrites, and hollow columns as temperatures drop from 0 to -35 °C (Schemenauer et al. 1981).
Snow crystals are formed either through the diffusion of water molecules from water droplets onto neighbouring ice crystals where the water molecules condense and freeze, or through the collision of large ice crystals and cloud droplets as the ice crystals fall. Snow crystal formation through vapour diffusion occurs most rapidly around -14 °C. At this temperature, snow crystal forms are the most complicated (Wallace and Hobbs 1977; McClung and Schaerer 1993).

Colliding snow crystals adhere and aggregate into snowflakes when temperatures are near 0 °C. Each snowflake may contain two to several hundred snow crystals and may grow from 1 to 10 mm in diameter in 20 minutes (Schemenauer et al. 1981). As temperatures drop below 0 °C, snowflake size decreases with decreasing temperature to -20 °C when aggregation ceases. The maximum diameter of snowflakes is 0.1 mm to several centimetres. Rimed crystals, graupel, or snow pellets form when cloud droplets freeze onto large snow crystals (300 µm in diameter or larger) at temperatures between -5 to -20 °C (Schemenauer et al. 1981).

In addition to an adequate supply of sub-zero atmospheric moisture and ice nuclei, snowfall also requires sufficient cloud height to permit snow crystal growth and temperatures less than 0 °C in most of the area through which the snow falls (Schemenauer et al. 1981). Since snow has such a large surface area in relation to its mass, it can remain suspended in the air column for a considerable length of time. During this time, snow may be transported by wind, may melt, or sublimate.

Wind redistribution of falling snow occurs at the macro, meso, and micro scales. Snowfall at the macro, or regional scale, is influenced by the movement of air masses over topographic barriers and large water bodies. At the mesoscale, snow may be redistributed over distances of 100 to 1000 m through the combined effect of wind, terrain, and vegetation. At the microscale of 10 to 100 m, snowfall is affected by surface roughness and airflow patterns (Schemenauer et al. 1981; Gray and Prowse 1993).
While falling snow is being transported by the wind, snow crystal mass changes through vapour exchange with the surrounding air. If the air temperature is above 0 °C, or if the vapour pressure is less than the saturated vapour pressure of ice at 0 °C (6.11 mb), falling snow may melt or sublimate before it reaches the ground (Satterlund and Adams 1992). The amount of energy required to sublimate snow at 0 °C is $2.834 \times 10^6$ J kg$^{-1}$ and equals the amount of energy to melt snow ($0.334 \times 10^6$ J kg$^{-1}$) plus the energy to evaporate water ($2.5 \times 10^6$ J kg$^{-1}$). This energy comes from a variety of sources, including solar and longwave radiation, and the convective transfer of heat between the air and the snow. Sublimation varies with available energy and the distance over which the snow falls (Satterlund and Adams 1992). Sublimation losses of wind-transported snow are potentially large and have been estimated to as much as double with each 10 °C rise in temperature between -20 and 0 °C, the percent mass loss per unit time increasing as particle size decreases (Schmidt 1972).

Air temperature also controls the dryness, hardness, and crystalline form of newly fallen snow. Generally, snow crystals which have fallen through a cold atmosphere are smaller and have simpler shapes than those which have passed through warmer air (McClung and Schaerer 1993). Snow falling at low temperatures is also drier and less dense than that falling at warmer temperatures (Geiger et al. 1995). Crystal sizes in fresh snow range from 50 µm to 5 mm in maximum dimension (Schemenauer et al. 1981).

### 2.3 Snow Accumulation

Accumulating snow is usually described by its depth, density, and water equivalent. The depth of water that would result from melting a given depth of snow, or the snow water equivalent (SWE), varies with snow density. The snowpack contains water in all of its three phases: solid, liquid, and vapour. The relative proportions of water in each phase vary with environmental conditions. The proportion of liquid water in the snowpack varies, even over short periods such as hours, depending on temperature, rate of melt within the pack, the water-holding capacity of the snowpack, drainage from the pack, and any additions of rain (Pomeroy and Goodison 1997).
Snow accumulation is affected by snowfall, topography, and vegetation. In a given climatic region, snow accumulation generally increases with increasing elevation, as a result of increased storm frequency, decreased evaporation, and decreased melt throughout the winter (Gray and Prowse 1993). The relationship between elevation and snow accumulation varies considerably from year to year. Snow accumulation also varies with slope position and orientation, decreasing along a slope oriented parallel to the prevailing winds and increasing in depressions and on lee slopes (Gray and Prowse 1993). Aspect influences the amount of energy reaching the snow surface and, as a consequence, melt and sublimation losses during the accumulation period. Tall vegetation reduces the landform related variability in SWE, the effect generally increasing with increasing vegetation density. However, within-stand variability in SWE was found to be higher under boreal coniferous than deciduous cover as a result of differences in snow interception efficiency (Pomeroy et al. 1998).

As falling snow reaches the surface, it may melt, be intercepted by vegetation, or may accumulate on the ground. The amount of snow intercepted increases with increasing snow crystal size and with decreasing air temperature, wind speed and snow density (Pomeroy and Gray 1995). Interception is also affected by the physical characteristics of the intercepting vegetation. In conifer canopies is affected, in order of importance, by storm size, canopy surface area, wind-temperature effects, and species growth habits such as branch orientation and strength, needle configuration and orientation, mass, surface area, age, and density (Schmidt and Troendle 1992; Gray and Prowse 1993). Hedstrom and Pomeroy (1998) found that interception efficiency of boreal forest canopies was affected by leaf area, canopy cover, species, initial snow load, air temperature, wind speed, time since last snowfall and snowfall amount. The snow that does not fall through canopy gaps gradually builds up, forming bridges between the needles and branches. This process increases the surface area on which any additional snow can be intercepted until the weight of the snow can no longer be supported.

The larger the storm, the more snow is intercepted. However, the rate of interception decreases with increasing storm size (Schmidt and Troendle 1992). Harestad and Bunnell (1981) suggested that in coniferous forests a smaller fraction of the total snowfall was
intercepted during winters of larger accumulation. They also suggested that in areas of heavy
snowfall, differences in the amount of forest canopy produce less of an effect on interception.
Schmidt and Troendle (1992) suggested that when winter storms are small (e.g., 5 to 25 mm of
water equivalent) 50% of the snowfall may be intercepted when conifer crown closure is 50% or more. In a 19-m tall jack pine (Pinus banksiana Lamb.) stand with a crown closure of 82%, Pomeroy et al. (1998) measured 9 mm of SWE interception during snowfalls of up to 16 mm SWE. Interception did not increase beyond this maximum amount.

The highest interception rates occur at temperatures of -3 to 0 °C (Pomeroy and Goodison 1997) and the lowest occur at wind speeds greater than 2 m s⁻¹ (Gray and Prowse 1993). During storm events depositing more than 1 mm of water equivalent, Wheeler (1987) found a significant (p=0.002) inverse relationship between the percent difference in open versus forest snow water equivalent and average wind speed. Schmidt and Troendle (1992) reported that interception of wind-transported snow increased at temperatures above -5 °C, since at these temperatures snow crystals are more cohesive and less likely to rebound from branches, needles, and previously-intercepted snow. At lower temperatures, the less cohesive snow is more likely to be redistributed by wind.

The exact proportion of the total snowfall that is redistributed once it has been intercepted is the subject of much debate. Estimates range from a minor proportion of the total snowfall to as high as 90% during individual storms. Miller (1962) cited several studies which showed that shaking snow covered branches and blasting trees with helicopter downdraft only removed 1/4 to 1/3 of the total snow load on a branch, and only from the top 2 to 3 m of the canopy. Wheeler (1987) suggested that only 2% of the difference between SWE in an opening versus an Engelmann spruce, subalpine fir, and lodgepole pine forest in Colorado could be explained by the redistribution of snow by wind. As snow ages, the ability of wind to transport intercepted snow decreases (Miller 1962; Schmidt and Troendle 1992). Schmidt and Troendle (1992) reported that, after snowfall, redistribution of snow by wind had a negligible effect on snow accumulation on the ground, since most of the snow dislodged and fell as a large mass to the forest floor near the tree on which it was originally intercepted. In comparisons of snow
accumulation in a variety of opening sizes and the surrounding Engelmann spruce, subalpine fir, and lodgepole pine forest, in south-west Alberta, Golding and Swanson (1986) concluded that increased accumulation in the openings was due to:

1. elimination of interception in the 8 to 13 ha clearcut blocks at Cabin Creek,
2. a combination of interception and redistribution in the 1/4 times the average tree height (1/4H) to 6 H radius circular cutblocks at James River, and
3. redistribution in the 3/4 to 1 1/4 H openings studied at Twin Creek.

Once held in the canopy, snow may sublimate. Sublimation of intercepted snow depends on wind speed, air temperature, humidity, and radiation as well as on the nature of the canopy itself, including canopy surface area (Schmidt and Troendle 1992). In the dense conifer canopies studied by Schmidt and Troendle (1992), all of the intercepted snow (30% of the total snowfall on average) was lost to sublimation. Woo et al. (2000) estimated that sublimation losses from a Boreal Forest canopy in Saskatchewan could amount to 5 mm SWE per day. At the same study area, sublimation losses varied from 40% of the total annual snowfall in a black spruce (Picea mariana (Mill.) B.S.P.) stand, to 31% in jack pine, and only 13% in a mixed aspen (Populus tremuloides Michx.) and spruce stand (Marsh 1999). Satterlund and Haupt (1970) found that less than 20% was lost. The remaining snow either melted, slid off, or was washed off by rain during the relatively warm and moist winters.

Most of the energy used in sublimation comes from warm dry air advected into the canopy (Schmidt and Troendle 1992). If the air were still, the drop in temperature and increase in humidity associated with sublimation would bring the sublimation process to a stop. Maximum sublimation occurs during clear periods between small frequent storms which deposit snow on cold stiff branches (Schmidt and Troendle 1992).

In forested environments, snow accumulation on the ground varies between stands of different species, canopy density, and stem distribution. Within the same stand, snow accumulation also varies with distance from individual trees, increasing away from a coniferous tree-trunk to a distance of approximately 3 m (Pomeroy and Goodison 1997; Faria et al. 2000). The amount
of forest canopy, often described by estimates of canopy closure, gap fraction, or leaf area, has been shown to be inversely related to SWE on the ground. The form of the relationship between these variables varies with climatic conditions (Metcalfe and Buttle 1998). In the Boreal Forest, Pomeroy and Goodison (1997) showed that snow accumulation was greater in stands of aspen than jack pine and least in black spruce. The increases in snow accumulation corresponded to the lack of foliage during winter in aspen and lower leaf area in pine relative to spruce. Pomeroy et al. (1998) state that up to 70% of the spatial variation in SWE under forest cover is related to winter leaf area.

Tree removal through logging, fire, insects, or disease, generally increases snow accumulation on the ground. Maximum increases have been observed in openings which are no more than 2 to 5H in width (Golding and Swanson 1986). In openings larger than 20H in width, snow accumulation may actually be less than in the adjacent forest due to redistribution by wind (Golding and Swanson 1986). A summary of the literature reporting comparisons of snow accumulation in 1 ha (approximately 5H) or larger openings with that in forests cited as pine or spruce-fir, shows increases in maximum SWE in the open ranging from 10 to 70% of that in the forest (Table 2.1).

### 2.4 Snowpack Metamorphism and Melt

On the ground, snow undergoes continual change in crystal form, surface conditions, snowpack temperature, water content, permeability, and density. Snowpack metamorphism occurs as a result of energy exchange between the air or the ground and the snowpack. The energy fluxes to and from the snowpack include radiant energy (shortwave and longwave), energy released through the condensation or sublimation of water (latent heat flux), energy transferred to or from the snow surface by wind (sensible heat flux), and energy conducted to the bottom of the snowpack from the ground (ground heat flux).

The balance between shortwave and longwave radiation gains to and losses from the snowpack is referred to as net radiation. Shortwave radiation includes direct solar radiation and diffuse
Table 2.1. Maximum snow water equivalent (SWE) and average melt rates (MR) in the open (O) and under forest types (F) similar to those in south-central B.C. and the ratios of SWE and MR in the forest to that in the open (FOSWE and FOMR).

<table>
<thead>
<tr>
<th>Author(s) (Year)</th>
<th>Location</th>
<th>Aspect</th>
<th>Forest Cover</th>
<th>Years of Record</th>
<th>SWE F (cm)</th>
<th>SWE O (cm)</th>
<th>FOSWE</th>
<th>MR F (cm d(^{-1}))</th>
<th>MR O (cm d(^{-1}))</th>
<th>FOMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Church (1912)</td>
<td>Nevada</td>
<td>flat</td>
<td>pine, fir(^8)</td>
<td>1</td>
<td>30.2</td>
<td>29.2</td>
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<td>0.7</td>
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<tr>
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<td>29.2</td>
<td>0.9</td>
<td>0.7</td>
<td>1</td>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Rosa (1956)</td>
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<td>pine, fir(^8)</td>
<td>NA</td>
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<td>8.9</td>
<td>0.7</td>
<td>0.5</td>
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<tr>
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<td>9.2</td>
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<td>0.7</td>
<td>1</td>
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<td>0.7</td>
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<td>9.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
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<tr>
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<td>1</td>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
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<td>pine(^1)</td>
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<td></td>
<td></td>
<td></td>
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<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
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<td>pine(^2)</td>
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<td>0.3</td>
<td>0.7</td>
<td>0.4</td>
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<td>0.6</td>
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<td></td>
</tr>
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<td>13.5</td>
<td>19.9</td>
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<td>2.3</td>
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<td></td>
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<tr>
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<td>40</td>
<td>43.7</td>
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<td>0.6</td>
<td>0.6</td>
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<tr>
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<td>63.7</td>
<td>0.6</td>
<td>1.6</td>
<td>2.5</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
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<tr>
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<td>Wyoming</td>
<td>N</td>
<td>pine(^1)</td>
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<tr>
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<td>NE</td>
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Table 2.1 con’t. Maximum snow water equivalent (SWE) and average melt rates (MR) in the open (O) and under forest types (F) similar to those in south-central B.C. and the ratios of SWE and MR in the forest to that in the open (FOSWE and FOMR).

<table>
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<tr>
<th>Author(s) (Year)</th>
<th>Location</th>
<th>Aspect</th>
<th>Forest Cover</th>
<th>Years of Record</th>
<th>SWE F (cm)</th>
<th>SWE O (cm)</th>
<th>FOSWE MR</th>
<th>MR F (cm d⁻¹)</th>
<th>MR O (cm d⁻¹)</th>
<th>FOMR</th>
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</thead>
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<tr>
<td>Troendle and Meiman (1984)</td>
<td>Colorado S</td>
<td>pine¹</td>
<td>13</td>
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<tr>
<td></td>
<td>Various, B.C. conifers</td>
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<td>Colorado N</td>
<td>spruce³, fir⁴</td>
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<td>42.5</td>
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<tr>
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<td>pine¹, fir³</td>
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<td>17.8</td>
<td>23.9</td>
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<td>0.6</td>
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<tr>
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<td>pine¹</td>
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<td>28.3</td>
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<tr>
<td>Faria et al. (2000)</td>
<td>Saskatchewan flat</td>
<td>spruce⁵, pine⁶, mixed⁷</td>
<td>1</td>
<td>7.2</td>
<td>8.0</td>
<td>10.4</td>
<td>0.7</td>
<td>0.8</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

1 lodgepole pine (*Pinus contorta* Dougl.)
2 Scots pine (*Pinus sylvestris* L.)
3 Engelmann spruce (*Picea engelmannii* Parry)
4 subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.)
5 black spruce (*Picea mariana* (Mill.) B.S.P.)
6 jack pine (*Pinus banksiana* Lamb.)
7 aspen - white spruce mix (*Populus tremuloides* Michx. and *Picea glauca* (Moench) Voss)
8 not cited
solar radiation (solar radiation that has been scattered in the atmosphere). The total amount of shortwave radiation reaching the earth’s surface is referred to as global solar radiation or solar irradiance. The percentage of solar radiation reaching any point on the earth’s surface and the snowpack is a function of slope, aspect, cloud cover, forest cover, and solar position.

Longwave radiation is emitted by gases and particles in the atmosphere (longwave irradiance), and by the earth’s surface. The total amount of energy emitted as longwave radiation depends on the humidity of the atmosphere, surface temperature, and emissivity of the emitter (Geiger et al. 1995). Emissivity is defined as the total radiant energy per unit time and unit area, emitted by a surface at a specified wavelength and temperature relative to that which would be emitted by a black body under the same conditions (Bailey et al. 1997). Snow (particularly fresh snow) is almost a full radiator in the longwave portion of the spectrum. The emissivity of snow ranges from 0.97 for dirty snow to 0.99 for fresh snow (Gray and Prowse 1993).

In the open, the amount of incoming solar radiation reaching the snowpack is a function of cloud cover and cloud base height. For a given cloud base height, the solar radiation reaching the surface decreases with increasing cloud cover. For a given cloud cover, solar radiation reaching the surface increases with increasing cloud base height. Cloud cover also affects the longwave portion of the energy balance. Since clouds are close to being full radiators, net longwave exchange on cloudy days is a function of snow surface and cloud-base temperature. If the cloud-base temperature is warmer than the snow surface, the net longwave exchange to the snow surface will be positive (Geiger et al. 1995).

In a forest, the type, density, and condition of the canopy influence the amount of both short and longwave radiation reaching the snowpack. Generally, as forest cover increases the direct solar radiation reaching the snow surface decreases exponentially while longwave radiation increases to a distance of two to three times the crown radius from the bole of a tree (Bohren and Thorud 1973). Under a mixed black and white spruce canopy, Woo and Giesbrecht (2000) found that shortwave radiation was reduced relative to the open but that longwave was enhanced, particularly during overcast conditions.
Snow absorbs a portion of the shortwave and almost all of the longwave radiation, the rest is reflected. The ratio of the solar radiation reflected by a surface to that incident on that surface is referred to as albedo. Albedo is dependent on both the wavelength of the radiation and on the characteristics of the surface itself, such as colour, geometry, moisture content, composition, and roughness. For example, at visible and near infra-red wavelengths more shortwave radiation is reflected by snow than by ice, or by a dry soil than by a coniferous forest. The albedo of fresh snow can be as high as 75 to 98% and as low as 20 to 30% for old snow (Geiger et al. 1995). To model snowmelt in the Boreal Forest, Hardy et al. (1997) used an albedo of 0.15 for black spruce litter estimated to cover approximately 60% of the snow surface. After a snow storm, they used an average albedo of 0.8. They suggested that when snowpacks are less than 10 to 15 cm in depth, albedo is reduced to that of the soil surface. Storck and Lettenmaier (1999) found that, over the snow-fall-free period, snow albedo under a Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) canopy decayed from 0.8 early in the spring to slightly less than 0.4 during mid-melt. In contrast, Pomeroy et al. (1998) suggest that the assumption of decaying albedo for a snow-covered surface over the ablation period is questionable. Based on field measurements, they attribute reductions in areal albedo to the progressive exposure of bare ground and vegetation rather than to changes in snow cover reflectance. In south-central B.C., Adams et al. (1998) measured an albedo of 0.7 during the peak melt period, and an average albedo of 0.6 was estimated over the entire melt period (D. Spittlehouse, pers. com. 2000).

The albedo of snow also varies with surface roughness, snow grain size, snowpack density, and whether the radiation reaching the snow surface is diffuse or direct (Pomeroy and Goodison 1997). In contrast to shortwave, only about 1.4% of the longwave radiation reaching a snow or ice surface is reflected. Therefore, snow is commonly considered a black body for this portion of the spectrum (Geiger et al. 1995).

Shortwave radiation can also be absorbed and reflected within the snowpack. The amount of shortwave radiation within the snowpack decreases exponentially with depth. Geiger et al. (1995) presented light penetration curves for ice and snow. These curves showed that as much
as 40% of the shortwave radiation penetrates to a depth of 10 cm. This energy may be reflected back to the surface or may contribute to the processes involved in snowpack metamorphism. Only 10% or less of the total solar irradiance reaches a depth of 25 cm (Geiger et al. 1995).

In forests, net radiation decreases as canopy density increases up to approximately 60%, at which point it again increases (Pomeroy and Goodison 1997). Under dense canopies, where wind speeds are low, increased longwave from the canopy and multiple reflections of solar radiation between the canopy and snowpack may more than compensate for the reductions in solar radiation with increasing canopy density (Bohren and Thorud 1973). Net radiation can also be greater under a deciduous than coniferous canopy (Pomeroy and Goodison 1997).

Though they are much smaller sources of energy, convective and latent heat exchanges also contribute to melt through turbulent heat transfer and the latent heat of vaporisation released by water condensation on the snow surface. Under forest cover, where wind speeds are low, these fluxes are small (Woo and Giesbrecht 2000). On a daily basis, ground heat flux is usually small (0 to 6 Wm$^{-2}$) in comparison to radiation, latent, and sensible heat fluxes, and is often ignored or capped in energy budget predictions of daily snowmelt (Pomeroy and Goodison 1997). Brooks et al. (1991) suggested that this approach is reasonable over short periods of time, but that ground melt could be important in the calculation of seasonal melt. The timing of snowmelt can be influenced by the cumulative effect of heat flux from the ground over the entire season (Pomeroy and Goodison 1997).

Rainfall can also have considerable influence over the energy budget of a snowpack, the size of affect depending on whether the rain water freezes or remains liquid in the pack. Rain water moving through a snowpack at 0 °C may not freeze, but will transfer energy to the pack until the energy content of the rain reaches thermal equilibrium with the pack (Male and Gray 1981). The energy added to the snowpack in this way is small compared to rain in a snowpack at below 0 °C. At these temperatures, rain will freeze releasing latent heat of fusion. This form of energy transfer can be considerable. As described by Male and Gray (1981), adding 10 mm of
rain at 0 °C to a 1 m deep snowpack with a density of 34% would raise the temperature of the pack from -5 to 0 °C on re-freezing. If the snowpack is ripe, the energy added by rainfall is a relatively minor contribution to snowmelt. Snowpacks are defined as “ripe” when the temperature of the whole pack is 0 °C and when the liquid water-holding capacity of the snowpack has been reached.

The energy budget of a melting snowpack can be summarized as (Gray and Prowse 1993):

\[ Q_m = Q_n + Q_h + Q_e + Q_a - \Delta U/\Delta t \]  

(1)

where:

- \( Q_m \) = energy available for melt (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_n \) = net radiation (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_h \) = convective transport of sensible heat between the air and snowpack (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_e \) = latent heat released through condensation of water vapour onto the snowpack or lost through evaporation (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_a \) = conduction of heat to the snowpack from the ground (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_a \) = advection of heat to the snowpack through rain (MJ m\(^{-2}\) d\(^{-1}\))
- \( \Delta U/\Delta t \) = rate of change of internal energy in the volume per unit surface area per unit time (MJ m\(^{-2}\) d\(^{-1}\))

The change in the internal energy content, \( \Delta U \) (MJ m\(^{-2}\)), of the snowpack is calculated as (Gray and Prowse 1993):

\[ \Delta U = (\rho_i C_i + \rho_w C_w + \rho_v C_v) \Delta T_i z_i \]  

(2)

where:

- \( \rho_i \) = density of snow and ice (~ 922 kg m\(^{-3}\))
- \( C_i \) = specific heat of snow and ice (~ 0.0021 MJ kg\(^{-1}\) °C\(^{-1}\))
- \( \rho_w \) = density of liquid water (~ 1000 kg m\(^{-3}\))
- \( C_w \) = specific heat of liquid water (~ 0.0042 MJ kg\(^{-1}\) °C\(^{-1}\))
- \( \rho_v \) = density of water vapour (kg m\(^{-3}\))
- \( C_v \) = specific heat of water vapour (MJ kg\(^{-1}\) °C\(^{-1}\))
- \( \Delta T_i \) = the change in snow temperature (°C)
- \( z_i \) = snow depth (m)

Gray and Prowse (1993) have suggested that in estimating snowmelt for deep snowpacks, such as those in forested environments, the change in internal energy content is small compared to the other energy balance components and for practical purposes can be omitted.
Once the amount of energy available for snowmelt has been calculated, the amount of melt water (SWE (m)) can be estimated from (Pomeroy and Goodison 1997):

\[
\text{SWE} = \frac{Q_m}{(\rho_w L_f B_i)}
\]

where:

- \(\rho_w\) = density of water (~1000 kg m\(^{-3}\))
- \(L_f\) = latent heat of fusion (0.335 MJ kg\(^{-1}\))
- \(B_i\) = thermal quality of snow (the fraction of ice in a unit mass of snow, generally between 0.95 and 0.97)

As air temperatures increase in spring, so does the temperature of the snowpack. Prior to snowmelt, the temperature may not be uniform throughout the pack. The position of the temperature maximum is a function of the intensity of incoming and outgoing radiation and the extinction rate of energy moving into the pack. Both daytime and night-time temperature maximums occur some centimetres below the snowpack surface (Sommerfeld and LaChapelle 1970).

The maximum difference in temperature between the surface and the warmest layer depends on the thermal conductivity of the snowpack. New snow has a low thermal conductivity (0.08 Wm\(^{-1}\)K\(^{-1}\)), which increases as the snowpack ages and becomes more dense (up to 0.42 Wm\(^{-1}\)K\(^{-1}\)) (Oke 1987). The low thermal conductivity of low-density snow results in the development of large vertical temperature gradients within the snowpack. These temperature gradients decrease as snow density increases (Geiger et al. 1995). Elevated sub-surface temperatures and the occurrence of sub-surface melting are most likely in low density snow when the air temperature is near zero (Koh and Jordan 1995).

Temperature gradients lead to vapour pressure gradients, resulting in the movement of water vapour from warmer to colder parts (either grains or layers) of the snowpack where the water vapour is condensed and re-deposited (Sommerfeld and LaChapelle 1970). The end result is increased densification leading to increased strength and hardness of the snow (Langham 1981).
Newly fallen snow is generally crystalline in structure and is of low density, ranging from 50 to 120 kg m$^{-3}$ (Pomeroy et al. 1998). As the snowpack ages, the snow becomes more granular and the liquid water content of the pack increases. As a result, the density of the snowpack increases reaching 200 to 300 kg m$^{-3}$ or more once the snow has settled and has been exposed to wind (McKay and Gray 1981). During snowmelt, snowpack densities are commonly in the range of 250 to 500 kg m$^{-3}$ (Pomeroy and Gray 1995; Pomeroy et al. 1998). Snowpack density can be further increased through the addition of rain.

A high density crust commonly forms at the top of the snowpack due to rain or melted snow freezing at the surface and through the condensation of water vapour, which has diffused along temperature gradients from warmer layers within the snowpack to the colder surface. In the snowpack, density does not always increase with depth. Ice layers affect the transmission of air and water through the pack both vertically and laterally. The resulting stratification in the snowpack is not uniform across the landscape producing large spatial variability in snow density and snowmelt (Langham 1981).

Sublimation from the snowpack occurs when the temperature is less than 0 °C and the vapour pressure of the air is less than that of the snow surface. These losses are small in spring since the air is humid, and in winter since energy is limited. Even under the most favourable conditions, sublimation generally does not exceed 6 mm d$^{-1}$ (Geiger et al. 1995) and seldom exceeds 1 mm d$^{-1}$, amounting to a total seasonal loss of 10 to 20 mm (Bengtsson 1980). Though water losses from the snowpack are small, the energy lost or added through sublimation or condensation can affect melt. Condensation of water vapour on to the snow surface can occur if the vapour pressure of the air is higher than that of the snow. This process releases sufficient energy into the pack to melt 7.5 times the quantity of water condensed (Geiger et al. 1995).

Snowmelt begins at the surface of the snowpack. The liquid water percolates down into the pack and refreezes until the pack becomes ripe. Unless water is ponded above an impermeable
layer in the snowpack, drainage usually begins once the water content of the pack reaches 5% (Satterlund and Adams 1992).

### 2.5 Water Movement Through the Snowpack

Once the snowpack is at 0 °C throughout its depth (*i.e.*, is isothermal) and the liquid water-holding capacity has been reached, water begins to drain from the pack. Liquid water-holding capacity is a function of the hygroscopic and capillary water remaining in the snowpack after gravity drainage (generally in the range of 0.03 to 0.05 kg kg\(^{-1}\)), the SWE and the internal energy content. During the peak melt period, 20% or more of the snowpack may be liquid water most of which will be draining through the pack (Male and Gray 1981).

The rate of water movement through the snowpack varies with the temperature, structure, and water content of the snowpack. Two broad thermal regimes are commonly recognized in discussions of water transmission through the snowpack: subzero and isothermal at 0 °C. For simplicity, many runoff models assume that when average snowpack temperatures are below 0 °C, melt water re-freezes within the pack and does not reach the ground surface. Under these conditions, energy must be added to the pack until its temperature is 0 °C throughout. Once the snowpack is isothermal at 0 °C over its entire depth, any additional melt water is available to either fill the liquid water-holding capacity of the pack or flow out to the ground. At night, energy is usually lost from the snowpack, so these losses must also be replaced the next day prior to the resumption of outflow from the pack (Male and Gray 1981).

As liquid water enters or moves through the snowpack, metamorphism occurs changing the water retention characteristics of the pack. As snow grains become larger and more rounded, pore space also increases making the snowpack more permeable and reducing its water-holding capacity. The water-holding capacity of a snowpack is highly variable ranging from zero to more than 10% by volume (Kattelmann 1986).
Water moving through the snowpack in response to gravity is affected by temperature and textural discontinuities and so does not necessarily move in a uniform wave (Gray and Prowse 1993). In snow below 0 °C, water infiltrating the snowpack re-freezes decreasing the permeability of the pack by filling in voids resulting in a lag between the onset of increased melt at the surface and runoff (Pfeffer and Humphrey 1996). If the cold content of the upper layers of snow is small enough to be removed by the heat released when melt water re-freezes on to the grains of snow, new ice will not fill the pore spaces. Under these conditions, if temperatures increase to 0 °C, the wetting front can descend (Gray and Prowse 1993).

As the amount of water ponded above a discontinuity in the snowpack increases, the head gradient across the discontinuity also increases, eventually allowing flow to occur to the lower layer. As this layer becomes more saturated, hydraulic conductivity increases until steady flow occurs across the original barrier (Pfeffer and Humphrey 1996).

In sub-freezing snow, as saturation increases in the fine-grained layer, the saturation of the coarser layer decreases due to the re-freezing of liquid water. If sufficient saturation is reached before pores in the coarse layer close off (i.e., the cold content is small), then an ice layer will not form and water can continue to pass the barrier. Water which accumulates above an ice layer may re-freeze and thicken the ice, or may flow laterally along the ice. Lateral variation in parameters affecting water flow through the pack allows water to break through some sections of the barrier while adding ice to others (Pfeffer and Humphrey 1996). McGurk and Kattelmann (1986) found that deep snowpacks in the Sierra Nevada, U.S., drained two to three times more rapidly early in the melt season than near the end. They attributed the rapid early season drainage to the presence of distinct channels through the snowpack which carried most of the flow.

As a result of these processes, runoff or outflow from the snowpack cannot simply be equated to melt at the surface (Pfeffer and Humphrey 1996). Detention in the snowpack can moderate peak streamflows by delaying the delivery of rain or melt water to channels, compared to areas with no or shallow snowpacks.
Snowmelt rates reported in the snow hydrology literature are most commonly calculated from repeated measurements of SWE over time and, therefore, represent the combined losses of water from the snowpack through sublimation, evaporation of melt water, or outflow. Seasonal loss rates reported in the literature range from 0.7 cm d\(^{-1}\) in the open to 2.5 cm d\(^{-1}\) under pine and from 0.3 to 1.7 cm d\(^{-1}\) under spruce or fir canopies (Table 2.1). Snowmelt rates within boreal forest stands have been found to be inversely correlated with SWE, melt rates increasing with decreasing SWE (Faria \textit{et al.} 2000). The covariance between these variables was found to increase with decreasing canopy density. Faria \textit{et al.} (2000) found that the effects of canopy density on SWE and snowmelt combined resulted in the more rapid depletion of the snowpack in a medium-density mixed aspen-spruce stand, followed by a medium density pine stand and a clearcut, and the slowest depletion rates in a high density black spruce stand. The total melt period in the spruce stand was prolonged by 12 days relative to the open (Woo \textit{et al.} 2000).

2.6 Summary

The formation, accumulation, metamorphism, and melting of snow are complex processes influenced by environmental conditions, surface cover, and the physical characteristics of the snowpack. Snow has unique physical properties, in that (Pomeroy and Goodison 1997):

1. at 0 °C, water exists in the snowpack as a solid, liquid, and vapour;
2. the latent heat of vaporization of snow is high so that when snow sublimates considerable energy is released into the environment, and when water vapour condenses onto the snow-surface energy is released into the pack;
3. the latent heat of fusion is high, adding or releasing energy to the snowpack or environment;
4. the thermal conductivity of snow is low making snow an excellent insulator (about six times more effective than soil);
5. the albedo of snow is high (for fresh snow about eight times that of bare soil or vegetation); and
6. snow cover is aerodynamically smooth so that for the same conditions wind speed is greater over snow than bare ground.

Each of these characteristics, together with the role of snow as an annual reservoir of water, give snow prominence as a hydrologic variable. Understanding the relationships between forest types, climate, and snowpack processes are key elements in the prediction of snowmelt-generated streamflow and the management of forested watersheds.
CHAPTER 3
THE STUDY AREAS

The field measurements for this study were completed over the 1995 to 1997 snow seasons at two study locations: Mayson Lake and Upper Penticton Creek (Figure 3.1). Mayson Lake is approximately 50 km northwest of Kamloops, and Upper Penticton Creek about 26 km northeast of Penticton, B.C. Both locations are considered to be dry, having a mean annual precipitation of less than 700 mm, with approximately 60% falling as snow (Lloyd et al. 1990). Data from both the Mayson Lake and Upper Penticton Creek locations were included in the snow accumulation and melt comparisons (Chapter 4), and in the investigation of linkages between forest structure and snow (Chapter 5). The intensive snowmelt and meteorological research described in Chapter 6 was completed at Mayson Lake only.

At Mayson Lake, snow measurements were made at four sites. The sites were approximately level and all were within a distance of 1 km. One site was clearcut and regenerating with lodgepole pine trees less than 1 m tall. The second site was forested with multi-layered mature (older than 100 years) Engelmann spruce, subalpine fir, and lodgepole pine trees. The third and fourth sites were reforested with juvenile lodgepole pine. One of the two juvenile stands was thinned and all stems were pruned to a height of 3 m. The Mayson Lake research sites are at an elevation of 1250 m and are classified as being in the Montane Spruce Biogeoclimatic Zone (Lloyd et al. 1990).

At Upper Penticton Creek, five sites were surveyed in two areas located approximately 5 km apart: 240 Creek and Dennis Creek. The study sites were: a clearcut and a mature lodgepole pine stand at 240 Creek and a clearcut, a mature Engelmann spruce-subalpine fir stand, and a juvenile stand of Engelmann spruce and subalpine fir at Dennis Creek. All five sites were on level terrain. The study sites at Upper Penticton Creek are at an elevation of 1600 m and are classified as being in the Engelmann Spruce - Subalpine Fir Biogeoclimatic Zone (Lloyd et al. 1990).
Figure 3.1  The general location of the study sites.
Figure 3.2. The location of the Mayson Lake study stands.

Figure 3.3. The location of the Upper Penticton Creek study stands.
The forest cover characteristics of the study sites are summarized in Table 3.1. The values provided are the average of measurements from 64 fixed-area plots each covering 0.005 ha. The plots were centered at each snow survey station in a 15 m by 15 m grid pattern over the study site. Detailed descriptions of the snow survey station layout and forest inventory methods are provided in Chapters 4 and 5, respectively.

Table 3.1. Average forest cover characteristics at Mayson Lake and Upper Penticton Creek.

<table>
<thead>
<tr>
<th>Location and Forest Cover</th>
<th>Average Tree Height (m)</th>
<th>Average Dominant and Codominant Tree Height (m)</th>
<th>Live Stems per Hectare</th>
<th>Basal Area (m² ha⁻¹)</th>
<th>Crown Closure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayson Lake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>10.1</td>
<td>23.1</td>
<td>3600</td>
<td>62</td>
<td>54</td>
</tr>
<tr>
<td>Juvenile pine</td>
<td>4.5</td>
<td>4.5</td>
<td>2600</td>
<td>12</td>
<td>28</td>
</tr>
<tr>
<td>Juvenile-thinned pine</td>
<td>6.4</td>
<td>6.4</td>
<td>1000</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>Upper Penticton Creek</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mature pine</td>
<td>14.7</td>
<td>17.8</td>
<td>4000</td>
<td>58</td>
<td>40</td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>6.6</td>
<td>18.8</td>
<td>3800</td>
<td>48</td>
<td>44</td>
</tr>
<tr>
<td>Juvenile spruce-fir</td>
<td>2.8</td>
<td>4.1</td>
<td>3400</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

At both Mayson Lake and Upper Penticton Creek, the average tree heights in the mature spruce-fir stands were approximately double those of the trees in the juvenile stands. The multi-layered nature of the spruce-fir stands is shown by the average heights of the dominant and codominant trees forming the upper canopy (Table 3.1), 23.1 and 18.8 m at Mayson Lake and Upper Penticton Creek, respectively, approximately two to three times taller than the stand average. At Upper Penticton Creek, the tallest trees in the juvenile spruce-fir stand were 4.1 m or double the average height of all trees in the stand. Differences between the stand average and the dominant and codominant heights were much smaller in the pine stands.
The density of stems was similar in both of the mature spruce-fir stands but up to 10% greater in the pine stand. Stand density was 10 to 30% less in the juvenile than mature stands, at Upper Penticton Creek and Mayson Lake, respectively, and 72% less in the juvenile-thinned stand. Basal area and crown closure most clearly highlight the differences among study stands. Average basal area in the juvenile stands at Mayson Lake was 12 and 20% of that in the mature spruce-fir stand. At Upper Penticton Creek, the average basal area in the juvenile stand was 12% of that in the mature spruce-fir. The juvenile stand at this location had limited crown closure. The mature spruce-fir and pine stands had a crown closure of approximately 40%. At Mayson Lake, crown closure in the juvenile stands was roughly half of that in the mature stand (21 and 28% compared to 54%).

The forest types included in this study were not replicated spatially, but rather were repeated over three years (i.e., replicates in time). This study design was necessary since it was impossible to find more than one complete group of stands, including clearcut, juvenile, and mature, in close proximity with similar characteristics. Particularly problematic was the location of juvenile stands of sufficient size to potentially affect snow cover.

Long-term snow survey data collected by the B.C. Ministry of Environment, Lands and Parks (2000) indicated that, on average, both study locations accumulate approximately 23 cm of SWE by April 1st. The snowpack has generally disappeared by early to late May. The date of disappearance at Mayson Lake precedes that at Upper Penticton Creek by up to two weeks. In 1995 through 1997, the average April 1st SWE in the clearcut at Mayson Lake was 22 cm, and 31 to 37 cm in the two Upper Penticton Creek clearcuts (Chapter 4). Snow depths of up to 80 cm were recorded and snow cover disappeared from all study sites by early to mid-May.
CHAPTER 4

SNOW ACCUMULATION AND MELT
IN INTERIOR FORESTS

4.1 Introduction

Snow accumulation and melt dominate the hydrology of most watersheds in south-central B.C. Each process is extremely variable, both spatially and temporally. Over large geographic areas snow accumulation and melt are influenced by climate and location, whereas at a specific location, such as a watershed, these processes are also influenced by topography and plant cover. When combined, large accumulations of snow and rapid melt may result in peak streamflows of sufficient magnitude to cause flooding, damage aquatic habitat, and compromise community water systems. In forested watersheds, cover may be altered by wildfire, insects, disease, forest regrowth, species conversion, logging, agriculture, and settlement. The quantification of cover-related influences on snow accumulation and melt is fundamental to our understanding of hydrologic processes, as well as to the prediction of watershed response to forest cover manipulation in forest development planning.

The influence of forest cover on snow hydrology has been the focus of many research projects worldwide. Summaries of this work are available in Bunnell et al. (1985), Stegman (1996), Marsh (1999), and Woo et al. (2000). In a review of variables influencing snow accumulation, Meiman (1987) summarized the literature by stating that over large areas elevation has the greatest effect, whereas at the site level, both snow accumulation and melt are influenced by forest cover. Snow accumulation is affected by the interception efficiency of the forest canopy and by both sublimation losses and the release of intercepted snow to the ground. These processes are a function of tree species, winter leaf area, canopy density, initial snow load, air temperature, wind speed and the frequency and size of snowfall events (Hedstrom and Pomeroy 1998). Sublimation losses, estimated as high as 40% for coniferous canopies (Pomeroy and
Schmidt 1993), reduce the amount of SWE available for melt (Chapter 2). Forest cover also affects snowmelt by reducing the amount of shortwave radiation reaching the snow surface, increasing the longwave, and attenuating the exchange of latent and sensible heat through the reduction of wind speed and near-surface temperature and humidity gradients relative to the open (Chapter 2). The reduced energy fluxes under dense canopies can delay snowpack depletion by 8 (Toews and Gluns 1986) to 12 (Woo et al. 2000) days. The effects of cover on the energy balance vary with winter canopy density and the distribution of canopy gaps throughout the stand (Pomeroy and Goodison 1997; Woo et al. 2000). Snowmelt and SWE co-vary, melt rates increasing with decreasing SWE, depending on canopy density. As canopy density decreases the covariance has been found to increase (Faria et al. 2000). The influence of forest cover on antecedent SWE and micrometeorological conditions together influence melt water outflow from the snowpack (Storck et al. 1999). Stand specific differences in these variables influence the hydrologic effects of logging and forest regrowth.

The snow research reported in the literature for forests similar to those found in south-central B.C. was summarized in Table 2.1 of Chapter 2. In addition to maximum SWE, average snowmelt rates, and site descriptors, Table 2.1 also includes the ratios of forest-to-open SWE and melt rates. By assuming that the SWE reported in the open accounts for both sampling-period and location variability, the ratios provide a standardized measure to compare among studies. Table 2.1 includes only those forest-to-open comparisons where the opening was either a meadow or a clearcut with no residual stems and was more than 1 ha or 5 times the average tree height (5H) in width.

A broad range of maximum SWE (6 to 90 cm) were reported in the literature for environments similar to those in this study. This reflects the large spatial and temporal variability typical of SWE. With few exceptions, higher SWE (5 to 70%) were measured in the openings of 5H (or more) than under forest canopies. The ratios of maximum SWE in the forest to the open ranged from 0.6 to 1, with 0.7 the most frequently-reported result.
The differences between average melt rates in forests and in the open were also highly variable. As for maximum SWE, average snowmelt rates in the open were most commonly higher than those in the forest. Studies cited average melt rates of 0.3 to 1.7 cm d\(^{-1}\) in the forest, and 0.4 to 2.5 cm d\(^{-1}\) in the open (Table 2.1). The ratios of melt rates in the forest to those in the open varied from 0.4 to 1, with 0.7 the most frequent result.

Little information was found for juvenile stands of similar species to those found in south-central B.C. Hardy and Hansen-Bristow (1990) reported that SWE measured in a mature (75 years old) Engelmann spruce stand in Montana was 0.8 times that in two juvenile (13 and 35 years old) lodgepole pine stands. The average tree heights in the juvenile stands were 4 m or less in one and up to 14 m in the other. They also found that average snowmelt rates in the mature stand were 0.6 and 0.8 times that in the 4 and 14 m tall juvenile stands, respectively.

Collating the results of SWE and melt comparisons, as in Table 2.1, to better understand hydrologic processes or to use in hydrologic models and procedures for watershed management is problematic for several reasons. Even after the values reported in the literature are standardized to reduce year of study and location related differences, the variability in the results makes it difficult to predict changes in snow accumulation and melt following clearcutting based on these studies alone. The literature shows results ranging from 40% less SWE in the forest than in the open to no difference. Similarly, differences in melt rate varied from zero to rates 60% slower in the forest. The reasons for such variable results are not identifiable from the literature, presenting another difficulty in extrapolating the results. Site descriptors provided in the literature such as aspect, elevation, and leading tree species, do not appear to explain the variation in the tabulated ratios. Detailed site characteristics such as stand density, crown distribution, or the meteorological characteristics of the study period are not commonly described in the literature. Snow research methods are also not consistent from study to study. For example, some authors report the average of nine or 10 samples in each study area on two dates in a single year (Hardy and Hansen-Bristow 1990), whereas others report averages of detailed grid sampling over extensive areas for many years (Seppanen 1961).
Though each study adds to our understanding of snow accumulation and melt processes, these differences in design make collating the results as locally applicable predictive tools challenging.

Guidelines for watershed management in B.C. (B.C. Ministry of Forests 1999) consider reductions in snow accumulation and melt rate from a maximum in the clearcut toward that in a mature forest to be directly related to forest regrowth. In this way, juvenile stands are said to ‘recover’. Recovery is defined as the ratio of the difference in SWE or melt between a clearcut and a juvenile stand over the difference between a clearcut and a mature forest, expressed as a percent (B.C. Ministry of Forests 1999). Rates of recovery are suggested based on several preliminary surveys but have not been quantified through detailed snow studies. Snow accumulation and melt processes in juvenile stands, relative to both the mature and clearcut conditions, must be understood in order to plan forest development to minimize adverse effects on the hydrograph.

The objective of the research described in this chapter was to quantify the differences in peak snow accumulation and in average melt rate, through repeated surveys over three years in six forest cover types, including three juvenile stands, typical of south-central B.C. The differences in peak snow accumulation and melt found in this research also formed the basis for detailed investigations of the relationships between forest cover characteristics, meteorological variables, and peak snow accumulation and melt described in subsequent chapters of this thesis.

4.2 Methods

4.2.1 Field Measurements

This investigation was conducted at both the Mayson Lake and Upper Penticton Creek study locations described in Chapter 3. SWE was measured at all nine study sites in 1995, 1996, and 1997. Measurements at Mayson Lake were made in early March, in mid-March, on April 1st, and then every three to four days throughout the snowmelt period. At Upper Penticton Creek, at both 240 Creek and Dennis Creek, SWE was measured in early March, April 1st, and then every two weeks until the end of snowmelt. The more intensive sampling at Mayson Lake was
undertaken to provide additional data for the detailed study of snowmelt processes described in Chapter 6.

Snow samples were collected vertically through the snowpack to the ground using a standard Federal snow tube and weighed with a calibrated spring balance from which water equivalent, in centimetres, was read directly. Errors associated with this snow sampler can be related to scale calibration, reading the scale, and the capability of the sampler to cut and retain a snow core. The Federal snow sampler gives positively-biased estimates of true SWE in comparison to gravimetric measurements (Work et al. 1965). In tests of accuracy, maximum errors of approximately 12% were reported over a range of SWE from 1 to 18 cm, and in the range of 7 to 12% for SWE values of about 21 to 217 cm (Goodison et al. 1981). Peterson and Brown (1975) also reported that the standard snow tube overestimates SWE but only at densities greater than 25%. Beyond a snow density of 25%, they found that overestimates increased up to a maximum error of 12% at snow densities greater than 50%.

Snow measurements were made at 64 permanent snow survey stations at each site. This sampling intensity was based on power analysis of pilot survey data from the two forest and clearcut sets of sites at Upper Penticton Creek. Sample sizes of 50 or more gave a power of 0.9 or more to detect differences in SWE of 2 to 3 cm between the forest and clearcut, or approximately 10% of the SWE measured in the forest, at an $\alpha = 0.05$ (Winkler and Spittlehouse 1995). In a subsequent analysis of several days of melt data from Mayson Lake, Spittlehouse and Winkler (1996) reported that with 50 samples, only seasonal melt rates that were 50% larger or smaller than those in the forest could be detected with a power of 0.9. These pilot study results clearly indicated the inadequacy of the standard 10-point snow survey method (B.C. Ministry of Environment 1981), used in water supply and flood forecasting, for comparing SWE and snowmelt under forest cover relative to the open. The pilot study results also showed that the sampling requirements were larger for snowmelt than for accumulation. Though the pilot survey provided insight into the amount of sampling necessary to quantify differences in SWE and melt between the two sites, the results reported in both references
should be used with caution, since they apply to the investigation of the pairs of study sites in particular, rather than to multiple cover types or to true replicates.

Since snow measurements involve destructive sampling, to minimize the variability introduced by this procedure all samples were collected in as close proximity as possible, within a 1 m radius of the snow survey station. Based on the repeated SWE measurements, two snowpack characteristics were compared. The first was April 1st SWE, which was assumed to be the maximum amount of water in the snowpack that year. The second variable was the average snowmelt rate over the season. This variable was calculated as the difference between SWE on April 1st and the date when snow covered only half of the area within a 1 m radius of the snow survey point, divided by the number of days between measurements. To contrast the measurements at the two locations and compare the results with work reported in the literature, the ratios of peak SWE or melt rate measured under forest cover to that in the clearcut were also calculated. Additional melt data obtained through the more frequent surveys at the Mayson Lake sites are presented in Chapter 6.

4.2.2 Data Summary and Analysis

Tabular summaries of all SWE and melt rate data were prepared and the data presented graphically as notched box plots (e.g., Figure 4.1). The box outlines the central half of the data set. The top and bottom edges of the box indicate the upper and lower quartiles and the centre of the notch formed by the box sides represents the median. The whiskers show the range of values less than or equal to 1.5 times the interquartile distance. An asterisk indicates an observation outside that range. These plots provide a clear illustration of the data distribution. When two data sets are compared, overlapping notches in the boxes generally indicate that the medians are not statistically different at the 0.05 level (Chambers et al. 1983).

One-way analysis of variance for fixed effects (Neter et al. 1990) was used to determine whether statistically significant differences in SWE and melt could be detected among the sites surveyed at each location. Scheffe’s test was used to identify which pairs of sites were different at each location. Repeated-measures analysis of variance was used to identify whether
consistent differences existed between sites throughout the study period or whether the differences varied from year to year (Neter et al. 1990). All statistical analyses were completed using SYSTAT 6.0 software (SPSS Inc. 1996). Statistical significance for all tests was determined using $\alpha = 0.05$.

Frequency histograms were plotted to visually evaluate the assumption of normality. Levene’s test (Wilkinson et al. 1996) was used to check for homogeneity of variance. In cases where the variances were not equal, data were transformed using logarithmic, power, and inverse normal frequency transformations. The analyses were then re-run and both residual and frequency histogram plots were checked as with the raw data.

4.3 Results and Discussion

Both peak SWE and melt rate data were approximately normally distributed and the errors associated with each set of measurements were independent. Heterogeneity of variance was detected in some of the data from both locations. Neither logarithmic, power, or inverse cumulative frequency distribution transformations resulted in greater homogeneity of variance among the sites surveyed. Since fixed effects analysis of variance (and Scheffe’s multiple comparison procedure) is robust against the effects of unequal variance on inferences using the F-distribution when sample sizes are large and approximately equal (Neter et al. 1990), as in this study, and since the transformations did not reduce the heterogeneity in variance among sites, the untransformed data were used in all analyses.

4.3.1 Snow Accumulation

Averages and standard deviations of April 1st SWE for each site at Mayson Lake and Upper Penticton Creek, as well as the ratios of SWE in the forest to those in the open, are provided in Table 4.1. Notched box plots of the data illustrate the median and the range of SWE at the study sites, by location and year (Figures 4.1 and 4.2).
Repeated-measures analysis of variance of April 1st SWE values at Mayson Lake and at Upper Penticton Creek showed significant interactions between year and site (Mayson Lake: p=0.000, F=6.922, df(time x site)=6, df(error)=502; Upper Penticton Creek: p=0.000, F=6.920, df(time x site)=8, df(error)=630). Because of these significant interactions, the effects of site on SWE and melt were analysed separately for each year.

At Mayson Lake, April 1st SWE in the clearcut was 30% higher in 1997 than in both 1995 and 1996. At Upper Penticton Creek, SWE in the clearcut was 14 and 24% higher in 1997 than in 1995 and 1996, respectively. April 1st SWE measured at long-term B.C. Ministry of Environment, Lands, and Parks’ (2000) snow survey stations were also higher in 1997 than in the previous two years of this study (Table 4.2). At the Tranquille station near Mayson Lake, SWE was 22% above normal in 1997 and 17% below normal in 1996. At the Greyback Reservoir station near Upper Penticton Creek, snowfall was above normal by 13, 17, and 43% in each of the three years, respectively. This range of conditions provided an opportunity to compare SWE at the study sites during years of both normal and above-normal snowfall. Data from the long-term stations indicated 4 to 8 cm higher SWE in the Upper Penticton Creek area than at Mayson Lake during the study period. However, the long-term normal values are equal at the two locations.

The results of fixed effects one-way analysis of variance showed significant differences in April 1st SWE among sites at Mayson Lake and among sites at Upper Penticton Creek in every year of the study (Table 4.3). The size of the differences varied substantially from year to year, but the largest differences did not coincide with the years of above normal snowfall. This was thought to be a result of an upper limit to the interception capacity of the forest canopies (Harestad and Bunnell 1981; Hedstrom and Pomeroy 1998).

At Mayson Lake, April 1st SWE in the clearcut was significantly different from that in the mature spruce-fir stand, in each of the three study years. Differences in SWE ranged from 6 to 9 cm, or 37 to 75% higher in the clearcut (Figure 4.1). SWE measured in the clearcut was also significantly larger (by 11 to 40%) than both juvenile stands in all years, with the exception of the juvenile-unthinned stand in 1996 (only 8% higher in the clearcut). No significant differences
Table 4.1. April 1st SWE and the ratio of SWE in the mature or juvenile stands relative to that in the clearcut (FOSWE) at Mayson Lake and Upper Penticton Creek.

<table>
<thead>
<tr>
<th>Location and Forest Cover</th>
<th>Mean (Standard Deviation)</th>
<th>Three Year Average (cm)</th>
<th>1995</th>
<th>1996</th>
<th>1997</th>
<th>FOSWE</th>
<th>1995</th>
<th>1996</th>
<th>1997</th>
<th>Three Year Average FOSWE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mayson Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>21 (4.1)</td>
<td>20 (3.7)</td>
<td>26 (3.0)</td>
<td>22</td>
<td></td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>12 (4.2)</td>
<td>14 (4.0)</td>
<td>19 (4.0)</td>
<td>15</td>
<td></td>
<td>0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Juvenile pine</td>
<td>15 (5.3)</td>
<td>18 (5.0)</td>
<td>23 (5.1)</td>
<td>19</td>
<td></td>
<td>0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Juvenile thinned pine</td>
<td>17 (4.1)</td>
<td>17 (3.8)</td>
<td>24 (4.5)</td>
<td>19</td>
<td></td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td><strong>Upper Penticton Creek</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>37 (4.5)</td>
<td>33 (4.5)</td>
<td>41 (6.5)</td>
<td>37</td>
<td></td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Mature pine</td>
<td>31 (3.1)</td>
<td>31 (3.5)</td>
<td>37 (5.0)</td>
<td>33</td>
<td></td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>30 (4.6)</td>
<td>28 (4.3)</td>
<td>35 (5.0)</td>
<td>31</td>
<td></td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>23 (6.9)</td>
<td>22 (5.3)</td>
<td>26 (7.9)</td>
<td>24</td>
<td></td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Juvenile spruce-fir</td>
<td>29 (3.9)</td>
<td>30 (4.6)</td>
<td>37 (3.4)</td>
<td>32</td>
<td></td>
<td>1.0</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.1. April 1st snow water equivalent (SWE) over three years, in a clearcut (CC), juvenile pine stand (J), juvenile-thinned pine stand (JT), and a mature spruce-fir stand (MF) at Mayson Lake.
Figure 4.2. April 1st snow water equivalent (SWE) over three years, in a clearcut (240-CC) and a mature pine stand (240-MF) at 240 Creek, and in a clearcut (D-CC), a mature spruce-fir stand (D-MF), and a juvenile spruce-fir stand (D-J) at Dennis Creek.
Table 4.2. A comparison of April 1st snow water equivalent (SWE) at the study locations and the Tranquille Lake and Greyback Reservoir long-term B.C. Ministry of Environment, Lands, and Parks snow survey stations, and normals for long-term stations.

<table>
<thead>
<tr>
<th>Location and Snow Course</th>
<th>Elevation (m)</th>
<th>1995 (% of normal)</th>
<th>1996 (% of normal)</th>
<th>1997 (% of normal)</th>
<th>Normal (cm)</th>
<th>Years of Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayson Lake Clearcut</td>
<td>1200</td>
<td>20</td>
<td>20</td>
<td>26</td>
<td>23</td>
<td>46</td>
</tr>
<tr>
<td>Tranquille Lake</td>
<td>1420</td>
<td>22 (96)</td>
<td>19 (83)</td>
<td>28 (122)</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Upper Penticton Creek</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240 Creek Clearcut</td>
<td>1600</td>
<td>37</td>
<td>33</td>
<td>41</td>
<td>23</td>
<td>43</td>
</tr>
<tr>
<td>Dennis Creek Clearcut</td>
<td>1600</td>
<td>30</td>
<td>28</td>
<td>35</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Greyback Reservoir</td>
<td>1550</td>
<td>26 (113)</td>
<td>27 (117)</td>
<td>33 (143)</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3. Analysis of variance results comparing April 1st SWE, by year, at Mayson Lake and Upper Penticton Creek.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayson Lake</td>
<td>1995</td>
<td>3</td>
<td>252</td>
<td>44.159</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>3</td>
<td>252</td>
<td>22.538</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>252</td>
<td>32.754</td>
</tr>
<tr>
<td>Upper Penticton Creek</td>
<td>1995</td>
<td>4</td>
<td>315</td>
<td>70.554</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>4</td>
<td>315</td>
<td>56.620</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>4</td>
<td>315</td>
<td>65.713</td>
</tr>
</tbody>
</table>
in April 1st SWE were measured between the two juvenile stands in any of the three years. Differences between the juvenile stands and the clearcut varied from 2 to 6 cm, respectively, depending on year. This amounted to an average reduction in April 1st SWE of 14% in the juvenile stands compared to the clearcut. However, SWE was still 27% higher in the juvenile stands than in the mature spruce-fir stand. This indicated a 43% recovery, or return towards pre-logging SWE in the juvenile stands at Mayson Lake.

At Upper Penticton Creek, April 1st SWE in both mature stands was significantly different from that in adjacent clearcuts in all years. Differences in April 1st SWE varied from 7 to 9 cm, or 27 to 35%, higher in the clearcut than in the mature spruce-fir stand (Figure 4.2). Much smaller differences, only 2 to 6 cm (6 to 19%), were measured between the clearcut and the mature pine stand. SWE in the juvenile stand at Upper Penticton Creek was also significantly larger (26 to 42%) than that in the spruce-fir stand, but not larger than that in the clearcut. Since April 1st SWE in the juvenile stand was equal to or slightly greater than in the clearcut, depending on the year, these data suggested that there has been no reduction in peak snow accumulation as a result of forest regrowth in this juvenile stand.

The ratios of average forest to clearcut SWE were 0.7 and 0.8 for the mature spruce-fir stands at Mayson Lake and Upper Penticton Creek, respectively, and 0.9 for the pine stand. The ratios of juvenile pine to clearcut SWE averaged 0.8 at Mayson Lake. At Upper Penticton Creek, on the other hand, the average ratio of juvenile spruce-fir to clearcut was 1.1. It is also interesting to note that SWE in the clearcut at 240 Creek was 5 to 7 cm, or 19%, higher than SWE in the clearcut at Dennis Creek, indicating that at the same elevation and within distances as small as 5 km, the effects of location can be as large as those related to forest cover.

The results of the clearcut and forest comparisons of April 1st SWE at Mayson Lake and Upper Penticton Creek fall within the range of those generally described in the literature (Table 2.1). The ratios of forest to clearcut SWE found in this study range from 0.7 to 0.9. The smallest ratios, or the biggest differences, both in the literature and in this study, were recorded in the spruce-fir stand and clearcut rather than in pine stands. This research, which included case
studies of both forest types in similar environments, demonstrated that the differences in the April 1st SWE between the clearcut and spruce-fir stands (27 and 47% on average) were substantially larger than for the pine stand (12% on average).

The smaller differences in April 1st SWE observed in the mature pine and clearcut comparison relative to the mature spruce-fir stands were thought to be related to differences in stand structure. The stand characteristics having the largest influence on snow interception are winter leaf area, canopy cover, and canopy structure (Hedstrom and Pomeroy 1998) (Chapter 2). In this study, the mature pine stand had a uniform single-layered canopy, whereas both mature spruce-fir stands were multi-layered with openings between groups of trees. The latter stand type was thought to provide a larger intercepting surface area from which snow could sublimate, resulting in smaller accumulations on the ground by April 1st. Schmidt and Troendle (1992) found that all of the snow intercepted by a dense conifer canopy, up to 30% of the total snowfall, sublimated. In the study area, intercepted snow was generally not observed to slide off branches and fall to the snowpack surface but rather was lost directly from the canopy. Further, intercepted snow did not melt and drip to the snowpack surface during the snow accumulation period. This effect was only observed following fresh snowfall during the peak melt period. Similar differences in forest versus clearcut snow accumulation comparisons were noted by Pomeroy and Goodison (1997) who found larger accumulations of snow under jack pine than black spruce stands, a result of the somewhat higher interception efficiency related to increased leaf area in the spruce stand (Hedstrom and Pomeroy 1998).

This study also indicated that SWE in the juvenile stands were more like those in the clearcut than in the mature stands. In the only other snow research found that included juvenile forest types, Hardy and Hansen-Bristow (1990) reported that maximum SWE in a 4 m tall juvenile stand was identical to that in an open meadow.

4.3.2 Average Snowmelt

Snowmelt rates at both Mayson Lake and Upper Penticton Creek ranged from an average of 0.4 cm d\(^{-1}\) in the spruce-fir stands to a maximum of 1 cm d\(^{-1}\) in the clearcut at Mayson Lake.
(Table 4.4; Figures 4.3 and 4.4). As with SWE, repeated-measures analysis of variance of the seasonal average melt rates at Mayson Lake and Upper Penticton Creek showed a significant interaction between site and year, indicating that differences between sites varied depending on the year (Mayson Lake: p=0.000, F=19.605, df(time x site)=6, df(error)=502; Upper Penticton Creek: p=0.000, F=17.572, df(time x site)=8, df(error)=630). Because of this interaction, data from each year of the study were analysed separately. One-way analysis of variance for fixed effects by year showed that some of the observed differences in snowmelt rates were statistically significant (p=0.000) (Table 4.5).

Using Scheffe’s test, statistically significant differences in melt rates were found between the clearcuts and adjacent mature stands, in all years. The differences between melt rates in the spruce-fir stand and in the clearcut were larger at Mayson Lake than at Upper Penticton Creek (Table 4.4). At Mayson Lake, the average melt rate in the clearcut was 0.58 cm d $^{-1}$ higher (141%) than that in the spruce-fir stand (Figure 4.3). At Upper Penticton Creek, the average snowmelt rate in the clearcut was 0.2 cm d $^{-1}$ higher (38%) than in the pine stand and 0.25 cm d $^{-1}$ higher (62%) than in the spruce-fir stand (Figure 4.4). The average ratios of forest to clearcut melt rates were 0.4 and 0.6 for the mature spruce-fir stands at Mayson Lake and Upper Penticton Creek, respectively, and 0.7 for the mature pine stand. The literature suggests that melt rates in the forest may be reduced by 25 to 40% relative to those in the clearcut (Gray and Prowse 1993). Snowmelt rates in the mature stands included in this study were 30 to 60% slower than those in the clearcut. The local results indicate larger potential effects of forest cover removal than suggested in the literature. These findings may be a result of local conditions or of the more frequent sampling schedule used in this study providing a better estimate of snowpack depletion.

Melt rates in the juvenile stands at Mayson Lake were significantly different from those in the mature spruce-fir stand in all three years of the study. Melt rates in the juvenile-thinned stand were from 0.41 to 0.7 cm d $^{-1}$ higher than those in the mature stand, and from 0.28 to
Table 4.4. Average snowmelt rates and the ratio of melt rates in the mature and juvenile stands relative to that in the clearcut (FOMR) at Mayson Lake and Upper Penticton Creek.

<table>
<thead>
<tr>
<th>Location and Forest Cover</th>
<th>Mean (Standard Deviation) 1995(cm d(^{-1}))</th>
<th>1996(cm d(^{-1}))</th>
<th>1997(cm d(^{-1}))</th>
<th>Three Year Average (cm d(^{-1}))</th>
<th>1995</th>
<th>1996</th>
<th>1997</th>
<th>Average FOMR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mayson Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>0.83 (0.16)</td>
<td>1.32 (0.25)</td>
<td>0.81 (0.10)</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>0.35 (0.11)</td>
<td>0.47 (0.30)</td>
<td>0.40 (0.07)</td>
<td>0.41</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Juvenile pine</td>
<td>0.77 (0.21)</td>
<td>1.02 (0.26)</td>
<td>0.68 (0.16)</td>
<td>0.82</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Juvenile thinned pine</td>
<td>0.78 (0.19)</td>
<td>1.17 (0.29)</td>
<td>0.81 (0.13)</td>
<td>0.92</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Upper Penticton Creek</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>0.80 (0.09)</td>
<td>0.59 (0.08)</td>
<td>0.76 (0.11)</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mature pine</td>
<td>0.54 (0.05)</td>
<td>0.44 (0.05)</td>
<td>0.59 (0.10)</td>
<td>0.52</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Clearcut</td>
<td>0.66 (0.10)</td>
<td>0.50 (0.07)</td>
<td>0.78 (0.11)</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>0.44 (0.10)</td>
<td>0.32 (0.07)</td>
<td>0.43 (0.13)</td>
<td>0.40</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Juvenile spruce-fir</td>
<td>0.65 (0.09)</td>
<td>0.56 (0.09)</td>
<td>0.76 (0.10)</td>
<td>0.66</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Figure 4.3. Average melt rates over three years, in a clearcut (CC), a juvenile pine stand (J), a juvenile-thinned pine stand (JT), and a mature spruce-fir stand (MF) at Mayson Lake.
Figure 4.4. Average melt rates over three years, in a clearcut (240-CC) and a mature pine stand (240-MF) at 240 Creek, and in a clearcut (D-CC), a mature spruce-fir stand (D-MF), and a juvenile spruce-fir stand (D-J) at Dennis Creek.
Table 4.5. Results of analysis of variance comparing average snowmelt rates by year at the Mayson Lake and Upper Penticton Creek study sites.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Site</th>
<th>df</th>
<th>Error</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayson Lake</td>
<td>1995</td>
<td>3</td>
<td>252</td>
<td></td>
<td>109.757</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>3</td>
<td>252</td>
<td></td>
<td>114.896</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>252</td>
<td></td>
<td>163.072</td>
<td>0.000</td>
</tr>
<tr>
<td>Upper Penticton Creek</td>
<td>1995</td>
<td>4</td>
<td>315</td>
<td></td>
<td>153.461</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>1996</td>
<td>4</td>
<td>315</td>
<td></td>
<td>131.452</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>4</td>
<td>315</td>
<td></td>
<td>117.113</td>
<td>0.000</td>
</tr>
</tbody>
</table>

0.55 cm d\(^{-1}\) higher in the juvenile-unthinned stand. No significant differences in melt rates were observed between the juvenile-thinned stand and clearcut in all years, or between the juvenile stand and clearcut in 1995. In 1996 and 1997, melt rates in the juvenile-unthinned stand were 7 to 23% slower than those in the clearcut. In 1997, the average melt rate in the juvenile-unthinned stand was significantly lower than that in the thinned stand by 0.13 cm d\(^{-1}\) or 16%. Melt rates in the juvenile spruce-fir stand at Upper Penticton Creek were larger than those in the mature spruce-fir stand in all years, by 0.26 cm d\(^{-1}\) on average, but were not different from those measured in the clearcut, except in 1996 when they were 0.06 cm d\(^{-1}\) higher.

The ratios of mature forest to clearcut melt rates in this study, and those reported in the literature, varied from 0.4 to 0.8. The ratios of juvenile stand to clearcut melt rates were 0.8 to 0.9 at Mayson Lake and 1.0 to 1.1 at Upper Penticton Creek. In Table 2.1, melt rates from the literature for clearcuts ranged from one to 2.3 times those in the forest. In this investigation, melt rates in the clearcuts were 2.4 and 1.6 times those in the mature spruce-fir stands at Mayson Lake and Upper Penticton Creek, respectively. Melt rates in the clearcut were 1.4 times larger than those in the pine stand (Table 4.4). Melt rates were reduced by less than 0.1 cm d\(^{-1}\) in the juvenile-thinned and by 0.17 cm d\(^{-1}\) in the juvenile-unthinned stand (10% and 17%), relative to the clearcuts. The differences between the juvenile stands at Mayson Lake are
likely a result of differences in stand characteristics produced by thinning and pruning. Melt rates in the juvenile spruce-fir stand were identical to those in the clearcut. Hardy and Hansen-Bristow (1990) reported that melt rates were reduced by 0.2 cm d\(^{-1}\) (20\%) in a stand of 10 to 14 m tall lodgepole pine. These results indicate that juvenile stands, such as those included in this investigation, have a small effect on snowmelt rates relative to the open.

The snowpack depletion periods for each site and year are shown in Table 4.6. The snowpack in the juvenile stands melted within five days of that in the clearcuts at both Mayson Lake and Upper Penticton Creek. The snowpack depletion period was 5 to 15 days longer in the mature stands than in the clearcuts, depending on year. No difference in the range of melt periods over the three years, or the average of 11 days over the study, was observed between the pine and spruce-fir stands at Upper Penticton Creek. This is likely the result of the higher April 1st SWE in the mature pine combined with the increased melt rate relative to the mature spruce. The effects of covariance in SWE and snowmelt have also been shown by Faria et al. (2000).

### Table 4.6. Days of snowmelt in the mature, juvenile, and clearcut stands at Mayson Lake and Upper Penticton Creek.

<table>
<thead>
<tr>
<th>Location and Forest Cover</th>
<th>Mean (Standard Deviation)</th>
<th>Three Year Average (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1995(days)</td>
<td>1996(days)</td>
</tr>
<tr>
<td><strong>Mayson Lake(^1)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>25 (2)</td>
<td>18 (2)</td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>33 (8)</td>
<td>35 (12)</td>
</tr>
<tr>
<td>Juvenile pine</td>
<td>20 (7)</td>
<td>22 (8)</td>
</tr>
<tr>
<td>Juvenile thinned pine</td>
<td>22 (4)</td>
<td>18 (4)</td>
</tr>
<tr>
<td><strong>Upper Penticton Creek(^2)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>46 (6)</td>
<td>56 (2)</td>
</tr>
<tr>
<td>Mature pine</td>
<td>58 (0)</td>
<td>70 (2)</td>
</tr>
<tr>
<td>Clearcut</td>
<td>47 (6)</td>
<td>56 (2)</td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>52 (8)</td>
<td>68 (6)</td>
</tr>
<tr>
<td>Juvenile spruce-fir</td>
<td>46 (6)</td>
<td>54 (7)</td>
</tr>
</tbody>
</table>

1 sampled every 3 days
2 sampled every 2 weeks
The differences in melt rates among the study sites were thought to correspond to differences in the energy available at the snowpack surface as a result of varying forest structures. Metcalfe and Buttle (1998) found an exponential relationship between snowmelt and canopy gap fraction in a boreal black spruce stand. Faria et al. (2000) reported that snow disappearance in a clearcut and in a medium density jack pine stand preceded that in a high density black spruce stand by 12 days. Toews and Gluns (1986) reported that snow disappeared 8.5 days earlier on average in a clearcut than in the mature forest in south-eastern B.C. The relationships between snowmelt, stand structure, and meteorological conditions in the stands at Mayson Lake are discussed in the remaining chapters of this thesis.

4.4 Conclusions

The results of this research confirm that significant changes in snow accumulation and melt rate can be expected with forest cover removal in south-central B.C. The results also indicate that the reduction in SWE following removal of a pine stand, such as that at Upper Penticton Creek, will be less than following the removal of the spruce-fir stand types studied. On average, 32 and 23% less April 1st SWE was found in the spruce-fir stands at Upper Penticton Creek and Mayson Lake, respectively, and 11% less in the mature pine stand than in the clearcuts. At Mayson Lake, average snowmelt rates in the mature spruce-fir were 0.4 times those in the clearcut. At Upper Penticton Creek, melt rates in the mature spruce-fir and mature pine stands were 0.6 and 0.7 times those in the clearcut, respectively. The snowpack disappeared from five to 17 days earlier in the clearcuts than in the mature stands, depending on year.

April 1st SWE in both juvenile pine stands and the juvenile spruce-fir stands were 14 and 0% less than in the clearcuts, respectively. Snowmelt rates in the juvenile pine and juvenile-thinned pine stands were 0.8 and 0.9 times those in the clearcut at Mayson Lake, respectively. No differences in melt rate were observed between the juvenile spruce-fir stand and clearcut at Upper Penticton Creek. The snowpack disappeared from two days earlier to five days later in the juvenile stands than in the clearcut, depending on year, and from two to four days earlier in the juvenile-thinned than juvenile stand. On average over the three years, April 1st SWE
‘recovery’ was 43% in both juvenile pine stands. Snowmelt ‘recovery’ was 13 and 29% in the juvenile-thinned and juvenile pine stand, respectively. No recovery was observed in the juvenile spruce-fir stand.

The results of field studies such as this provide data essential to watershed model calibration and the development of forest practices guidelines. Understanding the mechanisms through which the differences in SWE and melt rate among forest types occur, including stand characteristics and meteorological conditions, will enable broader interpretation of the results. A detailed investigation of the relationships between stand characteristics and the snow accumulation and melt results follows in Chapter 5.
CHAPTER 5

LINKING SNOW TO STAND CHARACTERISTICS

5.1 Introduction

Snow accumulation and melt vary with elevation, aspect, topography, vegetation, and weather. At a specific location, both processes are influenced by characteristics of the site, with forest cover as a dominant factor. In B.C., most domestic, irrigation, and industrial water originates in forested watersheds. The ever-increasing demand for water has focused the attention of both resource managers and the public on how the amount and delivery of water from these watersheds may be affected by changes in forest cover. Forest cover is removed for agriculture, grazing, mining, urbanization, lumber production, and other land uses, and is also altered through natural processes such as fire, insects, and disease. Such changes in forest cover may be permanent or temporary depending on forest establishment success and the rate of regrowth. The extent and degree of forest removal, or of forest regrowth, along with the meteorological conditions, influence the hydrologic effects of these changes.

In B.C.’s watershed assessment procedure (B.C. Ministry of Forests 1999), spring peak streamflows and forest cover are linked using the concept of “hydrological recovery”. Hydrological recovery is defined as “the process by which regeneration restores the hydrology of an area to pre-logging conditions” (B.C. Ministry of Forests 1999, p.26). It further explains that complete recovery involves all components of the hydrologic cycle but “because peak flows in ... interior ... areas tend to be generated by conditions or radiation snowmelt ... snowpack recovery is used as an index of true hydrological recovery”. Snowpack recovery is evaluated by the average tree height of the main canopy, a variable that is readily obtainable through the forest inventory system. Though average tree height provides some indication of snow interception and shade, it does not necessarily reflect crown surface area, canopy density, winter leaf area, and stem distribution or canopy gaps, stand characteristics known to influence snowpack processes (Chapter 2). Quantifying the relationships between forest inventory
variables and snowpack processes for forest planning purposes is the focus of ongoing research throughout the province.

Forest vegetation affects snow deposition, snow redistribution, and the exchange of energy to the snow surface (Chapter 2). Compared to open ground or low growing forms of vegetation, forests have large intercepting and radiating surface areas. For example, the surface area of a boreal spruce-fir canopy has been approximated as 1800 times larger than that of snow on the ground (Pomeroy and Schmidt 1993). Consequently, conversion from one cover type to another could have a large influence on snow interception, SWE on the ground, and radiant energy transfer to the snow surface (McKay and Gray 1981).

The structure of physical characteristics of a forest vary with species composition, site, age, stand health, and silvicultural treatments. Operationally, stands are commonly described by variables such as tree height, stem density, crown volume, and canopy closure (Oliver and Larson 1996), and in research by winter leaf area and canopy gap fraction (Metcalfe and Buttle 1998). The variation in structure among stands is generally assumed to contribute, either directly or indirectly, to the differences in snowpack processes beneath them.

Many studies have attempted to quantify relationships between forest characteristics and SWE or snowmelt. Based on a summary of the literature, McKay and Gray (1981) suggested that an inverse relationship exists between SWE and canopy density, making density a possible predictor of interception differences among forest types. They further suggested that canopy surface area affects energy transfer to the snow surface and may be a useful predictor of snowmelt. Lull and Rushmore (1960) found a 1 mm per degree-day decrease in snowmelt rate per 10% increase in crown closure. Packer (1971) reported a 7 mm decrease in daily snowmelt per 10% increase in canopy density on south facing slopes, and a 4 mm decrease on north aspects.

Meiman et al. (1968) suggested that canopy density was a useful index of SWE on the ground, reporting that the literature showed 8 to 56 mm increases in SWE for every 10% decrease in
canopy density, depending on the tree species. More recently, Moore and McCaughey (1997) found a 6.4% decrease in peak SWE per 10% increase in canopy density. They also reported a better correlation between canopy density and peak SWE under spruce-fir forests than under pine, and suggested that other forest-structure variables not measured in their study may also be influencing SWE. Pomeroy and Goodison (1997) reported a more or less linear decrease in the accumulation of SWE with increasing leaf area and noticeable differences in leaf area between stands of different species. SWE were highest under aspen (*Populus tremuloides* Michx.), less under jack pine (*Pinus banksiana* Lamb.) and least under black spruce (*Picea mariana* (Mill.) B.S.P.). Metcalfe and Buttle (1998) found an exponential increase in snowmelt rates with increasing canopy gap fraction in boreal stands. Using basal area as the measure of stand structure, Hansen (1969) reported a 2% increase in SWE per approximately 2 m$^2$ ha$^{-1}$ reduction in basal area.

Bunnell *et al.* (1985) reviewed North American forest-snow research from 1921 to 1975 to identify relationships between canopy cover and apparent snow interception. Several conclusions from their review are particularly important including that:

1. the effectiveness of forest canopies at intercepting snow, during a single storm and over the winter, decreased with snowfall, particularly in stands composed of species with flexible, pendant branches;
2. the ideal crown for snow interception was healthy, dense, long, and made of inflexible, horizontal branches;
3. during heavy snowfall, branch flexibility was more important than crown length (they reported that coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was 45 to 65% more efficient at intercepting snow than western white pine (*Pinus monticola* Dougl.);
4. the high branch flexibility and height-to-base ratios of young plantations made them inefficient interceptors of snow;
5. two storied coastal B.C. stands reduced snow on the ground by 20 to 30% over single storied stands; and
6. where crown closure was near or more than 40%, stands having few trees with deep crowns intercepted more snow than dense stands with shallow crowns.

Metcalfe and Buttle (1998) caution that processes such as snow redistribution, interception and sublimation are complex, so that snow accumulation cannot necessarily be easily related to canopy characteristics.

As background to the investigation described in this chapter, the results of forest-snow interaction research in forested environments similar to those found in south-central B.C. are summarized in Table 5.1. The authors cited in Table 5.1 quantified differences in SWE and melt under forest cover relative to the open, but did not attempt to correlate their results with stand characteristics. Their snow measurements have been standardized as the ratios FOSWE and FOMR, as described in Chapter 4, to reduce the effects of both the weather and location. The findings in Table 5.1 do not show any relationship between elevation or aspect and FOSWE or FOMR. Most of the studies were located on level terrain to minimize the variability associated with site position. The upper and most frequent values in the ranges of FOSWE indicated that spruce-fir stands may have slightly larger effects on snow accumulation than pine. Only five studies provided sufficient information to calculate FOMR. The differences in these ranges of FOMR between pine-open (0.3 to 0.5) and spruce-fir-open (0.6 to 0.8) comparisons are large. The differences in FOSWE and FOMR between these forest types is thought to be related to stand structure.
Table 5.1. Maximum snow water equivalent (SWE) and average melt rates (MR), summarized as the ratio of measurements under forest cover to those in the open (FO), and stand characteristics cited for snow research in forests similar to those in southern B.C.

<table>
<thead>
<tr>
<th>Author(s) (Year)</th>
<th>Location</th>
<th>FOSWE</th>
<th>FOMR</th>
<th>Elevation (m)</th>
<th>Aspect</th>
<th>Slope (%)</th>
<th>Species</th>
<th>Stems per Hectare</th>
<th>Diameter (cm)</th>
<th>Basal Area (m² ha⁻¹)</th>
<th>Height (m)</th>
<th>Crown Closure (%)</th>
<th>Crown Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Church (1912)</td>
<td>Nevada</td>
<td>1</td>
<td>0.7</td>
<td>1900</td>
<td>level</td>
<td>level</td>
<td>pine, fir</td>
<td>5</td>
<td>9</td>
<td>0.9</td>
<td>0.5</td>
<td>fir</td>
<td></td>
</tr>
<tr>
<td>Connaughton (1935)</td>
<td>Idaho</td>
<td>0.7</td>
<td>0.6</td>
<td>49max</td>
<td></td>
<td></td>
<td>pine</td>
<td>0.7</td>
<td>0.4</td>
<td>1</td>
<td>0.7</td>
<td>regen.</td>
<td>&lt;8yrs</td>
</tr>
<tr>
<td>Rosa (1956)</td>
<td>Idaho</td>
<td>0.7</td>
<td>0.6</td>
<td>1700</td>
<td></td>
<td></td>
<td>pine</td>
<td>0.8</td>
<td>1830</td>
<td>pine</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Idaho,Wyoming</td>
<td>0.8</td>
<td>2040</td>
<td></td>
<td></td>
<td></td>
<td>pine</td>
<td>0.8</td>
<td>2350</td>
<td>spruce-fir</td>
<td>30</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Utah</td>
<td>0.5</td>
<td>2320</td>
<td></td>
<td></td>
<td></td>
<td>spruce</td>
<td>0.5</td>
<td>2320</td>
<td></td>
<td>37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miner and Trappe (1957)</td>
<td>Oregon</td>
<td>0.4</td>
<td>north</td>
<td>1728</td>
<td></td>
<td></td>
<td>pine</td>
<td>0.4</td>
<td>0.4</td>
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Table 5.1 (con’t). Maximum snow water equivalent (SWE) and average melt rates (MR), summarized as the ratio of measurements under forest cover to those in the open (FO), and stand characteristics cited for snow research in forests similar to those in southern B.C.

<table>
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<th>FOSWE</th>
<th>FOMR</th>
<th>Elevation (m)</th>
<th>Aspect</th>
<th>Slope (%)</th>
<th>Forest Cover</th>
<th>Stems per Hectare</th>
<th>Diameter (cm)</th>
<th>Basal Area (m² ha⁻¹)</th>
<th>Height (m)</th>
<th>Crown Closure (%)</th>
<th>Crown Ratio (%)</th>
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</tbody>
</table>

1 lodgepole pine (<i>Pinus contorta</i> Doug.), 2 Scots pine (<i>Pinus sylvestris</i> L.), 3 Engelmann spruce (<i>Picea engelmannii</i> Parry), 4 subalpine fir (<i>Abies lasiocarpa</i> (Hook.) Nutt.), 5 not cited
Table 5.2 summarizes the results of work where canopy characteristics were correlated with SWE or melt, but that did not necessarily compare forested sites to clearcut areas. The most common forest-structure variables measured as predictors of SWE and melt were basal area (3 out of 6 studies) and canopy density (6 out of 8) (Table 5.2). Only three of the studies dealt with snowmelt. Of these, only two provided comment regarding the proportion of the variation in melt explained by individual canopy variables. Of the standard forest inventory variables, canopy density seemed to explain the greatest percentage (48 to 62%) of the variation in SWE (Table 5.2). Lull and Rushmore (1960) found 76% of the variation in melt could be explained by canopy density. Hudson (2000) concluded that the average height of the dominant and codominant trees in a stand was a useful index to a variable termed ‘recovery’ (the relative difference in accumulation and melt combined between mature and juvenile forest types compared to a clearcut). He reported that dominant and codominant tree height accounted for 48% of the variation in the recovery index. Metcalfe and Buttle (1998) found that canopy gap fraction, available for their research area, explained 92 to 94% of the variation in snowmelt in a boreal forest.

Researchers have found that using forest-structure variables to predict SWE or melt was more promising at the stand rather than plot level and over broad differences in stand characteristics. The variability in SWE at the plot level from one sampling period to the next often masks differences attributable to smaller variations in forest-structure, such as among juvenile stands or among similar stands. The work of Wood et al. (1988) and Woods et al. (1995) suggests that the smallest area representative of the continuum (a representative elementary area) can be determined to identify the most appropriate spatial scale at which to quantify hydrologic processes. The scale at which forest cover affects snow accumulation and melt in different stand types is not known.

Using the literature to develop quantitative relationships between stand structure and snowpack variables for south-central B.C., has not been successful. This difficulty is, in part, because of the diversity in forest types under which that research was conducted, and also because of the wide variation in measurement, analysis, and reporting techniques. For example, the pine stands studied by Hart (1963) had dense canopies with 83 to 90% crown closure. These crown closures are substantially higher than those common throughout south-central B.C. where the maximum is much
Table 5.2. A summary of research correlating forest canopy characteristics with maximum snow water equivalent (SWE) or snowmelt rate (*√* indicates variables considered; * indicates variables in final correlations; a range of coefficients of determination (multiple \(R^2\); single \(r^2\)) shows the annual variability in results).

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<th>Aspect</th>
<th>Slope</th>
<th>Species</th>
<th>Stems</th>
<th>Basal Area (BA)</th>
<th>Crown Cover (CC)</th>
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Table 5.2 (con’t). A summary of research correlating forest canopy characteristics with maximum snow water equivalent (SWE) or snowmelt rate (√ indicates variables considered; * indicates variables in final correlations; a range of coefficients of determination (multiple $R^2$; single $r^2$) shows the annual variability in results).

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<th>Aspect</th>
<th>Slope</th>
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<th>Stems</th>
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</tbody>
</table>

(Y = both SWE and melt) CC 0.48 Crown Height 0.48
lower (e.g., 40 to 54% at the sites investigated in this study). Rarely has research included multiple canopy variables, repeated measurements, or diverse forest types. The specific stand and snowpack characteristics considered in these studies presumably represented the research objectives, available resources, and the forestry interests or backgrounds of the researchers. Many studies have focused on snow depth rather than on SWE, which is the variable of interest to hydrologists. Very few papers describe attempts to correlate stand characteristics with snowmelt. Other researchers also did not standardize snow measurements, to minimize the effects of conditions specific to their study area, complicating the extrapolation of the results to other locations. Researchers most successful in developing relationships between stand structure and snow accumulation or melt used variables such as winter leaf area or canopy gap fraction (Metcalf and Buttle 1998), variables not measured operationally and, therefore, not available for forest development planning.

The identification of forest inventory variables that could be used to predict the relative differences in peak SWE and average melt rates under forest cover of different species, stand structures, and stages of regrowth would be invaluable in forest development planning. This information would also be useful in improving the snowmelt runoff simulation components of the hydrologic models, such as DHSVM (Wigmosta et al. 1994), currently being tested for B.C. wildland conditions (Beckers et al. 2000; Whitaker et al. 2000).

The objective of the investigation described in this chapter was to identify forest inventory variables that could be used to predict relative changes in peak SWE and average melt rate with the removal or regrowth of several forest types common to south-central B.C. It incorporates the measurements of both April 1st SWE and melt rate repeated over three years, as described in Chapter 4. The investigation of relationships between snowpack and forest inventory variables in this research included juvenile stands at each study location.
5.2 Methods

5.2.1 Field Measurements

This investigation was undertaken at both the Mayson Lake and Upper Penticton Creek study locations described in Chapter 3. Snow accumulation and melt data were collected at 64 survey points at each of the nine study sites, during the spring of 1995, 1996, and 1997, spaced in a 15 by 15 m grid covering approximately 1 ha. Snow measurements at each survey point were made within a 1 m radius of the station marker, using a standard Federal snow tube. Snow measurements were made in early March, mid-March, April 1st and then every three to four days at Mayson Lake and every two weeks at Upper Penticton Creek, through the snowmelt period. Maximum SWE was represented by the April 1st measurement and melt rates were calculated over the period beginning on April 1st, until the date when snow covered only half of the area within a 1 m radius of each snow survey point. Detailed descriptions of snow survey procedures and sampling techniques, as well as of the differences in April 1st SWE and melt rates at each study site, were provided in Chapter 4.

Tree and stand characteristics were measured at each snow survey sample point in 1996. Stand characteristics did not change during the three-year study period. The juvenile trees added less than a metre to their height and the mature stands were not modified by insect, disease or blowdown during the study. Each snow survey station marker indicated the centre of a 4 m radius plot (0.005 ha) within which all trees, 1 m in height or taller, were measured. With this sampling intensity, trees were measured in 33% of the 1 ha area. Tree and stand characteristics were described by forest inventory variables, or variables that could be calculated from them, in three broad groups representing the species mix, stem, and canopy. The species mix was thought to reflect general tree form and distribution. The stem descriptors were intended to represent stand structure, density, and stage of development. The canopy variables represented the depth, volume, and extent of foliage in the stand. Species, condition (live or snag), diameter outside bark at breast height (dbh; 1.3 m above
ground), height, height to live crown, and crown radius were noted for each tree. Basal area, crown length, crown base area, and crown volume were then calculated for each tree.

Tree height (m) of the mature stands was measured using a clinometer and 30 m tape. Heights of the juvenile trees were measured using a height pole. Tree dbhs (cm) were measured with a diameter tape. Basal area per tree (m$^2$) was calculated from the dbh assuming trees were circular in cross-section. Crown length (m) was measured using a clinometer in the same way as tree height. Crown length ($L_c$) (m) was assumed to extend from the top of the tree to the base of the live crown, taken as the lowest whorl of branches with green foliage. Crown ratio (m/m) was calculated as crown length divided by total tree height. Crown radius (m) was measured from the stem to the projected outermost margin of the crown in the four cardinal directions. Crown area ($A_c$) (m$^2$) was then estimated using the average crown radius and calculating the area of a circle with this radius. Crown volume ($V_c$) (m$^3$) was estimated assuming that the crown shape approximated that of a cone (Mawson et al. 1976), and was calculated as:

$$V_c = A_c \cdot L_c / 3 \quad (4)$$

Crown length to crown base area ratio was calculated for each tree as an indicator of the amount of snow intercepting surface (Bunnell et al. 1985).

Crown closure was measured using a “moosehorn”. The moosehorn is constructed of a short length of 7.5 cm diameter plastic pipe. The pipe has an eye-piece at the bottom, an internal mirror and a grid of dots at the top. The moosehorn is held up to the eye and the number of dots falling on open spaces counted. The proportion of dots representing either openings, or crown closure, is then calculated. This instrument has been used by other researchers as a simple method of obtaining consistent estimates of crown closure where narrow angles of view are likely to be the most appropriate (Bunnell and Vale 1990). In this study, dots were counted while facing in each of the four main compass bearings around the snow survey station marker. The results were then averaged and crown closure were reported as a percent.
Individual tree measurements were totalled or averaged, depending on the variable, to obtain values for each plot. The characteristics summarized for each plot were: species mix, total stems, total stems by species, total number of live stems, total number of snags, average tree height, average dbh, total basal area of all species, average height to live crown, average crown length, average crown ratio, total crown base area, average height to base ratio, total crown surface area, total crown volume, and crown closure.

5.2.2 Data Summary and Analysis

The data in this study were analyzed at two scales: for individual plots (576) and as site-averages (9). By considering each plot separately, a much broader range of forest-structures could be represented, providing 384 examples of peak SWE and average melt under forest conditions and 192 clearcut examples. The site averages provided six forest and three clearcut measures.

Individual peak SWE and melt rates for each clearcut and forested plot, and similarly for the average of the snowpack variables for each site, were used to calculate standardized ratios of peak SWE and melt. These standardized ratios of peak SWE and melt rate removed variability related to location so that results from all study locations could be combined. Data for each year were analyzed separately to provide an indication of whether relationships between the forest-structure and snowpack variables changed from year to year.

Peak SWE and melt rate ratios for each plot and site were plotted against all forest-structure variables to identify any relationships. Correlations among independent variables were assessed with Pearson correlation matrices using SYSTAT 6.0 software (SPSS Inc. 1996). Single and multiple linear regression techniques were used to identify significant correlations among snowpack and forest-structure variables. A square-root transformation was applied to the forest-structure variables crown volume and basal area to linearize their relationships with the snowpack variables. Regression analyses were completed using SAS software (SAS
Statistical significance for all tests was determined using $\alpha = 0.01$. Residuals were plotted to visually evaluate the assumptions of normality and homogeneity of variance. Once potential models were selected, residuals were plotted and the ‘best’ model was chosen based on comparison of single or multiple coefficient of determination values, standard errors of the estimate, significance of the F values, and residual plots.

5.3 Results and Discussion

As described in Chapter 4, both peak SWE and average melt rates during this study varied significantly with site and year, probably as a result of forest cover, stage of stand development, meteorological conditions or the interactions among them. The ratios of April 1st SWE in the mature stands and the clearcuts at Mayson Lake and Upper Penticton Creek ranged from 0.7 to 0.9 cm cm$^{-1}$. Larger differences between the mature stands and clearcuts were observed where the predominant species were spruce-fir (FOSWE = 0.7 cm cm$^{-1}$) rather than lodgepole pine (FOSWE = 0.9 cm cm$^{-1}$).

A similar pattern was observed for snowmelt. The juvenile stands of pine and spruce-fir had varying effects on SWE and melt (FOSWE = 0.7 to 1.1 cm cm$^{-1}$ and FOMR = 0.8 to 1.1 cm d$^{-1}$ (cm d$^{-1}$)$^{-1}$). In those years where differences were statistically significant, the results obtained in the juvenile stands were generally much closer to those observed in the clearcut than in the mature stand. In 1996, more snow and more rapid melt were measured in the young spruce-fir stand at Upper Penticton Creek than in the adjacent clearcut.

The inventory of stand characteristics showed differences in tree size, stem density, and extent of canopy, both vertically and horizontally, among sites (Table 5.3). Average stand height in the mature spruce-fir stands at Mayson Lake and Upper Penticton Creek was approximately twice that in the juvenile stands. The average tree height in the pine stand at Upper Penticton Creek was 14.7 m, double that of the average for the spruce-fir stand. Average basal areas in the spruce-fir stands were six and eight times those in the juvenile stands at Mayson Lake and
Table 5.3. Averages and standard deviations (SD) of stand characteristics for the 64 sample points at each of the Mayson Lake and Upper Penticton Creek study stands.

<table>
<thead>
<tr>
<th>Forest Structure Variable</th>
<th>Mayson Lake</th>
<th>Upper Penticton Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Juvenile-thinned Mean (SD)</td>
<td>Mature Forest Mean (SD)</td>
</tr>
<tr>
<td></td>
<td>Juvenile Mean (SD)</td>
<td>Mature Forest Mean (SD)</td>
</tr>
<tr>
<td></td>
<td>Mature Forest Mean (SD)</td>
<td>Juvenile Mean (SD)</td>
</tr>
<tr>
<td>Tree species</td>
<td>pine</td>
<td>pine, spruce-fir</td>
</tr>
<tr>
<td>Total stems per ha</td>
<td>1000 (400)</td>
<td>6400 (1600)</td>
</tr>
<tr>
<td></td>
<td>2600 (1600)</td>
<td>4600 (1800)</td>
</tr>
<tr>
<td>Stems of lodgepole pine per ha</td>
<td>800 (400)</td>
<td>3600 (1200)</td>
</tr>
<tr>
<td></td>
<td>1400 (800)</td>
<td>0 (200)</td>
</tr>
<tr>
<td>Stems of spruce-subalpine fir per ha</td>
<td>200 (200)</td>
<td>400 (1000)</td>
</tr>
<tr>
<td></td>
<td>1000 (1400)</td>
<td>3800 (1600)</td>
</tr>
<tr>
<td>Live stems per ha</td>
<td>1000 (400)</td>
<td>4000 (1000)</td>
</tr>
<tr>
<td></td>
<td>2600 (1600)</td>
<td>3800 (1800)</td>
</tr>
<tr>
<td>Snags per ha</td>
<td>&lt;200</td>
<td>&lt;200</td>
</tr>
<tr>
<td>Average tree height (m)</td>
<td>6.4 (1.5)</td>
<td>14.7 (2.5)</td>
</tr>
<tr>
<td>Total basal area (m²/ha)</td>
<td>8 (10)</td>
<td>58 (12)</td>
</tr>
<tr>
<td>Average crown length (m)</td>
<td>3.9 (0.9)</td>
<td>4.0 (0.9)</td>
</tr>
<tr>
<td>Average crown ratio (m/m)</td>
<td>0.6 (0.1)</td>
<td>0.3 (0.1)</td>
</tr>
<tr>
<td>Total crown base area (m²/ha)</td>
<td>4160 (2100)</td>
<td>4240 (1380)</td>
</tr>
<tr>
<td>Average height to base ratio (m/m²)</td>
<td>1.8 (0.4)</td>
<td>3.7 (0.9)</td>
</tr>
<tr>
<td>Total crown surface area (m²/ha)</td>
<td>3060 (1400)</td>
<td>1440 (440)</td>
</tr>
<tr>
<td>Total crown volume (m³/ha)</td>
<td>6600 (3660)</td>
<td>6440 (2560)</td>
</tr>
<tr>
<td>Crown closure (%)</td>
<td>21 (30)</td>
<td>40 (20)</td>
</tr>
</tbody>
</table>

67
Upper Penticton Creek, respectively. The crown volume in the spruce-fir stand at Mayson Lake was 1.7 times that in the juvenile stand and 2.9 times that in the juvenile-thinned stand. At Upper Penticton Creek, the crown volume of the spruce-fir stand was 2.7 times that of the pine and 2.6 times that of the juvenile stand. The characteristics of each study stand can be seen in photo panels 1 through 4 and 6 through 8 (Appendix 1).

5.3.1 Peak Snow Accumulation

The coefficients of determination ($r^2$), showing the proportion of the variation in FOSWE among plots explained by each of the forest inventory variables, are presented in Table 5.4. At the Mayson Lake and Upper Penticton Creek sites, crown length, the square root of crown volume, and crown closure appeared to be the most suitable variables for predicting FOSWE. Statistics for the relationships between these variables and FOSWE are summarized in Table 5.5. Over the study period, average crown length explained 12 to 18% of the variation in April 1st FOSWE among plots with standard errors of the estimate (SE$_e$) of 0.18 to 0.21 cm cm$^{-1}$, depending on year. The square root of crown volume explained 17 to 22% of the variation in FOSWE with SE$_e$ of 0.17 to 0.21 cm cm$^{-1}$ and crown closure 26 to 28% of the variation with SE$_e$ of 0.17 to 0.19 cm cm$^{-1}$. The inverse relationships between crown length, the square root of crown volume, and April 1st FOSWE are illustrated in Figures 5.1 and 5.2. In the chart of plot crown closure versus FOSWE, the wide scatter of points does not indicate a clear relationship between these variables (Figure 5.3). Nevertheless, of the variables measured, crown closure was the most representative of crown distribution. Since the statistics for the relationship between crown closure and FOSWE were relatively high compared to other forest inventory variables and since crown closure was thought to be physically relevant, this variable was included in the multivariate models tested.

The multivariate models using crown closure and crown length explained 31 to 33% of the variation in April 1st FOSWE, with SE$_e$ of 0.17 to 0.19 cm cm$^{-1}$, depending on year. The multivariate models using crown closure and square root of crown volume explained 34 to 36%
Table 5.4. A summary of the proportion of the variation (shown as the coefficient of determination $r^2$) in standardized April 1st SWE (FOSWE) and average snowmelt rates (FOMR) explained by the forest inventory variables measured at Mayson Lake and Upper Penticton Creek

<table>
<thead>
<tr>
<th>Snow and Forest Structure Variables (per plot)</th>
<th>Among Plots (n=384)</th>
<th></th>
<th></th>
<th>Among Stands (n=6)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total stems</td>
<td>0</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total stems of pine</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td>Total stems of spruce and fir</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td>Total live stems</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total snags</td>
<td>0</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Average tree height</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>Average crown length</td>
<td>0.13</td>
<td>0.15</td>
<td>0.18</td>
<td>0.86</td>
<td>0.85</td>
</tr>
<tr>
<td>Average crown ratio</td>
<td>0.03</td>
<td>0.06</td>
<td>0.07</td>
<td>0.10</td>
<td>0.19</td>
</tr>
<tr>
<td>Total crown surface area</td>
<td>0.06</td>
<td>0.08</td>
<td>0.08</td>
<td>0.38</td>
<td>0.45</td>
</tr>
<tr>
<td>Square root of total crown volume</td>
<td>0.19</td>
<td>0.20</td>
<td>0.22</td>
<td>0.67</td>
<td>0.69</td>
</tr>
<tr>
<td>Crown closure</td>
<td>0.28</td>
<td>0.28</td>
<td>0.26</td>
<td>0.68</td>
<td>0.75</td>
</tr>
<tr>
<td>Square root of total basal area</td>
<td>0.12</td>
<td>0.16</td>
<td>0.21</td>
<td>0.30</td>
<td>0.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FOMR</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total stems</td>
<td>0.13</td>
<td>0.12</td>
<td>0.13</td>
<td>0.35</td>
<td>0.33</td>
<td>0.32</td>
</tr>
<tr>
<td>Total stems of pine</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td>Total stems of spruce and fir</td>
<td>0.06</td>
<td>0.06</td>
<td>0.13</td>
<td>0.14</td>
<td>0.18</td>
<td>0.35</td>
</tr>
<tr>
<td>Total live stems</td>
<td>0.09</td>
<td>0.07</td>
<td>0.11</td>
<td>0.3</td>
<td>0.32</td>
<td>0.4</td>
</tr>
<tr>
<td>Total snags</td>
<td>0.11</td>
<td>0.09</td>
<td>0.06</td>
<td>0.26</td>
<td>0.21</td>
<td>0.12</td>
</tr>
<tr>
<td>Average tree height</td>
<td>0.20</td>
<td>0.17</td>
<td>0.11</td>
<td>0.44</td>
<td>0.35</td>
<td>0.19</td>
</tr>
<tr>
<td>Average crown length</td>
<td>0.13</td>
<td>0.12</td>
<td>0.15</td>
<td>0.74</td>
<td>0.74</td>
<td>0.58</td>
</tr>
<tr>
<td>Average crown ratio</td>
<td>0.21</td>
<td>0.17</td>
<td>0.11</td>
<td>0.40</td>
<td>0.31</td>
<td>0.17</td>
</tr>
<tr>
<td>Total crown surface area</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Square root of total crown volume</td>
<td>0.17</td>
<td>0.20</td>
<td>0.31</td>
<td>0.56</td>
<td>0.70</td>
<td>0.81</td>
</tr>
<tr>
<td>Crown closure</td>
<td>0.17</td>
<td>0.15</td>
<td>0.19</td>
<td>0.83</td>
<td>0.88</td>
<td>0.78</td>
</tr>
<tr>
<td>Square root of total basal area</td>
<td>0.42</td>
<td>0.41</td>
<td>0.43</td>
<td>0.86</td>
<td>0.83</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Figure 5.1. The ratio of forest to clearcut average April 1st SWE (FOSWE) over three years versus the square root of total crown volume \((\text{m}^3)^{1/2}\) for all 50 m\(^2\) plots at Mayson Lake and Upper Penticton Creek.

Figure 5.2. The ratio of forest to clearcut average April 1st SWE (FOSWE) over three years versus average crown length \((\text{m}^2)\) for each 50 m\(^2\) plot at Mayson Lake and Upper Penticton Creek.
Figure 5.3. The ratio of forest to clearcut average April 1st SWE (FOSWE) over three years versus the crown closure (%) for each 50 m² plot at Mayson Lake and Upper Penticton Creek.

of the variation in April 1st FOSWE with SE of 0.16 to 0.18 cm cm⁻¹, results similar to those obtained using crown length. Since crown length is far simpler to measure in the field than crown volume, crown length along with crown closure are concluded to be the best stand structure variables for predicting relative FOSWE among the plots surveyed (Table 5.5).

When plot data were averaged to represent each stand, average crown length explained the largest proportion of the variation in FOSWE among stands, 79 to 86% over the study period, with SE of 0.05 to 0.06 cm cm⁻¹ (Table 5.4). Models were not improved with the inclusion of additional stand structure variables. Multivariate models including combinations of crown length, crown volume, and crown closure were tested and none were significant in all three years of the study. Based on these results, average crown length was recommended as the variable best able to predict FOSWE among the stands included in this study. A preliminary relationship between April 1st FOSWE and crown length (73% of the variability explained with
Table 5.5. Forest inventory variables explaining the greatest proportion of the variability in standardized ratios of April 1st SWE (FOSWE) and snowmelt rates (FOMR) among plots (n=384) at Mayson Lake and Upper Penticton Creek.

<table>
<thead>
<tr>
<th>Snowpack Variable</th>
<th>Forest Structure Variable</th>
<th>Year</th>
<th>Single or Multiple Coefficient of Determination</th>
<th>Standard Error of the Estimate (cm)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOSWE</td>
<td>Average crown length</td>
<td>1995</td>
<td>0.13</td>
<td>0.21</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1996</td>
<td>0.15</td>
<td>0.20</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997</td>
<td>0.18</td>
<td>0.18</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Square root of total crown volume</td>
<td>1995</td>
<td>0.19</td>
<td>0.20</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1996</td>
<td>0.20</td>
<td>0.20</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997</td>
<td>0.25</td>
<td>0.17</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Average crown closure</td>
<td>1995</td>
<td>0.28</td>
<td>0.19</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1996</td>
<td>0.28</td>
<td>0.19</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997</td>
<td>0.26</td>
<td>0.17</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Crown closure and crown length</td>
<td>1995</td>
<td>0.31</td>
<td>0.19</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1996</td>
<td>0.33</td>
<td>0.18</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997</td>
<td>0.33</td>
<td>0.17</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Crown closure and crown volume</td>
<td>1995</td>
<td>0.34</td>
<td>0.18</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1996</td>
<td>0.35</td>
<td>0.18</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997</td>
<td>0.36</td>
<td>0.16</td>
<td>0.0001</td>
</tr>
<tr>
<td>FOMR</td>
<td>Square root of basal area</td>
<td>1995</td>
<td>0.42</td>
<td>0.20</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1996</td>
<td>0.41</td>
<td>0.25</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997</td>
<td>0.43</td>
<td>0.18</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Table 5.6. Forest inventory models explaining the greatest proportion of the variability in standardized ratios of April 1st SWE (FOSWE) and snowmelt rates (FOMR) for all study sites and years at Mayson Lake and Upper Penticton Creek, combined (n=18).

<table>
<thead>
<tr>
<th>Snowpack Variable</th>
<th>Forest Structure Variable and Model</th>
<th>Single or Multiple Coefficient of Determination</th>
<th>Standard Error of the Estimate</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOSWE</td>
<td>Average crown length (CL)</td>
<td>FOSWE = 1.42 - 0.15 (CL)</td>
<td>0.73</td>
<td>0.07</td>
</tr>
<tr>
<td>FOMR</td>
<td>Average square root of basal area (SRBA)</td>
<td>FOMR = 1.19 - 1.14 (SRBA)</td>
<td>0.79</td>
<td>0.10</td>
</tr>
</tbody>
</table>
**5.3.2 Average Snowmelt Rate**

Of the 13 forest inventory variables measured, the square root of basal area explained the largest proportion of the variation (41 to 43%) in plot FOMR (Table 5.4, Figure 5.5), with $SE_e$ of 0.18 to 0.25 cm d$^{-1}$ (cm d$^{-1}$)$^{-1}$ (Table 5.5), depending on year. When all plot data were averaged for each stand, average crown length, crown closure, and the square root of basal area
appeared to explain the greatest proportion of the variability in FOMR among stands. However, the only model that was significant was the one based on the square root of basal area. This stand structure variable explained 73% of the variation in FOMR from stand to stand with a $\text{SE}_e$ of 0.10 cm d$^{-1}$ (cm d$^{-1}$)$^{-1}$ (Table 5.6).

No multivariate models were found that provided improved predictions of FOMR, either among plots or among stands. A preliminary relationship between the square root of basal area and FOMR for all years of the study combined is included in Table 5.6 and illustrated in Figure 5.6.

Figure 5.5. The ratio of forest to clearcut average melt rate (FOMR) over three years versus the square root of total basal area ($\left(\text{m}^2\right)^{1/2}$) for each 50 m$^2$ plot at Mayson Lake and Upper Penticton Creek.
Only two studies were found in the literature which attempted to use standard forest inventory variables as predictors of snowmelt (Lull and Rushmore 1960; Packer 1971). Both studies found crown closure to be a useful index of snowmelt rate, explaining 76 and 74% of the variability in snowmelt, respectively. They did not, however, include other forest-structure variables in their analyses. They also did not standardize their results making it difficult to compare them with the results of this study. Hudson (2000) found that the height of the main canopy was the variable explaining the largest proportion of the variability in a recovery index (including both snow accumulation and melt) among sites. In this investigation, tree height did
not explain more than 13% of the variability in FOSWE among stands and 19 to 44% of the variability in FOMR depending on year. Canopy gap fraction was found to be the stand characteristic explaining most (92 to 94%) of the variability in snowmelt in a boreal forest (Metcalfe and Buttle 1998).

5.4 Conclusions

Based on the SWE and snowmelt measurements collected from 1995 to 1997, several forest inventory characteristics were found to be more highly correlated with snowpack processes than others. The variables that together explained the greatest variability in April 1st FOSWE among plots were average crown length and crown closure (31 to 33% of the variation among plots explained). These variables were thought to reflect differences in snow interception capacity among the study stands. The square root of basal area per plot explained 41 to 43% of the variability in FOMR among plots. Basal area was thought to provide an indication of total forest cover, including the canopy and stems, and an indirect representation of beneath canopy meteorological conditions and the energy available for snowmelt.

When plot data were averaged to represent the stand, average stand crown length explained 73% of the variability among sites in FOSWE and the square root of the basal area 79% of the variability in FOMR. Both models had low standard errors of the estimate, 0.07 for FOSWE and 0.10 for FOMR. These results have shown that stand characteristics can be used to predict FOMR and FOSWE at the stand scale. The results also highlight the problems associated with the oversimplification of complex processes. Average tree height, the variable currently used in B.C. to assess “recovery”, only explained up to 7% of the variability in peak FOSWE among plots, and up to 20% of that in FOMR. At the stand scale, tree height still only explained up to 14 and 44% of the variability in peak FOSWE and FOMR, respectively. Though readily available, tree height does not provide an adequate representation of either snow interception or the effects of forest cover on the snow surface energy balance. Relationships between other forest inventory variables and measures of stand structure, such as those described in this thesis,
are likely to be more useful in evaluating potential changes in snow accumulation and melt following logging and with forest re-growth.

The work completed as part of this investigation is unique in that several different juvenile stand types were included in the development of models to predict FOSWE and FOMR. The importance of scale considerations in snow accumulation and melt research have also been highlighted by the results presented here. The field data collected at Mayson Lake and Upper Penticton Creek have shown that snow accumulation and melt are influenced at a scale between the plot and stand sizes chosen for this study (0.005 and 1 ha, respectively). This analysis used standardized ratios of snow characteristics in the development of relationships with forest structure, removing the effects of location and climate and providing the opportunity to apply the results over a broader area.

The forest inventory variables identified in this study provide a relative indication of the processes controlling snow accumulation and melt in the study stands. If consistent over a broader area, the relationships between the stand attributes identified and FOSWE and FOMR could be used for calibration of snow accumulation and melt models and in forest development planning. The effects of stand structure, as described by forest inventory variables, on below-canopy meteorological conditions and snowmelt are discussed in Chapter 6.
CHAPTER 6

DETAILED INVESTIGATION OF SNOWMELT DYNAMICS

6.1 Introduction

Understanding snowmelt dynamics in forested watersheds is important both in forest development planning and in hydrologic modelling. In most field research, snowmelt is represented by the reduction in snow water equivalent (SWE), measured with a standard snow tube (Chapter 4) during the survey interval or averaged over the entire melt period. Measurements of SWE loss include water lost as drainage from the base of the snowpack and through evaporation and sublimation, the combination of the three losses being referred to as ablation. Most commonly, however, all forms of water loss from the snowpack are reported as melt.

The literature cites average snow melt rates in the range of 0.4 to 2.5 cm d$^{-1}$ in open areas, and 0.3 to 1.7 cm d$^{-1}$ under forest canopies similar to those in south-central B.C (Table 2.1). At Mayson Lake, B.C., the three-year average ‘snowmelt’ rates over the season were 0.35 cm d$^{-1}$ in a spruce-fir stand and 1.32 cm d$^{-1}$ in a clearcut (Chapter 4). The separation of ablation into water lost as drainage at the base of the snowpack from that lost to evaporation or sublimation is essential to understanding snowmelt contributions to spring streamflows and the effects of forest cover on hydrologic processes.

In Finland, Lemmelä and Kuusisto (1974) reported that 2 to 10% of the snowpack evaporated over the entire melt season, depending on the year. They measured evaporation losses of 0.025 cm during the 12-hour daytime period and 0.003 cm during the night. In a summary of snow evaporation research worldwide, Kuusisto (1986) cited rates of up to 0.06 cm d$^{-1}$. In five out of the 19 sets of measurements included in his summary, researchers observed condensation
to be more important than evaporation. In Sweden, Bengtsson (1980) reported that evaporation losses averaged 0.036 cm d\(^{-1}\), and that losses rarely exceeded 0.1 cm d\(^{-1}\) (0.06 cm d\(^{-1}\) during the daytime). He concluded that evaporation is of minor importance. Bernier and Swanson (1992) also found low daily snow evaporation rates in a lodgepole pine forest and openings in Alberta ranging from an average of 0.11 to 0.25 cm d\(^{-1}\) in a large cut and a full forest, respectively. They suggested that even though these losses seem small on a daily basis, over a 100 day period this would amount to almost one-half of the total winter snow accumulation. Bernier (1989) reported that in an artificial stand of 2.5 m tall lodgepole pine trees in Alberta, snow evaporation was a function of the angle of view between the anemometer and tops of the surrounding trees. At a stem density of 1650 stems per ha, the snow evaporation rate was equal to that in the open. At 2500 stems per ha the snow evaporation rate decreased to one-third of that in the open.

If an average evaporation rate of 0.06 cm d\(^{-1}\) (the maximum rate repeated by Kuuisto (1986)) were assumed for the Mayson Lake study clearcut, evaporation would account for 4% of the total water loss measured per day during the melt period. In a study of forest-canopy effects on the energy balance at Mayson Lake, latent heat flux densities measured under forest cover and in a clearcut were less than 2 Wm\(^{-2}\) (Adams et al. 1998). These fluxes indicate negligible (less than 0.05 cm d\(^{-1}\)) evaporation losses from, or condensation on, the snowpack during melt.

If evaporation losses from the snowpack are small, measurements of SWE loss should provide good estimates of water outflow to the soil surface. However, these manual measurements are time consuming and generally made infrequently. For streamflow estimation, daily or hourly measurements of snowmelt are required. In hydrologic research, these continuous measurements of snowmelt are made with snowmelt lysimeters.

A lysimeter is a device that captures melt water as it drains out of the snowpack and measures either its weight or volume. Lysimeters can be classified as one of two main types: enclosed or unenclosed. In an enclosed lysimeter, the collector is surrounded by a barrier that completely isolates the column of snow whereas in the unenclosed type only a raised rim surrounds the
collector (Kattelmann 1984). Because water can move both horizontally and vertically within the snowpack, researchers report better agreement between lysimeter outflow and water balance computations when the snow above the lysimeter is separated from the surrounding pack, particularly on sloping terrain (Haupt 1972; Greenan and Anderson 1984). Slots cut in the snow and artificial barriers, such as plastic sheets on metal frames (Haupt 1969b) or heat rings (Greenan and Anderson 1984), inserted in to the snow have been used. However, barriers also present problems, such as alteration of melt patterns along the borders of the snow column once the barrier becomes exposed during melt (Haupt 1969a).

The lysimeter represents a discontinuity in the snowpack resulting in a vertical pressure gradient and a two to three centimetre-thick saturated layer above the collector. Because the water pressure is greater in this saturated zone than beyond the perimeter of the discontinuity, water can flow laterally out of the collection zone resulting in an underestimate of melt. A low rim, 12 to 15 cm in height, is thought to contain the entire pressure-gradient-zone under most conditions (Kattelmann 1984).

A wide variety of lysimeter designs have been reported in the literature and a summary of types designed to 1983 was provided by Kattelmann (1984). The designs of ground-based unenclosed lysimeters ranged from square to circular or triangular and from wood to metal or plastic with surface areas of 0.0064 to 120 m$^2$. Beaudry (1984) used 0.5 m$^2$ lysimeters constructed from the lower portion of 45 gallon barrels, cut at an angle similar to that of the slope, buried up to 1 cm from the barrel lip and loosely filled with gravel to filter the water before it reached the drain. Because of the small surface area of these lysimeters, water flowing through the snowpack was found to be concentrated toward or away from the lysimeters resulting in melt rates that were not indicative of melt over a larger area. Ice lenses forming in the snowpack above the lysimeter also obstructed water flow down in to the lysimeters. This design was abandoned in favour of large (22 m$^2$) reinforced-plastic triangular sheet lysimeters, which were reported to work well. To compare snow accumulation and melt under various intensities of forest cutting in western Oregon, Storck et al. (1999) constructed 2.6 m$^2$ wood-
frame lysimeters lined with impermeable geo-textile and buried drains and pipes. They also built two 25 m$^2$ weighing lysimeters each installed around an individual tree plus a 12.5 m$^2$ weighing lysimeter in an opening. Most commonly, lysimeters drain to tipping buckets that measure the volume of outflow.

Descriptions of snowmelt lysimetry in the literature highlight the difficulties of measuring environmental variables in remote wildland locations under adverse conditions. Most researchers describe at least one of the following problems at some time during lysimeter operation:

- icing at the drain, throughout the lysimeter itself, in the discharge line, in the collection reservoir, or in the tipping bucket,
- flooding of the lysimeter, outflow reservoir, or tipping buckets,
- magnetic switch, electronic, or power failure due to ice, water, or cold,
- leakage,
- surge flows at the onset of melt,
- vandalism,
- damage by wild animals or livestock, and
- large differences in outflow measured by more than one lysimeter at the same site.

Lysimeters provide point estimates of melt water outflow from a snowpack. Since their surface area is small relative to the spatial variability under forest cover, they are affected by both their position in relation to microtopographic features and by the canopy above them. Kattelman (1984) reported that differences between adjacent 2 m$^2$ lysimeters may be in orders of magnitude and recommended using as large a lysimeter as the study site and resources allow. He further suggested that at least two lysimeters should be used at each study site to provide an indication of the spatial variability, as well as of the quality and representativeness of the measurements.

Snowmelt research with lysimeters has been conducted primarily in open or sparsely wooded areas. Schultz (1973) reported the installation of lysimeters under mature forests in Colorado. More recently, Storck et al. (1999) presented work in coast transition Douglas-fir ($Pseudotsuga menziesii$ (Mirb.) Franco) forests of Oregon in which stands were selectively logged to different stand densities. Several attempts at measuring snowmelt using various
lysimeter designs have been made in B.C. However, not all have been successful and none have been conducted in the south-central interior or in the forest types included in this investigation. Beaudry (1984) studied snowmelt outflows from lysimeters placed in the open and under a coastal western red-cedar (Thuja plicata Donn) and western hemlock (Tsuga heterophylla (Raf.) Sarg.) forest. In the interior, Nassey (1994) presented lysimeter outflows measured in a clearcut near Castlegar. No references were found in the literature which reported the use of lysimeters in juvenile stands, or to describe the meteorological conditions associated with daily melt in these stands relative to clearcut or mature forest types.

In general, snowmelt rates measured using lysimeters exceed those obtained from averaged intermittent manual SWE measurements. At Mayson Lake, average melt rates of 0.35 to 1.32 cm d\(^{-1}\), depending on site and year, were reported in Chapter 4. These averages include overestimates of late season melt as a result of water draining from the snow tube during extraction from the snowpack. Regardless of these potential late season overestimates, the averages measured at Mayson Lake are substantially smaller compared to maximum outflow rates reported in the literature. Haupt (1969b) reported maximum rates of outflow from snowmelt lysimeters in Idaho of 5.2 cm d\(^{-1}\) during clear weather. At Murphy Creek near Castlegar, B.C., Nassey (1994) reported a maximum daily lysimeter outflow of 2.3 cm in comparison to the average SWE loss of 1.2 cm d\(^{-1}\) over the melt period. Kattelmann et al. (1998) summarized the maximum snowmelt rates reported in the literature and suggested that under typical mountain conditions 5.0 cm d\(^{-1}\) is the maximum snowmelt rate likely. Using an energy balance approach, they calculated melt rates of up to 7.5 cm d\(^{-1}\) and measured maximum lysimeter outflow rates of 3.0 to 5.0 cm d\(^{-1}\). They summarized the conditions most conducive to rapid snowmelt in the absence of rain as:

- long days near the solstice,
- clear days with cloudy nights,
- warm, humid air combined with high wind conditions,
- low snow albedo,
- a discontinuous and shallow snowpack so that light can penetrate to the ground surface, and
- sites with local sources of longwave radiation.
Snow melts as a result of radiative, latent, and sensible energy fluxes to the pack. The relative proportions of each of these energy fluxes varies with solar position, sky conditions, characteristics of the snowpack, and forest cover, as discussed in Chapter 2. In the field, energy flux measurements are extremely difficult and are further complicated by forest cover. More commonly, the physical processes driving snowmelt are characterized by the standard meteorological measurements of air temperature, snow temperature, wind speed, solar irradiance, and relative humidity. Air temperature is used as an index of the radiative fluxes and temperature, relative humidity, and wind speed are used as indices of latent and sensible fluxes (Gray and Prowse 1993). Relationships between snowmelt and these variables are not available for B.C. If these meteorological variables are to be used to predict snowmelt under diverse forest conditions, then the effects of forest cover on the relationships between these variables and snowmelt must be understood.

The objectives of the research described in this chapter were to quantify daily snowmelt using lysimeters under several forest cover types including juvenile stands, to compare snow ablation calculated from standard snow tube measurements with measured lysimeter outflow, and to describe relationships between meteorological conditions and snowmelt in the clearcut, juvenile, and mature stands at Mayson Lake.

6.2 Methods

6.2.1 Snow Water Equivalent

SWE was measured at 64 permanent survey stations at each of the four Mayson Lake study sites (clearcut, juvenile-thinned, juvenile, and mature spruce-fir). The survey stations were spaced in a 15 by 15 m grid over approximately 1 ha. Measurements were made weekly during early spring and then every three to four days throughout the snowmelt period, using a standard federal snow tube, as described in Chapter 4.
Snow ablation rates were calculated as the reduction in SWE divided by the number of days between surveys. Two sets of ablation rates are presented: the average for the entire melt period and the maximum rate measured over three days. These ablation rates represent total water loss from the snowpack through melt, evaporation, and sublimation. The proportion of each form of water loss cannot be separated in data collected using standard manual snow survey measurements. The SWE measurements also do not indicate absolute additions and losses from the snowpack, but rather indicate the balance of new snowfall, rain, and losses in the period between measurements.

### 6.2.2 Snowmelt Lysimeters

At Mayson Lake, melt water outflow from the base of the snowpack was measured using lysimeters. Eight lysimeters and tipping buckets were used, two placed in each of the spruce-fir stand, two juvenile stands, and clearcut. The lysimeters were positioned within the snow survey grids described in Chapter 4 to be representative of the average forest cover and to be as equidistant from all surrounding trees as possible. The mineral soil was exposed and levelled prior to lysimeter placement to ensure contact over the entire lysimeter base. The lysimeters were slightly sloped to aid drainage.

The lysimeters were constructed using 2.4 by 1.2 m sheets of plywood for the base and 1 by 15 cm boards as sidewalls. The plywood frame was then covered with white fibreglass (Photo panel 5, Appendix 1). These construction materials have low thermal conductivity and high albedo, approximating the thermal characteristics of the snowpack. Separation of the snow column above the lysimeter was not thought to be important at Mayson Lake, because all sites were level and the snowpack was shallow (less than 1 m deep). Based on recommendations in the literature (Kattelmann 1984), the height of the sidewalls (15 cm) was assumed adequate to protect against lateral movement of water at the base of the snowpack. These lysimeters were portable, robust, and relatively inexpensive, characteristics which were particularly important considering their location in the field.
The lysimeters drained to a tipping-bucket assembly through a standard tub drain and buried irrigation pipe. Each bucket had a capacity of 460 ml. Since the collecting surface area of each lysimeter was 2.8 m², each tip represented 0.016 cm of melt water outflow. The tipping buckets were placed in dug-out areas below ground level to minimize the risk of freezing. A ditch drained melt water away from the dug-out to prevent flooding. The excavated area was covered with a sheet of insulated plywood. Soil was packed around the bottom edge of each lysimeter, the drainage assembly, and the plywood roof covering the tipping bucket dug-out. The tipping buckets were uncovered early each spring before melt and any ice was removed. The units were resealed, the covers replaced, and the area resurfaced with snow.

Minor problems were experienced with the drainage assembly since the junctions of the drainpipe and lysimeter were fragile. Several seals at this junction had to be repaired after the lysimeters were transported to the field. Once in position and protected by soil no leakage was observed during discharge tests.

At each study site, a climate station was installed next to the lysimeters (Appendix 1, Photo panels 1 to 3). Each climate station provided daily maximum, minimum, and average air temperature, wind speed, relative humidity, average snowpack temperature at 10, 20, 30, 40, and 50 cm above the ground surface, and temperature at the base of the snowpack inside the lysimeter (Table 6.1). At the clearcut site, rainfall and solar radiation were also measured. All climate data were collected hourly and summarized daily. These data were also used in a study of the energy balance of melting snow (Adams et al. 1998).

The forest cover of each study site was described through an intensive inventory of all trees within a 4 m radius plot centered on each of the snow survey stations as described in Chapter 5.

6.2.3 Data Summary and Analysis

Daily averages or totals of meteorological measurements and lysimeter outflows were used in this investigation. For six days during the 1995 melt season, April 6 to 12 (Days 96 to 102),
Table 6.1. A summary of snowmelt and daily micrometeorological measurements made (√) in the clearcut (CC), the juvenile-thinned (JT), juvenile (J), and mature (MF) stands at Mayson Lake.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Instrument</th>
<th>Specifications</th>
<th>CC</th>
<th>JT</th>
<th>J</th>
<th>MF</th>
<th>Samples per Stand Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow water equivalent (cm)</td>
<td>Standard federal snow tube</td>
<td>-3% to 12% (1)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>64</td>
</tr>
<tr>
<td>Snowmelt (cm hr⁻¹)</td>
<td>Lysimeter/tipping bucket</td>
<td>0.16 mm per tip</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>2</td>
</tr>
<tr>
<td>Snow temperature (°C) at 10, 20, 30, 40, and 50 cm above the ground</td>
<td>Copper/constantan thermocouples</td>
<td>0.2 °C (2)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Rain (mm)</td>
<td>Jarek tipping bucket</td>
<td>0.25 mm (2)</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Air temperature (°C) at 2 m</td>
<td>Vaisalla temperature/humidity probe</td>
<td>0.2 °C (2)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Relative humidity (%) at 2 m</td>
<td>Vaisalla temperature/humidity probe</td>
<td>3% (2)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Wind speed (m s⁻¹) at 3 m</td>
<td>RM Young wind sentry</td>
<td>0.1 (3)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Wind speed (m s⁻¹) at 3 m</td>
<td>MetOne anemometer</td>
<td>0.1 (3)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>1</td>
</tr>
<tr>
<td>Solar radiation (Wm⁻²)</td>
<td>LI-COR LI-200 pyranometer</td>
<td>1% (3)</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

1 In the range if 1.2 to 18 cm of SWE (Goodison et al. 1981)
2 Spittlehouse (1989)
3 R. Adams (1995, pers. comm.)
daily average and maximum air temperatures, solar irradiance, and wind speed data were missing in the clearcut due to equipment malfunction. The missing temperature data were estimated using the relationship between air temperature in the juvenile-thinned stand and in the clearcut for the entire melt period. Similarly, the missing six days of solar irradiance data were estimated using the relationship between maximum daily air temperature and solar irradiance for the entire melt period. Relationships with the highest coefficient of determination ($r^2$) and smallest standard error of the estimate ($\text{SE}_e$) were chosen for filling in the missing data (Table 6.2).

Table 6.2. Equations used to generate the missing April 6 to 12, 1995 temperature ($T$) and solar irradiance data at Mayson Lake and their associated coefficients of determination ($r^2$) and standard error of the estimates ($\text{SE}_e$).

<table>
<thead>
<tr>
<th>Equation</th>
<th>$r^2$</th>
<th>$\text{SE}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted $T_{\text{air average}}<em>{\text{clearcut}}$ = 0.32 + 0.94 $T</em>{\text{air average}}_{\text{juvenile-thinned}}$</td>
<td>0.99</td>
<td>0.05 °C</td>
</tr>
<tr>
<td>Predicted $T_{\text{air maximum}}<em>{\text{clearcut}}$ = -1.85 + 1.05 $T</em>{\text{air maximum}}_{\text{juvenile-thinned}}$</td>
<td>0.76</td>
<td>3.20 °C</td>
</tr>
<tr>
<td>Predicted Solar Irradiance$<em>{\text{clearcut}}$ = 5.88 + 0.86 $T</em>{\text{air maximum}}_{\text{clearcut}}$</td>
<td>0.62</td>
<td>4.42 MJ d$^{-1}$</td>
</tr>
</tbody>
</table>

Single and multiple linear regression techniques, using SAS software (SAS Institute Inc. 1988), were used to quantify relationships among snowpack and meteorological variables. Statistical significance was determined using $\alpha = 0.05$. The relationships between variables were compared using the $r^2$ values, the $\text{SE}_e$ values, significance of the regression, and the residual plots.

Lysimeter data were compared to manual snow tube measurements and any differences in total accumulated water loss or outflow over the melt season, or in daily melt, maximum melt, and average melt were described. Lysimeter and meteorological data were graphed to identify patterns in these data and linkages between them.
6.3 Results and Discussion

6.3.1 Snow Water Equivalent

The patterns of snow accumulation and ablation during 1995 at the Mayson Lake study sites, as measured with the snow tube, are summarized in Table 6.3 and shown in Figure 6.1. On April 1st, SWE was 75% higher in the clearcut and 33% higher in the juvenile stands than in the spruce-fir stand. As calculated from the snow tube measurements, average snow melt rates over the melt season were 2.4 times greater in the clearcut than in the spruce-fir stand. Melt rates in the juvenile stands more closely approximated those in the clearcut than those in the spruce-fir stand.

Table 6.3. A summary of snowpack characteristics, means and standard deviations, based on snow tube and lysimeter outflow measurements during 1995 at Mayson Lake.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Clearcut</th>
<th>Mean (Standard deviation)</th>
<th>Mature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>April 1 snow water equivalent (cm)</td>
<td>20.5 (4.5)</td>
<td>16.7 (4.1)</td>
</tr>
<tr>
<td></td>
<td>Days of melt</td>
<td>25 (2)</td>
<td>22 (4)</td>
</tr>
<tr>
<td></td>
<td>Average melt rate (cm d(^{-1})) from April 1 to April 29</td>
<td>0.83 (0.17)</td>
<td>0.78 (0.19)</td>
</tr>
<tr>
<td></td>
<td>Maximum melt rate (cm d(^{-1}))</td>
<td>3.99 (1.18)</td>
<td>3.14 (0.87)</td>
</tr>
<tr>
<td></td>
<td>Day of maximum melt</td>
<td>117</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>Total accumulated loss (cm)</td>
<td>22.5</td>
<td>21.3</td>
</tr>
<tr>
<td>Lysimeters</td>
<td>Average melt rate (cm d(^{-1})) from April 1 to April 29</td>
<td>0.68 and 0.49</td>
<td>0.43 and 0.36</td>
</tr>
<tr>
<td></td>
<td>Maximum melt rate (cm d(^{-1}))</td>
<td>2.88 and 2.98</td>
<td>1.15 and 1.30</td>
</tr>
<tr>
<td></td>
<td>Day of maximum melt</td>
<td>117</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>Total accumulated outflow (cm)</td>
<td>21.7 and 19.9</td>
<td>18.3 and 18.3</td>
</tr>
</tbody>
</table>

1 Overestimate due to water loss during core extraction
2 Ice in these lysimeters rendered the data unusable
Figure 6.1. Snow water equivalent (top) and density (bottom) in the clearcut (CC), juvenile-thinned (JT), juvenile (J), and mature spruce-fir (MF) stands at Mayson Lake.
Snow densities were within 5% of one another at all sites throughout 1995 and increased from 20 to 42% over the melt season (Figure 6.1). Slightly lower densities (ranging from 17 to 36% over the season) were recorded in the mature spruce-fir stand than at the other sites in 1995, a result not obtained in succeeding years. In 1995, this difference was likely due to lower air temperatures in the mature spruce-fir stand, the density of snow decreasing exponentially with decreasing air temperature below zero (Gray and Prowse 1993). The average daily air temperature over the 1995 melt period was -1.8, -0.8, -0.6, and -0.4 ºC in the spruce-fir, juvenile, juvenile-thinned, and clearcut stands, respectively. Since the differences in snowpack density over the melt season among the Mayson Lake study sites were small, this variable is unlikely to have a substantive effect on their relative melt rates.

At the end of the melt season, large errors occurred in the manual snow measurements as shown by the apparent decrease in density over the last three measurements in Figure 6.1. These errors were a result of water draining from the snow tube when the snow core was extracted from the pack. This type of error may result in reported overestimates of maximum melt rates.

Though significant differences in April 1st SWE were observed among the sites at Mayson Lake (Chapter 4; Table 6.3), the total accumulated SWE loss at the end of the season was similar for all but the mature spruce-fir site (Table 6.3). This effect is likely a result of periodic snowfall over the melt season and differences in the non-melt losses of this snowfall. Some of the additional snowfall was likely intercepted and sublimated from the juvenile-thinned canopy, a large proportion by the unthinned, and all by the mature spruce-fir canopy. This result is of consequence when evaluating the effects of forest regrowth on the relative amounts of melt water available for spring runoff under various forest cover conditions (i.e., even though on April 1st large differences were observed between the juvenile and clearcut sites, the total melt water yielded under each condition was similar).
6.3.2 Snowmelt Lysimeters

The lysimeters worked well in the clearcut and juvenile stands throughout the 1995 snowmelt season. However, in the spruce-fir stand, both lysimeters failed due to severe icing problems (Photo panel 5, Appendix 1). The icing problems in the mature spruce-fir stand were attributed to the shallower snowpack (*i.e.*, 52 cm on April 1st compared to 67 and 75 cm in the juvenile stands and clearcut, respectively) and to melting snow on the canopy dripping into the lysimeter boxes and refreezing. This was observed on several occasions when air temperatures in the open were high and snowpack temperatures low. Thick layers of ice were also observed during manual snow tube measurements indicating that melt, throughfall, and refreezing occurred throughout the stand. An attempt to repeat the lysimeter measurements in 1996 was unsuccessful due to icing problems at all sites except in the juvenile-thinned stand.

To investigate the effects of snow depth on ice formation in the lysimeters, two lysimeters were relocated from Mayson Lake to an area with deep snowpacks (2 m or more) in late 1996. No icing problems were observed under the deeper snowpacks throughout the 1997 melt season, a result also reported by others (Schultz 1973; D. Toews, pers. comm. 1998). However, at the new location, the heavier snowpack crushed one of the tipping bucket assemblies.

The lysimeters did not affect observable patterns of snow accumulation or melt in the pack immediately above them (other than ice at the drains), did not leak, and were extremely durable, withstanding repeated investigation by cattle prior to snowfall.

6.3.3 Comparison of Lysimeter Outflows with Snowpack Water Losses

In the clearcut, the accumulated outflow from both lysimeters and the manual SWE loss measurements were in good agreement (Figure 6.2). At the end of the season, the total accumulated outflow were 21.7 and 19.9 cm from Lysimeters 1 and 2, respectively, and the total manually-measured loss was 22.5 cm (Table 6.3). Up to April 11th, outflow from
Figure 6.2. Accumulated lysimeter outflow compared to accumulated snowpack water loss (SWE) measured manually in the clearcut at Mayson Lake.

Lysimeter 2 was assumed equal to that of Lysimeter 1. This assumption was necessary because the magnetic switch on Lysimeter 2 had failed during the winter and was not replaced until that date. Assuming equal early season outflow from Lysimeters 1 and 2 was thought to be reasonable because of the close agreement between them during the period when both were operational.

At the juvenile-thinned site, lysimeter outflow followed the same general pattern over the melt season as did the manually measured SWE loss (Figure 6.3). At the end of the season, total accumulated water loss estimated for the site with the manual measurements was 14% higher than those measured with the lysimeters. The average total accumulated lysimeter outflow was 18.3 cm compared to the losses estimated for the site, 21.3 cm, based on averages of the
manual measurements. This difference may be accounted for by SWE measurement error, by underestimated lysimeter outflows during maximum melt as a result of spillage while the tipping buckets were in mid-cycle (Kattelmann 1984), or by lysimeter position in an area of shallower snow cover than the site average. The latter two possibilities likely had a substantial effect on the differences noted since the manual measurements at each lysimeter location were even larger than the site average (i.e., the accumulated SWE loss for the site was 21.3 cm compared to 26 cm at the snow survey station next to the lysimeter). Also the two lysimeters at this site were not in perfect agreement, most likely a result of the high spatial variability over small distances (i.e., the lysimeters were within 10 m of each other). During the peak melt period, the lysimeter outflows indicated larger daily water losses than those obtained from the manual measurements.

In the juvenile stand, outflow from Lysimeter 5 lagged behind the onset of SWE loss measured manually (Figure 6.4). This may have been a result of microsite differences or of minor ice
build up around the lysimeter drain. Once outflow from the lysimeters began, the pattern of water loss in Lysimeter 5 closely approximated that of the manual measurements. Accumulated outflow from Lysimeter 5 over the entire melt period was 18.6 cm compared to the 20.1 cm SWE loss measured manually. This was considered good agreement. Outflows from Lysimeter 6 were highly affected by ice in the lysimeter box and were not used. Data from the lysimeter with no malfunctions during the season and that most closely followed the manually measured SWE losses at each site were used for the remaining analyses (i.e., Lysimeters 1, 3, and 5).

Figure 6.4. Accumulated lysimeter outflow compared to accumulated snowpack water loss (SWE) measured manually in the juvenile stand at Mayson Lake.

Energy flux measurements at the study sites by Adams et al. (1998) showed that evaporation losses from the snowpack during the spring melt period were extremely small, less than 0.05 cm d\(^{-1}\). This result suggests that measurements of SWE loss from the snowpack over the melt season provide a good estimate of water being delivered to the snow-soil interface and that both the manual and lysimeter measurements provide valid estimates of snowmelt.
Day 119 (April 29) was the last day considered in this study, since the snow had disappeared from all sites except the mature spruce-fir stand and precipitation on Day 120 fell as rain. Prior to this date, rainfall was recorded infrequently and was always less than 0.4 cm d$^{-1}$ during the continuous melt period.

### 6.3.4 Comparison of Daily Snowmelt Among Stands

In 1995, some snowmelt outflow occurred throughout the late winter at all sites at Mayson Lake (Figure 6.5). Melt in the juvenile-thinned stand rapidly overtook that at the other sites by the onset of continuous melt. Relatively continuous snowmelt began on Day 72 (March 13) in the juvenile-thinned stand, Day 86 (March 27) in the clearcut and Day 89 (March 30) in the juvenile stand. The slight delay in melt at the juvenile site could have been a result of temporary ice blockage in the drainage system or could have been real.

Up to Day 90 (March 31), daily snowmelt in the juvenile-thinned stand was greater than in either the clearcut or juvenile stand. After this date, melt in the clearcut closely followed that in the juvenile-thinned stand until Day 110, when most of the snow had disappeared in the latter and melt rates increased dramatically in the former. The rate of snowpack depletion at the juvenile site was slower than at the juvenile-thinned site, approximating that in the clearcut.

Approximately 50% of the total melt volume (Figure 6.6) was lost from the juvenile-thinned stand by Day 96 (April 6) compared to Day 112 (April 22) in the clearcut and juvenile stand and Day 115 (April 25) in the spruce-fir stand. When all snow water had been lost from the clearcut and juvenile sites, 30% of the total SWE remained in the mature spruce-fir stand. The snowpack had completely disappeared by Day 119 (April 29) in the clearcut and juvenile stands, and by Day 130 (May 10) in the mature spruce-fir stand.
Figure 6.5. Daily snowmelt outflow from the lysimeter in the clearcut (CC), juvenile-thinned stand (JT), and juvenile (J) stand at Mayson Lake.

Figure 6.6. Percent of total snowmelt measured with lysimeters in the clearcut (CC), juvenile-thinned (JT), and juvenile (J) stands and manually in the mature spruce-fir stand (MF) over the melt season at Mayson Lake.
Maximum daily lysimeter outflow rates varied from 2.9 cm d\(^{-1}\) in the clearcut and 2.6 cm d\(^{-1}\) in the juvenile stand to 1.2 cm d\(^{-1}\) in the juvenile-thinned stand (Table 6.3). These rates were approximately five, four, and three times greater than the average over the entire season at each of the three sites, respectively (Table 6.3). The manually-measured maximum SWE loss rates were higher than the lysimeter outflows, most probably due to water draining from the snow cores as they were extracted from the pack late in the season. This sampling problem occurred at all sites, but was most extreme in the juvenile-thinned stand, where the differences in manual and lysimeter maximum snowmelt rates were greatest (Table 6.3). The manual measurements did not show the differences between the juvenile-thinned and juvenile stands evident in the lysimeter outflow data. Presumably, these differences were masked in the estimates based on the manual measurements as a result of averaging to obtain an overall site value and of the less frequent sampling.

The lysimeter outflow data indicated that maximum melt occurred on the same dates in the clearcut and in the juvenile stand, eight days after that in the juvenile-thinned stand. The manually-measured site averages also showed that maximum melt occurred earlier in the juvenile-thinned stand than in the clearcut (Table 6.3). The manual snow tube measurements showed earlier peak melt rates in the juvenile-unthinned stand, by three days, than in the juvenile-thinned stand, a different result than obtained with the lysimeters. This discrepancy is again most likely a result of comparing site average SWE data with point lysimeter measurements and less frequent manual measurements.

This research has provided new information for juvenile stands. The results illustrate the importance of understanding the relationships between forest structure and snowmelt, since not only does snowmelt differ between the juvenile and clearcut conditions but it also differs between the two structurally-distinct juvenile stands. Other researchers have used lysimeters to describe snowmelt under clearcut and mature stand conditions (Beaudry 1984) and to quantify the dispersion of intercepted snow (Storck and Lettenmaier 1999). However, the differences in daily melt between forest cover types, particularly the amount and distribution of stem and canopy growth necessary for juvenile stands to affect snowmelt, have not been quantified. This
investigation shows that the juvenile stand at Mayson Lake had little effect on snowmelt relative to that in the clearcut. The total accumulated water loss at the end of the melt period was only slightly less than in the clearcut. In contrast, maximum daily and average melt rates appear to have been moderated by the juvenile-thinned stand. In this stand, the onset of melt was considerably advanced (by one week) relative to the clearcut and juvenile-unthinned stand.

6.3.4 Meteorological Variables and Snowmelt

All meteorological data (Table 6.1) were graphed and assessed visually. The proportion of the variation in daily snowmelt explained by each of the meteorological variables is summarized in Table 6.4.

In the clearcut, total daily solar irradiance varied from 5 to 25 MJ m\(^{-2}\) d\(^{-1}\) depending on both the day of the year during the melt season and on whether conditions were clear or overcast (Figure 6.7). Lysimeter outflows in the clearcut generally, but not always, increased on days with higher solar irradiance. In the clearcut, solar irradiance explained 36% of the variability in melt. Detailed investigations of the decreases in solar irradiance with increasing forest cover are necessary to directly relate this variable to daily snowmelt at treed sites.

Differences between sites were observed in maximum daily air temperature, average daily air temperature above 0 °C, temperature at 10 cm above the base of the snowpack, minimum relative humidity, and maximum wind speed. Maximum daily air temperatures were similar at all sites except in the mature spruce-fir stand, where temperatures were lower throughout the melt season, varying from 0 to 5 °C. Average daily temperature above 0 °C showed the effects of the mature spruce-fir stand more clearly (Figure 6.8; Table 6.5), 1 to 1.4 °C colder than the juvenile stands and clearcut, respectively. The average daily air temperature above 0 °C explained 56, 62, and 72% of the variability in daily melt in the juvenile-thinned stand, juvenile stand, and clearcut, respectively (Table 6.4). When all sites were combined, air temperature above 0 °C explained 63% of the variability in daily snowmelt.
Table 6.4. The proportion of the variation in daily snowmelt (shown as the coefficient of determination) explained by meteorological variables at Mayson Lake.

<table>
<thead>
<tr>
<th>Meteorological Variable</th>
<th>Clearcut</th>
<th>Coefficient of determination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Juvenile Thinned</td>
<td>Juvenile</td>
</tr>
<tr>
<td>Average daily air temperature above 0 ºC</td>
<td>0.72</td>
<td>0.56</td>
</tr>
<tr>
<td>Yesterday’s average daily air temperature above 0 ºC</td>
<td>0.50</td>
<td>0.21</td>
</tr>
<tr>
<td>Snowpack temperature at 10 cm above ground (ºC)</td>
<td>0.35</td>
<td>0.02</td>
</tr>
<tr>
<td>Maximum wind speed</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>Minimum relative humidity</td>
<td>0.36</td>
<td>0.17</td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.5. Average daily air temperature above 0 ºC, maximum daily wind speed, minimum relative humidity, and snowpack temperature at 10 cm above the ground surface, in the study stands at Mayson Lake.

<table>
<thead>
<tr>
<th>Meteorological Variable</th>
<th>Clearcut</th>
<th>Mean (Standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Juvenile Thinned</td>
<td>Juvenile</td>
</tr>
<tr>
<td>Average daily air temperature above 0 ºC</td>
<td>2.4 (2.0)</td>
<td>2.0 (1.8)</td>
</tr>
<tr>
<td>Maximum wind speed (m s⁻¹)</td>
<td>6.5 (2.0)</td>
<td>2.3 (0.5)</td>
</tr>
<tr>
<td>Minimum relative humidity (%)</td>
<td>32 (13)</td>
<td>32 (12)</td>
</tr>
<tr>
<td>Snowpack temperature at 10 cm above ground (ºC)</td>
<td>0.1 (0.3)</td>
<td>0.7 (1.2)</td>
</tr>
</tbody>
</table>
Figure 6.7. Total daily solar irradiance and daily lysimeter outflow in the clearcut at Mayson Lake.

Figure 6.8. Average daily air temperatures above 0 °C in the clearcut (CC), juvenile-thinned (JT), juvenile (J), and mature spruce-fir stands (MF), at Mayson Lake.
Accumulated daily snowmelt plotted against accumulated air temperature above 0 °C showed that substantially more melt occurred at lower accumulated temperatures above 0 °C in the juvenile-thinned stand than at the other study sites (Figure 6.9). This is thought to be a result of greater shortwave radiation fluxes through the open canopy and of higher longwave fluxes to the snow surface than would occur in the denser-unthinned juvenile stand. Crown closure increased from zero in the clearcut to 21% in the juvenile-thinned stand to 28% in the juvenile stand and crown volume from zero to 6,600 to 11,400 m³ ha⁻¹ (Chapter 5).

![Graph](image)

Figure 6.9. Accumulated daily snowmelt versus the accumulated average daily air temperature 0 °C in the clearcut (CC), juvenile-thinned (JT), and juvenile (J) stands, in 1995 at Mayson Lake.

In a study of energy fluxes on April 22 and 23, 1995 (Days 113 and 114), Adams et al. (1998) found that most of the energy at the snow surface in the clearcut was in the form of shortwave radiation. Approximately, the same amount of shortwave energy reached the surface of the snowpack in the juvenile-thinned stand due to the openness of its canopy. In contrast, the
energy available for snowmelt in the mature spruce-fir stand was dominated by longwave irradiance, the forest canopy reducing shortwave irradiance at the snow surface (canopy closure in the forest was 54% and crown volume 19,400 m$^3$ ha$^{-1}$ (Chapter 5)). The combined effects of reduced solar irradiance and lower air temperatures would result in lower longwave fluxes in the mature spruce-fir and an extended melt period. In 1995, the total days of melt (Table 6.3) in the clearcut and juvenile stands were 20 to 25 days compared to 33 days in the mature spruce-fir.

Snowpack temperatures were measured at approximately 10, 20, 30, 40, and 50 cm above the ground near the lysimeters. These temperature measurements indicated that the snowpack at all sites became isothermal on the same date, Day 70 (March 11), even though temperatures at the base of the snowpack were approximately 2 °C colder in the mature spruce-fir stand than at the other three sites, prior to that date. Temperatures at the base of the snowpack, taken as the measurement at 10 cm above the ground surface, are shown in Figure 6.10. Temperatures at the base of the snowpack in the lysimeters also reached 0 °C by Day 70 except in the spruce-fir stand where they remained below zero until Day 84 (March 25).

Minimum daily average relative humidity was similar at all sites except the mature spruce-fir, where the minimum humidity was consistently higher by 10 to 20% (Figure 6.11). Maximum wind speeds (Figure 6.12) were highest in the clearcut at 4 to 11 m s$^{-1}$ compared to 1.5 to 3.5 m s$^{-1}$ in the juvenile stand and zero in the mature spruce-fir.

No literature was found describing winter meteorological and corresponding snowmelt conditions in juvenile stands. The results of this investigation show the effects of juvenile forest cover on air temperature, wind speed, and relative humidity, and can be interpreted in relation to the potential energy available for snowmelt. Air temperature provides an indication of longwave radiation and very crudely of shortwave radiation. Humidity indicates latent energy fluxes while wind speed is indicative of both the latent and sensible energy fluxes to the snowpack. Even though the relationships between these meteorological variables and the total
Figure 6.10. Average daily snowpack temperature at 10 cm above the ground in the clearcut (CC), juvenile-thinned (JT), juvenile (J), and mature spruce-fir (MF) stands at Mayson Lake.

Figure 6.11. Minimum daily relative humidity in the clearcut (CC), juvenile-thinned (JT), juvenile (J), and mature spruce-fir (MF) stands at Mayson Lake.
energy available for melt are not necessarily additive or compensating relative to forest cover (Gray and Prowse 1993), they do provide an indication of the effects of stand structure on snowmelt and are commonly used to predict snowmelt. The relationships between the meteorological variables found to differ most substantially among the cover types at Mayson Lake, and be most highly correlated with snowmelt, were used to investigate their effects on melt through both an empirical temperature-index and an energy budget modelling approach in Chapter 7.
6.4 Conclusions

Below canopy meteorological conditions, particularly wind speed, snow temperature, and air temperature above 0 ºC varied among the study stands at Mayson Lake. On average, wind speed was reduced by 30 and 100% relative to the clearcut in the juvenile and mature stands, respectively. Prior to the onset of melt, snowpack temperatures in the mature spruce-fir stand were 2 ºC colder on average than in the clearcut and juvenile stands. During the melt period, the snowpack was 0.7 ºC warmer on average in the juvenile-thinned stand than at the other sites.

The snowpack became isothermal at all sites on the same date. In the juvenile-thinned stand, snowmelt outflow began 20 and 17 days earlier than in the clearcut and juvenile stand, respectively, the total accumulation of melt was more rapid, and the snowpack disappeared earlier than in either the clearcut or juvenile-unthinned stand. The maximum melt rate and date of maximum melt in the juvenile stand were not different from those in the clearcut. The maximum melt rate in the juvenile stand was approximately twice that in the juvenile-thinned stand. The maximum snowmelt rates were five, three, and four times larger in the clearcut, juvenile-thinned, and juvenile stands, respectively, than the average over the season. The date of maximum melt was the same in the clearcut and in the juvenile stand, and one week later than that in the juvenile-thinned stand.

At the end of the melt season, the total accumulated lysimeter outflow was 16% less in the juvenile-thinned stand and 14% less in the juvenile stand than in the clearcut. The differences in total SWE loss calculated from the manual measurements were somewhat smaller than those measured with the lysimeters, the juvenile-thinned and the juvenile stands being 5 and 11% less than the clearcut, respectively. The variation in results was most probably due to the effects of high spatial variability on point lysimeter measurements relative to the site average and errors in the manual estimates due to drainage during snow core extraction.
The results show that daily and maximum melt rates, as well as the timing of maximum melt were not different in the juvenile stand than in the clearcut. However, in the juvenile-thinned stand the onset of melt was sooner and the rate at which melt water outflow accumulated was more rapid than in the clearcut, even though the maximum and average daily melt rates for the season were lower.

Melt rates at all sites were shown to increase with increasing air temperature above 0 ºC. This variable alone explained 63% of the variation in daily snowmelt at all sites. When the temperature of the snowpack at 10 cm above the ground was included in the regression analysis and when daily lysimeter outflow at each site was considered separately, 71 to 77% of the variability in melt was explained. Maximum wind speed and minimum relative humidity also varied among sites but as predictors explained less than 20% of the variability in daily melt.

The snowmelt lysimeters used in this study worked well during the 1995 melt season in the clearcut, juvenile-thinned, and juvenile stands at Mayson Lake. The design did not influence the accumulation or melting of snow above the lysimeter. The lysimeters were robust, transportable, and economical to build. With modifications to resolve the icing problems experienced in the mature spruce-fir stand, the lysimeters would be useful tools for studying differences in snowmelt, continuously over the season, among forest cover types.

This investigation provided a detailed comparison of daily snowmelt among examples of forest cover types common throughout south-central B.C., and the meteorological conditions associated with melt. To the best of the author’s knowledge, such comparisons for juvenile stands, relative to mature and clearcut conditions, were previously unreported. The results also provided the continuous data necessary for the investigation of snowmelt modelling described in Chapter 7.
CHAPTER 7

APPLICATION OF RESULTS TO SNOWMELT MODELLING

7.1 Introduction

The ability to predict snow accumulation and melt under diverse conditions is important in flood forecasting, water supply management, forest development planning, and in the study of hydrology. Interest in the snowmelt prediction has led to the development of numerous snowmelt models (Yang et al. 2000), ranging in complexity from physically-based or process models to empirical models. Models can be lumped, distributed, or a combination of the two. They can predict events over large land areas such as a watershed, or at much smaller scales such as a site or a single stand of trees.

Over large scales, or for periods of time greater than a day, the effects of the spatial variability in forest cover may be relatively small compared to the variability in weather and physiography. In this case, empirical models may provide reasonable estimates of snowmelt. At the stand-level, or over short periods of time, the effects of forest cover may be large. Modelling snowmelt under these conditions requires accurate representation of forest influences on snowmelt processes.

Snowmelt models developed for purposes such as flood prediction are usually empirical, based on statistical relationships between inputs and outputs. They are spatially lumped and do not generally represent physical processes in any detail (Blöschl et al. 1991a; Landsberg and Gower 1997). However, empirical models are generally simple, have minimal data requirements, and so are operationally practical. They may be adequate in circumstances where watershed conditions do not change or where daily or longer estimates of snowmelt are required. Temperature-index snowmelt prediction methods are examples of this type of model.
To understand how hydrologic processes, such as snowmelt, vary under diverse conditions, a model that represents the actual physical processes governing the system being studied is required. Physically-based models require a detailed understanding of the inter-relationships between site characteristics, such as topography, forest cover, and meteorological conditions, and the snowpack. The spatial and temporal variability in both the system and the processes being modelled must also be accounted for. As a result, physically-based models are potentially more transferable than empirical models and can be used to study varying conditions such as forest cover manipulation (Landsberg and Gower 1997). However, such models require values for many parameters that are often unavailable or poorly understood and that are difficult to measure. Consequently, physically-based models are generally used as research tools. An example of a physically-based hydrologic model developed for forested watersheds is the Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al. 1994). Where knowledge regarding specific processes is incomplete, physically-based models will also contain empirical components.

Models used to predict forestry-related changes in snowmelt generated streamflow, whether at the site or watershed scale, must consider spatial and temporal variability in both snow and forest cover. However, such data are often limited (Blöschl et al. 1991b). Hardy et al. (1997) suggested that confidence in the output of spatially-distributed models depends on the model’s ability to predict snowmelt based on physical processes at the stand scale. Research on the interactions between forest cover, meteorological processes, and snowmelt in boreal jack pine (Pinus banksiana Lamb.), black spruce (Picea mariana (Mill.), and aspen (Populus tremuloides Michx.) forests, and in maritime Douglas-fir forests, is ongoing (Hardy et al. 1997; Pomeroy et al. 1998; Storck and Lettenmaier 1999). In B.C., research is being conducted at various locations to compare snowmelt in the open with that under forest cover (Hudson 2000; D.Toews, pers. comm., 2000).

Yang et al. (2000) surveyed researchers world-wide and compiled a summary of snowmelt models used for hydrologic, weather forecasting, and global circulation applications. Of the 45 responses they received, only eight models were described as designed to improve our
understanding of snow hydrology, or for runoff forecasting (Table 7.1). Of the eight models, two were cited as able to account for spatial variability related to forest cover. Therefore, out of the 45 snowmelt models only two (DHSVM and SNTHERM modified for coniferous forests (Hardy et al. 1997)) appear to have applicability in forest development planning. Of the eight snow hydrology and runoff forecasting models, seven used an energy budget approach to estimate snowmelt and the eighth was based on the temperature-index method.

7.1.1 Temperature-index Models

Temperature-index models provide a simple method of estimating snowmelt from a single variable while all other factors influencing melt are parameterized. Air temperature is a useful predictor of snowmelt, because it is both easy to measure and provides a good indication of available energy. Temperature-index models for predicting snowmelt generally follow the form (Gray and Prowse 1993):

\[ M = M_r (T_a - T_b) \]  

where:  
\( M \) = snowmelt (mm) (over a selected time interval, often daily)  
\( M_r \) = melt-rate factor (mm °C\(^{-1}\) d\(^{-1}\))  
\( T_a \) = index air temperature (°C) (usually average or maximum daily)  
\( T_b \) = base temperature at which no snowmelt is observed (°C) (generally 0 °C)

The melt-rate factor is derived by regressing observed daily melt against air temperature and varies with atmospheric conditions, time, topography, cover, and snowpack properties. Melt-rate factors reported for open areas range from 3.5 to 6 mm °C\(^{-1}\) d\(^{-1}\), and for forested areas from 0.9 to 1.8 mm °C\(^{-1}\) d\(^{-1}\). The temperature-index model can also be modified to include the depth of water added through rain (Gray and Prowse 1993).

The temperature-index method has been used to predict snowmelt at both a point and for entire basins with varying success. Based on a re-analysis of U.S. Army Corps of Engineers
Table 7.1. A summary of snowmelt models that include the effects of vegetation and that were developed to understand snowpack processes or for runoff forecasting (modified from Yang et al. 2000).

<table>
<thead>
<tr>
<th>Model (Location)</th>
<th>Vegetation Type</th>
<th>Vegetation Height</th>
<th>Vegetation Density</th>
<th>Vegetation Cover</th>
<th>Allows for the Effects of Vegetation on Interception</th>
<th>Allows for the Effects of Vegetation on Albedo</th>
<th>Allows for the Effects of Vegetation on Surface Roughness</th>
<th>Allows for Spatial Variability in Forest</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHSVM (Washington)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>Interception is a function of leaf area index adjusted for temperature</td>
</tr>
<tr>
<td>HBV (Sweden)</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>accounts for vegetation height, density, and cover using two categories</td>
</tr>
<tr>
<td>ISBA - ES (France)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>SEMS (Colorado)</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>Interception is based on a predefined snow-holding capacity</td>
</tr>
<tr>
<td>SHAW (Idaho)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Interception is a function of leaf area</td>
</tr>
<tr>
<td>SNTHERM (N.Hampshire)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Uses empirical relationships based on measurements of snow on the ground</td>
</tr>
<tr>
<td>SOIL (Sweden)</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Interception is based on leaf area</td>
</tr>
<tr>
<td>SSIB (China)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>Interception = 0.1mm(leaf area index)</td>
</tr>
</tbody>
</table>

X included in the model
USACE data, Quick (1986) suggested that temperature accounted for 76 to 86% of the snowmelt during a 30-day analysis period. McGurk (1985) found that the temperature-index method worked reasonably well when applied in the same area for which it was calibrated. Rango and Martinec (1995) and others (Gray and Prowse 1993; Yang et al. 2000) found the temperature-index method to be reliable for predicting snowmelt over periods of a week to the entire season. They suggested that daily melt estimates based on this method may be inaccurate early in the season since nighttime refreezing of meltwater in the pack is not accounted for.

In a comparison of model types in south-western Alberta, Dickinson (1982) stated that for watersheds with both open areas and Engelmann spruce, subalpine fir, and lodgepole pine forest cover snowmelt estimated using the temperature-index method was as good a predictor of the spring hydrograph at the watershed scale as the more physically-based distributed model. At the stand-level, some researchers have found temperature-index models to be less reliable indicators of snowmelt in the open than in the forest (Dickinson 1982, Gray and Prowse 1993). Under open conditions, net shortwave radiation, as well as the latent and sensible heat fluxes, fluctuate widely and are not directly related to air temperature. Nevertheless, a wide variety of temperature-index models have been developed and are cited as producing good results in both forested and open environments (Gray and Prowse 1993).

The University of British Columbia (U.B.C.) Watershed Model (U.B.C. Mountain Hydrology Group 1993), developed for forecasting runoff input to hydroelectric reservoirs, includes an option for calculating snowmelt using the temperature-index method for forested and for open conditions. For temperature, the equation for the forest uses mean daily. In the open, the model assumes that the radiation component of the equation is most important and uses maximum daily temperature.

Though simple, this method does not provide a model which is readily transferable since the constants are based on a specific set of spatial and temporal conditions. Methods of estimating snowmelt through representation of physical processes are based on the energy balance. These models are more complex and data-demanding but are more likely to be able to predict melt
over shorter time periods (daily or less) and at smaller scales (such as a stand) than a temperature-index model.

### 7.1.2 Energy Budget Models

Energy budget models simulate the continuous gain and loss of energy to the snowpack. These models are essential for comparing diurnal processes under varying environmental and forest cover conditions. However, they require the input of site-specific meteorological conditions and must correctly represent the relationships between these variables, forest cover, and snowmelt. The relationships between these variables are generally modelled using an approach based on the equation presented in Section 2.4. The various components of the energy budget are most commonly estimated using equations developed by the USACE (1960) (Appendix 2).

For example, the U.B.C. Watershed Model (U.B.C. Mountain Hydrology Group 1993) provides for the option of calculating snowmelt by an energy budget approach. The model calculates snowmelt by elevation band and allows the user to enter information on the forested area per band and the density of the canopy. In the forest, modelled snowmelt is dominated by net longwave radiation and in the clearcut by shortwave (Quick 1986). Snowmelt from each elevation band is combined to produce the hydrograph at the outlet of the watershed.

Prevost et al. (1991) attempted to predict snowmelt at the stand-level in the Boreal Forest of Quebec. They measured melt using a 20 m$^2$ lysimeter over a period of eight clear snowmelt days and compared the measured outflow with the melt predicted using a temperature-index and an energy budget model. On a daily basis, they found that the temperature-index and energy budget methods predicted 86 and 88% of the measured snowmelt, respectively. Differences between the two models were greatest when air temperatures were low. In a comparison of continuous long-term data extending over three years, both models again compared well with the measured outflow. Prevost et al. (1991) suggested that under a dense forest canopy, radiation dominates the energy balance. They also suggested that energy exchange from wind, precipitation, and the soil are negligible and can be ignored. This being the case, they recommended use of the temperature-index method.
The complex interactions between energy budget variables complicate snowmelt prediction, particularly since the measurement and/or estimation of the contribution of the individual variables themselves is also complicated. Most studies have investigated the relative magnitude of energy budget components in non-forested situations (Table 7.2). Net radiation has been found to be the largest source of energy for snowmelt, on average 74% of the total based on the studies cited in Table 7.2. In a similar summary of earlier work provided by Gray and Prowse (1993), net radiation contributed over 50% of the energy for snowmelt, on average. Latent energy fluxes are generally due to condensation. Over large open areas, sensible energy fluxes have been reported as accounting for 5 to 79% of the total energy available for snowmelt (Table 7.2; Gray and Prowse 1993). Local advection of energy from snow-free patches, with higher surface temperatures, to adjacent snow-covered areas has been shown to greatly increase the sensible heat available to melt the remaining snow (Neumann and Marsh 1998). The effectiveness of advected energy decreases with increasing snow patch size, and increases with wind speed and decreasing patch size. In a mature boreal jack pine forest, researchers found that net convective energy accounted for 22% of the total available for melt (Woo et al. 2000).

Energy budget measurements and calculations under forest cover are much more complex than in the open. This is because forest cover acts as either a source or a sink of heat depending on the type of forest, particularly the distribution of stems and canopy, and on atmospheric conditions (Male and Gray 1981). Based on energy flux measurements at Mayson Lake, B.C., Adams et al. (1998) reported that the energy balance was dominated by net radiation. In the clearcut, shortwave radiation drove snowmelt whereas longwave radiation was the largest source of energy in the forest. Net radiation under the forest canopy was approximately 40% of that measured in the clearcut.

Storck and Lettenmaier (1999) used standard micrometeorological measurements to calculate the energy balance of snow intercepted on a Douglas-fir canopy and accumulated on the ground in a temperate maritime environment. They suggested that mid-winter melt was driven by turbulent heat fluxes, while the dominant source of energy during spring snowmelt was net radiation. In modelling melt at the stand scale, they assumed that shortwave radiation below the canopy was 16% of that in the open, and they reduced the longwave component by an
Table 7.2. A summary of the energy available for snowmelt ($Q_m$), snowmelt calculated assuming all available energy produces melt, and the relative contributions of average daily net radiation ($Q_n$), latent heat flux density ($Q_e$), and sensible heat flux density ($Q_h$), from field studies in large open areas.

<table>
<thead>
<tr>
<th>Author(s) (Year)</th>
<th>Location</th>
<th>Month or Season</th>
<th>$Q_n$ (Wm$^{-2}$)</th>
<th>$Q_e$ (Wm$^{-2}$)</th>
<th>$Q_h$ (Wm$^{-2}$)</th>
<th>$Q_m$ (Wm$^{-2}$)</th>
<th>Snow Melt$^1$ (cm d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harding (1986)</td>
<td>Norway</td>
<td>May</td>
<td>25</td>
<td>0.3</td>
<td>21.4</td>
<td>46.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Marks and Dozier (1992)</td>
<td>California</td>
<td>June</td>
<td>93</td>
<td>-71</td>
<td>92</td>
<td>115</td>
<td>3.1</td>
</tr>
<tr>
<td>Plüss and Mazzoni (1994)</td>
<td>Switzerland</td>
<td>May</td>
<td>36</td>
<td>-1</td>
<td>3</td>
<td>38</td>
<td>1.0</td>
</tr>
<tr>
<td>Fohn (1973)</td>
<td>Peyto Glacier</td>
<td>July</td>
<td>79.8</td>
<td>14.5</td>
<td>87</td>
<td>181.3</td>
<td>4.9</td>
</tr>
<tr>
<td>La Casiniere (1974)</td>
<td>France</td>
<td>July</td>
<td>20.8</td>
<td>-4.9</td>
<td>5.0</td>
<td>20.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Martin (1975)</td>
<td>France</td>
<td>Summer</td>
<td>32.0</td>
<td>-3.5</td>
<td>24.3</td>
<td>52.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Funk (1984)</td>
<td>Switzerland</td>
<td>Summer</td>
<td>90</td>
<td>-2</td>
<td>81</td>
<td>169</td>
<td>4.6</td>
</tr>
<tr>
<td>Calanca and Heuberger (1990)</td>
<td>China</td>
<td>NA</td>
<td>60</td>
<td>-15</td>
<td>17</td>
<td>62</td>
<td>1.7</td>
</tr>
</tbody>
</table>

$^1$ Melt (cm d$^{-1}$) = 8.64 $Q_m$ (Wm$^{-2}$) / $\rho_w$ L$_f$ B$_i$ where: $\rho_w = 1000$ kg m$^{-3}$, L$_f = 0.333$ MJ kg$^{-1}$ and B$_i = 0.95$

average canopy coverage factor. They found that estimates of leaf area index, the temperature at which falling snow became rain, surface roughness, and albedo were highly influential in the estimation of the melting of intercepted snow and, consequently, of snow on the ground. During the period of rapid snowmelt, their model was particularly sensitive to estimates of albedo. Using an albedo of 0.8 decaying to 0.4 over the melt season, substantially improved model output compared to results using albedos recommended by the USACE (1960). Other researchers have also found albedo to be an influential variable in modelling snowmelt at the stand-level using an energy budget approach. Hardy et al. (1997) found that simulations of snowmelt under black spruce were improved by lowering late-season albedo to 0.2. Gray and Prowse (1993) cite an albedo of 0.2 for a coniferous forest with snow as an over rather than below canopy value. Pomeroy et al. (1998) suggest that the assumption of decaying albedo over the ablation period is questionable where the surface is snow covered. They attribute
reductions in areal albedo to the progressive exposure of bare ground and vegetation rather
than to changes in snow cover reflectance. During the peak melt period, Adams et al. (1998)
measured an albedo of 0.7 over continuous snow cover at Mayson Lake, and an average albedo
of 0.6 was estimated over the entire melt period (D. Spittlehouse, pers. com. 2000).

At the watershed scale, Blöschl et al. (1991a) stated that, for small catchments, the main
difficulties in snowmelt modelling were related to the accurate estimation of the spatial
variability in albedo and in SWE. In an application of the DHSVM model in the Redfish
Watershed, located near Nelson, B.C., Whitaker and Alila (1998) found that adjusting the
albedo curves downward from those provided by the USACE (1960) considerably improved the
prediction of snowmelt at the watershed scale. Prior to the adjustment, snowmelt was
underestimated early in the season and overestimated later in the season.

It is likely that the albedo adjustments in snowmelt modelling compensate for various errors in
the representation of energy fluxes to the snowpack under differing forest conditions. The
sources of error are the estimation of short and longwave radiation under various forest cover
conditions, cloud cover, albedo, the contribution of latent or sensible energy fluxes,
imperfections in the mathematical representations of the processes, and averaging these
processes over too long a time period such as a day. Though adjustments to parameters such as
albedo enable modellers to simulate the snowmelt hydrograph, it remains unclear as to whether
they represent the actual value.

Validation of snowmelt models developed by parameterizing the representations of physical
processes under diverse forest conditions has been limited. Very little detailed snow and energy
budget field data are available for model verification. Of the models summarized by Yang et al.
(2000), only DHSVM and SNTHERM were cited as having been tested with forest field data.
Researchers responding to the survey by Yang et al. (2000) commonly stated that future
improvements to the performance of their models at the watershed scale would include a better
accounting for canopy-snow interactions at the stand-level and validation with field
measurements.
At the stand-level, work by Storck and Lettenmaier (1999) in a coastal Douglas-fir stand, and by Hardy et al. (1997) in both a boreal jack pine and an aspen stand, has focused on the interactions between forest cover and components of the snowmelt energy balance. Storck and Lettenmaier investigated rain-on-snow driven melt events under mature forest cover and shelterwood cuttings relative to a clearcut. Using standard meteorological measurements, they found that an energy balance approach to modelling both the melting of intercepted snow and snow on the ground produced accurate results at both the plot and stand scales. They recommended that similar research was necessary in cold climates, and where radiation dominated snowmelt events. Hardy et al. (1997) also found that an energy balance approach provided good estimates of melt water delivered to the soil surface. They suggested that understanding the relationships between snowmelt and forest cover, and the ability to model snowmelt at the stand-level, is prerequisite to confidence in the results of spatially distributed modelling at the watershed scale.

The validation of snowmelt model assumptions and output for diverse forest types requires an understanding of the snowmelt processes under specific cover conditions. Model validation with field data is particularly important when accuracy rather than the trend is a requirement and when the objectives of modelling are to test hydrologic hypotheses or evaluate forest management options in hydrologically sensitive watersheds. This information is not available for the cold climates and forest types found in the interior of B.C., where snowmelt events are predominantly radiation driven.

The objective of the research presented in this chapter was to use the results of the field research described earlier in this thesis in an application of the temperature-index and energy budget approaches to snowmelt modelling at the stand scale. The performance of the two approaches under clearcut, juvenile, and mature forest conditions were evaluated and the potential for improving predictions of snowmelt through the incorporation of stand structure characteristics and FOMR ratios in each approach was investigated.
7.2 Methods

Temperature-index models and an energy budget model were developed and applied to the clearcut, juvenile-thinned, unthinned, and mature stands at Mayson Lake. Daily snowmelt and meteorological data collected for the period March 27 (Day 86) to April 25 (Day 115), 1995 were used in both models. During this period snow was melting at all sites and the meteorological data set was complete. The intent was not to develop new models, but rather to understand how field data such as that from Mayson Lake might be incorporated in generalized examples of the two most common approaches to snowmelt modelling.

The coefficients for the temperature-index models were obtained through linear regression using SAS software (SAS Institute Inc. 1988). The significance of the relationships was determined using $\alpha = 0.05$. Residuals were plotted to visually evaluate the assumptions of normality and homogeneity of variance. Variables included in model development included the meteorological and stand structure variables determined previously (Chapters 6 and 5, respectively) to explain the greatest proportion of the variability in snowmelt among stands.

The performance of each model was assessed by comparing predicted daily melt, patterns of melt over the season, and accumulated melt at the end of the season with daily melt measured by the snowmelt lysimeters. Predicted and measured daily snowmelt and accumulated melt were graphed and visually evaluated. Root mean squared deviations ($\left(\frac{\sum (\text{measured daily melt} - \text{predicted daily melt})^2}{\text{number of observations}}\right)^{\frac{1}{2}}$) (Pysklywec et al. 1968) were calculated for each model and were used as quantitative indicators of their relative performance.

7.3 Results and Discussion

Of the daily temperature variables available for Mayson Lake, including average, maximum, minimum, average above 0 ºC, and snowpack temperature at various depths, the temperature-index models explaining the largest proportion of the variability in daily melt with the lowest standard error of the estimate were those based on average daily air temperature above 0 ºC and the temperature of the snowpack at 10 cm above ground (Table 7.3). These temperature-
index models accounted for 62 to 75% of the variability in daily lysimeter outflow over the melt period in each stand, with standard errors of the estimate of 0.19 to 0.28 cm d\(^{-1}\). When all stands were combined, the temperature-index model accounted for 63% of the variability in daily lysimeter outflow over the melt period, with a standard error of the estimate of 0.26 cm d\(^{-1}\) (Table 7.3). The inclusion of snowpack base temperature in the models for Mayson Lake was a slightly different approach to the standard, single variable, air temperature models cited in the literature and improved daily estimates by 14 to 21% \(i.e.\) the SE\(_e\) was reduced from 0.24 to 0.19 cm d\(^{-1}\) and from 0.28 to 0.24 cm d\(^{-1}\) in the juvenile-thinned and juvenile stands, respectively). This second variable is thought to address, at least in part, differences in internal energy of the snowpack among the study stands.

Table 7.3. Temperature-index models used to predict daily snowmelt at Mayson Lake and the associated coefficients of determination (single \(r^2\); multiple \(R^2\)) and standard errors of the estimate (SE\(_e\)).

<table>
<thead>
<tr>
<th>Temperature-index model</th>
<th>(r^2) or (R^2)</th>
<th>SE(_e) (cm d(^{-1}))</th>
<th>(p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted (M) <em>clearcut</em> (= 0 + 0.2 T_{air \ above \ 0 ^\circ C})</td>
<td>0.72</td>
<td>0.25</td>
<td>0.0001</td>
</tr>
<tr>
<td>Predicted (M) <em>juvenile-thinned</em> (= 0.2 + 0.2 T_{air \ above \ 0 ^\circ C} - 0.2 T_{snow})</td>
<td>0.75</td>
<td>0.19</td>
<td>0.0001</td>
</tr>
<tr>
<td>Predicted (M) <em>juvenile</em> (= 1.3 + 0.2 T_{air \ above \ 0 ^\circ C} + 7.6 T_{snow})</td>
<td>0.62</td>
<td>0.28</td>
<td>0.0001</td>
</tr>
<tr>
<td>Predicted (M) <em>all</em> (= 0.1 + 0.2 T_{air \ above \ 0 ^\circ C})</td>
<td>0.63</td>
<td>0.26</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

If additional lysimeter outflow data had been available, the models would have been used to predict daily melt in a different year from that for which they had been calibrated. Because of the data constraints, it was not possible to determine whether the model coefficients provided here could be expected to produce similarly reliable predictions in other years. Adding stand structure variables, such as average stand basal area (Chapter 5), did not improve model performance. This was likely due to the few stand types included in this research. Stand
structure variables may, however, be useful in the development of models for a broader range of forest covers.

Predictions of daily snowmelt using the full energy balance (Appendix 2) were not in good agreement with field measurements. Using the bulk transfer coefficients cited in Male and Gray (1981) (Appendix 2), the calculated 24 hour average latent and sensible heat fluxes in the clearcut were substantially larger than the measured values of zero and 19 Wm$^{-2}$, respectively (Adams et al. 1998). The latent and sensible heat fluxes during snowmelt at Mayson Lake were thought to be small due to atmospheric stability, and the largest fluxes measured to the snowpack were short and longwave energy (Adams et al. 1998). Pomeroy et al. (1998) state that all methods for estimating turbulent transfer overestimate the downward convective energy available for melt depending on the stability correction used and that estimates of melt rate are improved by simply using net radiation and ground heat flux. Based on these results, the complete energy balance model was simplified to a daily radiation budget model as follows:

$$M = (cSg(1 - \alpha) + 0.0864(c\varepsilon_a\sigma T_a^4 + (1-c)\varepsilon_t\sigma T_t^4 - \varepsilon_s\sigma T_s^4))100 / \rho_w L_f B_i$$

where:
- $M$ = melt (cm d$^{-1}$)
- $S_g$ = solar irradiance (MJ m$^{-2}$ d$^{-1}$)
- $\alpha$ = albedo of the snow surface
- $c$ = canopy cover factor (from Chapter 4) = 1 in the open
- $\varepsilon_a$ = emissivity of the sky
- $\varepsilon_t$ = emissivity of the trees = $\approx$1
- $\varepsilon_s$ = emissivity of the snow = $\approx$1
- $\sigma$ = 5.67 x $10^{-8}$ Wm$^{-2}$ K$^{-4}$
- $T_a$ = 24 hour average air temperature (K)
- $T_t$ = 24 hour average tree temperature (K)
- $T_s$ = 24 hour average snow temperature (K)
- $\rho_w$ = density of water = 1000 kg m$^{-3}$
- $L_f$ = latent heat of fusion = 0.333 MJ kg$^{-1}$
- $B_i$ = thermal quality of snow (fraction of ice per unit mass of wet snow)

The constant, 0.0864 accounts for the number of seconds in a day and the number of J in a MJ.
The emissivity of the sky was calculated using:

\[ \varepsilon_a = (1 - 0.84n)(0.72 + 0.005(T_a - 273)) + 0.84n \quad (7) \]

where: \( n \) = fractional cloud cover

The fractional cloud cover was estimated using \( 1 - S_g^{\text{measured}} / S_g^{\text{maximum}} \) (Spittlehouse and Black 1981). \( S_g^{\text{measured}} \) is the measured solar irradiance and \( S_g^{\text{maximum}} \) is the estimated solar irradiance if the day were clear. It was estimated from the relationship between daily solar irradiance and the day of the year (D), measured on clear days between days 86 and 115. For this short period, the relationship was linear as follows \( (r^2 = 0.99; \text{SE}_e = 0.42 \text{ MJ m}^{-2} \text{ d}^{-1}) \):

\[ S_g^{\text{maximum}} = \ 1.7 + 0.21D \quad (8) \]

### 7.3.1 Snowmelt Modelled for the Clearcut

The temperature-index model performed well in the clearcut, the root mean squared deviation equalling 0.26 cm d\(^{-1}\) (Table 7.4). This model predicted the accumulation of melt water outflow during 1995 within 13 and 5% of that measured with the lysimeter and snow tube, respectively (Figure 7.1; Table 7.5). The temperature-index model also predicted snowmelt timing well, but overestimated daily melt early in the season and underestimated mid-season melt peaks (Figure 7.1). The maximum melt rate predicted by the temperature-index model was underestimated by 7% of that measured with the lysimeter and the average daily melt rate for the season by 20% (Table 7.5). Note that daily melt and the accumulation of melt water during the season measured with the lysimeter differ from the SWE loss measured with the snow tube until the end of the season. This is attributed to the influence of high spatial variability on point versus site average measurements (Chapter 5).
Table 7.4. A summary of assumptions in the models used to predict daily snowmelt at Mayson Lake and their corresponding root mean squared deviations (RMSD).

<table>
<thead>
<tr>
<th>Forest cover</th>
<th>Albedo</th>
<th>Canopy Cover Factor</th>
<th>RMSD Temperature-Index (cm d⁻¹)</th>
<th>RMSD Radiation Budget (cm d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearcut</td>
<td>0.60</td>
<td>1</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>Juvenile-thinned</td>
<td>0.55</td>
<td>0.9</td>
<td>0.22</td>
<td>0.40</td>
</tr>
<tr>
<td>Juvenile</td>
<td>0.60</td>
<td>0.8</td>
<td>0.27</td>
<td>0.22</td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>0.50</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Ratio of snowmelt under forest cover to that in the clearcut from Chapter 4.

The temperature-index model performed well in this investigation both because it was calibrated for the specific study conditions and because latent and sensible energy fluxes to the snowpack at the study sites were small (Adams et al. 1998). Where latent and sensible energy fluxes are small, temperature-index models have provided good results under a variety of conditions from heavy forest to Taiga (Gray and Prowse 1993). Gray and Prowse (1993) have suggested that using a temperature variable such as air temperature above 0 ºC rather than the daily average would improve model performance, as in this study, where diurnal fluctuations in air temperature are wide. The temperature-index method may also be improved with additional years of data for model calibration. Other researchers have found that predictions are improved by adjusting the melt factor over the season since this coefficient may increase with increasing solar radiation and changing snowpack conditions (Gray and Prowse 1993).

In the daily radiation budget model, an average albedo over the melt period of 0.6 (Adams et al. 1998; revised D. Spittlehouse, pers. comm. 2000) was used to calculate shortwave radiation losses in the clearcut (Table 7.4). All other variables were measured in the field. Modelled net shortwave and longwave radiation fluxes are shown in Figure 7.2 and net radiation in Figure 7.3. Snowmelt predicted using the radiation budget model occurs when net radiation is positive as shown in Figure 7.1.
Figure 7.1. Daily (top) and accumulated (bottom) predicted (temperature-index and radiation budget models) and observed (lysimeter outflow and snow tube measurements of SWE loss) snowmelt in the clearcut at Mayson Lake.
Table 7.5. A summary of snowmelt predicted for March 27 to April 25, 1995, using a standard temperature-index and a daily radiation budget model, compared to measured snowmelt at Mayson Lake.

<table>
<thead>
<tr>
<th>Snowmelt Variable and Forest Cover</th>
<th>Measured Using the Lysimeter (cm)</th>
<th>Average Measured Using the Snow Tube (cm)</th>
<th>Predicted Using the Temperature-Index (cm)</th>
<th>% Difference % Difference</th>
<th>Predicted Using the Radiation Budget Model (cm)</th>
<th>% Difference % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearcut</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>-20</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Juvenile - thinned</td>
<td>0.5</td>
<td>0.6</td>
<td>0.4</td>
<td>-20</td>
<td>0.7</td>
<td>+40</td>
</tr>
<tr>
<td>Juvenile</td>
<td>0.4</td>
<td>0.6</td>
<td>0.4</td>
<td>0</td>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.3</td>
<td>0.3</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.4</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximum Melt Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>1.5</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1.4</td>
<td>-7</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>+13</td>
</tr>
<tr>
<td>Juvenile - thinned</td>
<td>1.2</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1.0</td>
<td>-17</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>+50</td>
</tr>
<tr>
<td>Juvenile</td>
<td>1.6</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1.6</td>
<td>0</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>-6</td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1.4</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
<td>NA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total Accumulated Melt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearcut</td>
<td>14.1</td>
<td>13.0</td>
<td>12.3</td>
<td>-13</td>
<td>14.6</td>
<td>+3</td>
</tr>
<tr>
<td>Juvenile - thinned</td>
<td>17.8</td>
<td>17.8</td>
<td>12.7</td>
<td>-29</td>
<td>19.0</td>
<td>+7</td>
</tr>
<tr>
<td>Juvenile</td>
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<td>16.9</td>
<td>13.1</td>
<td>+1</td>
<td>13.0</td>
<td>0</td>
</tr>
<tr>
<td>Mature spruce-fir</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
<td>6.3</td>
<td>9.7</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
<td>10.0</td>
<td>NA&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

1 Not available due to ice blockage in lysimeter drain.
2 Not included since these variables were overestimated using the snow tube measurements as a result of water loss during extraction.
Figure 7.2. Modelled daily (24 hour) short (top) and longwave (bottom) radiation fluxes to the snowpack at Mayson Lake.
Figure 7.3. Modelled daily (24 hour) net radiation fluxes to the snowpack at Mayson Lake.

In the clearcut, the daily radiation budget exactly predicted the average daily melt rate over the season and the total accumulated melt within 3% of that measured with the lysimeter (Figure 7.1). The radiation budget model overestimated maximum daily melt by 13% compared to the lysimeter measurement (Table 7.5). The root mean squared deviation for the daily radiation budget model was 0.26 cm d$^{-1}$ (Table 7.4), indicating similar performance to the temperature-index model.

Though both models performed reasonably well, the radiation budget model is preferred since it is the least parameterized and should, therefore, be the most portable. The meteorological variables used in both models fluctuate widely over a day. Following periods of sub-zero temperatures such as cold nights, significant outflow from the snowpack can not occur until the pack again becomes isothermal. The ability to account for this lag in melt generation and improved performance of the radiation budget model would be possible using a shorter time-step. An hourly time-step, for example, could account for heat lost from and gained by the
snowpack throughout the day and would likely reduce the underestimate on day 97 and the overestimate of melt on day 106.

7.3.2 Snowmelt Modelled For Juvenile and Juvenile-Thinned Stands

In the juvenile stand, the albedo of the snow surface was assumed to be the same as that in the clearcut (0.6) since only minor amounts of litter were observed on the snow surface. This albedo also produced snowmelt estimates most closely approximating those measured using the lysimeter. In the juvenile-thinned stand, an albedo of 0.55 resulted in the best approximation of melt. Even though the snow surface was not more highly littered in this stand, it was thought that this slightly lower albedo, in part, accounted for the effect of patches of bare ground that appeared earlier in the melt period in this stand than in the others and the possible additional energy for melt advected from these snow-free patches.

Solar irradiance was reduced by the ratio of snowmelt in the juvenile and juvenile-thinned stands relative to the clearcut (FOMR) described in Chapter 4 (Table 7.4; Figure 7.2). These ratios were used because relationships between canopy characteristics and below canopy net radiation are not available for the forest types studied and measures such as canopy gap fraction used in estimating below canopy radiation in other areas (Metcalf and Buttle 1998) are also not locally available. The FOMR ratios measured in each study stand were assumed to represent the effects of each stand type on melt processes and, therefore, broadly characterise reductions in solar irradiance under each forest type. Using FOMR to reduce solar irradiance produced better results than simply using canopy closure, the latter resulting in extremely large underestimates of accumulated snowmelt. Though crown closure is often used to account for the effects of forest cover on net radiation, the relationship between these variables does not account for repeated reflection of shortwave radiation, absorption of radiation reflected from the snowpack, or re-radiation of longwave radiation by the trees (Gray and Prowse 1993). The inclusion of melt rate ratios in the radiation budget model was a useful method of accounting for the various interactions between the trees and net radiation. Daily net radiation modelled in the juvenile and juvenile-thinned stands is shown in Figure 7.3. Although net shortwave is
Higher in the juvenile-thinned than the juvenile stand, net longwave is less, resulting in no
difference in net radiation between the two stands.

Similar overall results to those in the clearcut were found using the temperature-index and daily
radiation budget models to predict daily snowmelt in the juvenile stand. In the juvenile stand,
the daily radiation budget model closely estimated both average daily melt over the season and
total accumulated melt as measured by the lysimeter (Table 7.5). The radiation budget model
estimated the maximum daily melt rate within 6% of that measured. Both models
overestimated early season melt but closely predicted later melt (Figure 7.4). The root mean
squared deviations in daily melt using the temperature-index and radiation budget models were
0.27 cm d\(^{-1}\) and 0.22 cm d\(^{-1}\), respectively (Table 7.4). The radiation budget model would again,
however, be preferred since it is more likely to perform equally well in a different year or at a
different location and would not require re-calibration to the new conditions.

In the juvenile-thinned stand, both models underestimated daily snowmelt relative to that
measured with the lysimeter early in the season. Late in the season melt was underestimated
using the temperature-index model and overestimated with the radiation budget (Figure 7.5).
Total accumulated melt at the end of the season was best predicted by the daily radiation budget
model, within 7% of that measured with the lysimeter (Table 7.4). The apparent improved
prediction of total accumulated melt by the radiation budget was a result of compensating early
and late season errors. Average daily melt over the season was most closely estimated by the
temperature-index model. This variable was underestimated by 20% and overestimated by 40%
using the temperature-index and the daily radiation budget models, respectively. The
temperature-index model underestimated the maximum daily melt rate by 17% and the daily
radiation budget overestimated this variable by 50%. The root mean squared deviation in daily
snowmelt using the temperature-index model was 0.22 cm d\(^{-1}\) and using the daily radiation
budget was 0.40 cm d\(^{-1}\) (Table 7.5). Neither model performed as well in the juvenile-thinned
stand as at the other two sites. This may be a result of the more complex interrelationships
between forest cover and longwave and shortwave radiation under the relatively open canopy
and between the dark exposed stems in the thinned stand. The importance of models capable of
representing these complex processes is again highlighted by these results.
Figure 7.4. Daily (top) and accumulated (bottom) predicted (temperature-index and radiation budget models) and observed (lysimeter outflow and snow tube measurements of SWE loss) snowmelt in the juvenile stand at Mayson Lake.
Figure 7.5. Daily (top) and accumulated (bottom) predicted (temperature-index and radiation budget models) and observed (lysimeter outflow and snow tube measurements of SWE loss) snowmelt in the juvenile-thinned stand at Mayson Lake.
7.3.3 Snowmelt Modelled For the Mature Spruce-Fir Stand

In the mature spruce-fir stand, the albedo of the snow surface was assumed to be 0.5. This value resulted in a predicted total melt most closely approximating that measured with the snow tube. This value is slightly higher than the 0.4 suggested for late season melting snow in the literature (Grey and Prowse 1993) and over-the-canopy values often used in snowmelt models (Hardy et al. 1997). Solar irradiance was reduced by the FOMR for the stand (Chapter 4; Table 7.4; Figure 7.2). Modelled net radiation in the mature spruce-fir stand was similar to that in the juvenile stand and clearcut but lower than in the juvenile-thinned stand until the end of the melt season when net radiation was much lower in the mature stand than at all other sites (Figure 7.3). Although the net shortwave radiation was lowest in the mature stand, net longwave was highest (Figure 7.2). The modelled daily snowmelt could not be compared to outflow measurements since the lysimeters at this site froze (Chapter 6). Instead, the predicted accumulated melt was compared to the accumulated SWE loss determined from the snow tube measurements (Figure 7.6).

The temperature-index model predicted much larger values of daily snowmelt early in the season than did the daily radiation budget. Larger values of late season melt were predicted by the radiation budget (Figure 7.6). The comparison of predicted accumulated melt with the SWE loss measurements showed that the daily radiation budget model is a better predictor of accumulated melt in the mature spruce-fir stand than the temperature-index model until late in the season. The late season differences between the accumulated melt predicted by the radiation budget and those measured with the snow tube may be overstated as a result of problems associated with snow tube measurements late in the season (Chapter 6). The late season overestimates by the radiation budget may have been smaller when compared to lysimeter outflow measurements, or may have been reduced with hourly data and improved estimates of below canopy net radiation. These results indicate that the ability to account for specific physical processes is essential in complex environments.
Figure 7.6. Daily (top) and accumulated (bottom) predicted (temperature-index and radiation budget models) and observed (snow tube measurements of SWE loss) snowmelt in the spruce-fir stand at Mayson Lake.
7.4 Conclusions

Temperature-index and daily radiation budget models were used to predict snowmelt in a clearcut, two juvenile stands, and a mature stand at Mayson Lake. The temperature-index model was based on air temperature above 0 °C and snowpack base temperature. The daily radiation budget model was based on short and longwave gains and losses to the snowpack, with assumptions made regarding albedo, cloud cover, and the amount of short and longwave radiation intercepted by the juvenile and mature forest cover.

Both the temperature-index and radiation budget models performed well in the clearcut and in the juvenile stand. Both models closely predicted average daily, maximum, and total accumulated melt at these sites, though the temperature-index method did not perform quite as well in the clearcut. In the juvenile-thinned stand the temperature-index method performed better than the radiation budget late in the season when the latter substantially overestimated daily melt. In the mature spruce-fir stand, radiation budget model more closely predicted accumulated snowmelt as measured by the snow tube.

The good performance of the temperature-index method in this investigation is thought to be largely a result of calibrating the model coefficients to achieve the best fit between the dependent and independent variables for the study site and year. In the clearcut, the success of the temperature-index model is also a function of the extremely small latent and sensible energy fluxes to the snowpack at the study site. Nevertheless, considering that air temperature is one of the few operationally available field measurements, even limited application of this type of model may be useful for forest planning. However, since this model is empirical rather than physically based, it should not be expected to model melt as well under circumstances that vary from those for which it was developed such as in a different location or to evaluate the effects of changing forest cover on snowmelt. In contrast, the radiation budget model is expected to be portable and more suitable in complex forested environments, if relationships between below-canopy solar irradiance and canopy characteristics can be developed for B.C. forest types.
This investigation highlights the importance of quantifying the relationships between standard meteorological data, such as air temperature and snow temperature, and forest cover in order to develop tools for predicting snowmelt. Actual field measurements of albedo, in a variety of stands types would greatly improve our understanding of the application of simple mathematical representations of the complex energy budget processes under forest cover. This work has also shown that understanding the extent to which standard meteorological variables can be used to represent the energy fluxes to the snowpack is important in snowmelt modelling. Research to quantify the energy fluxes to melting snow under diverse forest cover conditions is prerequisite to the development of models at the stand scale. Awareness of how these relationships are likely to change with forest modification is essential in the development of watershed models for forest development planning.
CHAPTER 8

CONCLUSIONS

In B.C., spring snowmelt generates the large hydrograph peaks characteristic of most interior streams. Snow accumulation and melt research has historically focussed on flood forecasting and water supply management through field measurements in varying environments repeated in time. More recently, the fundamental processes affecting snow accumulation and melt have been investigated and the results incorporated into global circulation and physically-based watershed models. In most B.C. watersheds, the influence of forest cover on snow accumulation and melt are integral to the understanding of the local hydrology. However, relatively little research has been completed in B.C. either exploring the interrelationships between forest cover and snow accumulation or melt (Toews and Gluns 1986; Winkler 1999; Hudson 2000) or the fundamental meteorological processes affecting these relationships (Beaudry 1984; Nassey 1994; Adams et al. 1998), particularly in juvenile stands (Hudson 2000). Consequently, provincial guidelines for watershed management (B.C. Ministry of Forests 1999) are largely based on research in other provinces and countries. Such extrapolation of survey work in other areas for which little stand structure information has been reported and of detailed process research at specific research sites is problematic. Not only do questions remain regarding basic hydrologic processes over a broad range of environments but, with increasing regulatory constraints on watershed management, the lack of local information often results in unresolvable resource-use conflicts.

The primary goals of the research described in this thesis were to address gaps in hydrologic knowledge related to peak snow accumulation and melt processes in south-central B.C. This study investigated relationships between forest cover, meteorological conditions, peak snow accumulation, and snowmelt, measured in several stand types typical of southern-interior forests. The study also evaluated the simplification of these relationships for operational application at the plot and stand scale. The research provided new information regarding
fundamental hydrologic processes and methods to improve operational planning in forested watersheds.

The work involved detailed field measurements, data analyses, and modelling of peak snow accumulation, melt, stand structure, and meteorological conditions. In 1995, 1996, and 1997, SWE was measured at 576 stations over nine sites at Mayson Lake and Upper Penticton Creek. Of these sites, three were clearcut, and six were forested. The forested sites included two mature spruce-fir stands, a mature pine, a juvenile pine, a juvenile-thinned pine, and a juvenile spruce-fir stand. A detailed description of stand structure, using standard and modified inventory variables, was made at each measurement point. Continuous measurements of snowmelt using lysimeters, and of meteorological conditions, were made at Mayson Lake during the 1995 melt season. The specific results of this research, relate to peak snow accumulation, snowmelt, and snowmelt modelling.

Peak Snow Accumulation

Peak snow accumulation, represented by April 1st SWE, was 23% and 32% less on average in the mature spruce-fir stands than in the clearcut at Upper Penticton Creek and Mayson Lake, respectively, and 14% less in the juvenile and juvenile-thinned pine, and 11% less in the mature pine than in the clearcut. No difference in April 1st SWE was found between the juvenile spruce-fir stand and clearcut. The reduction in April 1st SWE resulting from forest regrowth relative to the clearcut, or recovery based on average stand height as defined in the provincial watershed assessment guidelines (B.C. Ministry of Forests 1999), was zero in the juvenile spruce-fir stand and 43% in the juvenile pine stands. The expected recovery according to the guidelines was zero, 25% and 50% for the juvenile spruce-fir, juvenile and juvenile-thinned pine stands, respectively. The large difference in measured versus guidebook recovery for the juvenile pine stand and the relatively good agreement for the juvenile-thinned stand, indicates that the variable tree height does not adequately represent the snow interception capacity of varying stand types.
The variation in peak SWE among stands relative to the clearcut corresponds to differences in stand structure. Of the stand structure variables considered in this study, those that reflected crown size and distribution over the study sites explained more of the variation in peak SWE than did other inventory variables such as average tree height. Research has shown that snow interception is a function of stand characteristics such winter leaf area or canopy gap fraction (Hedstrom and Pomeroy 1998). However, since these variables are not measured operationally, an estimate of crown volume, crown length, and canopy density, were used as potential indicators of standardised peak SWE in this study. Total estimated crown volume in the mature pine stand was one-third or less of that in the mature spruce-fir stands. Further, the mature pine stand had a single layered canopy compared to the multi-layered spruce-fir canopies. The multi-layered canopy structure likely increased the snow interception capacity of the spruce-fir stands relative to the mature pine. Crown length was greatest in the mature spruce-fir stands followed in decreasing order by the mature pine, the juvenile pine, and the juvenile spruce-fir stands. Crown length was found to be the forest inventory measurement most highly correlated with standardised peak SWE, explaining 73% of the variability among stands.

Snowmelt

In all years, differences in average snowmelt rates relative to the clearcut were largest in the mature spruce-fir stands (0.4 times that in the clearcut at Mayson Lake and 0.6 at Upper Penticton Creek), followed by the mature pine stand (0.7), the juvenile pine stand (0.8), and the juvenile-thinned pine stand (0.9). No difference in melt rate was found between the juvenile spruce-fir stand and the clearcut. The melt period was prolonged in the juvenile stands by up to five days over that in the clearcut and by up to 17 days in the mature stands, depending on year. Snowmelt ‘recovery’ was zero in the juvenile spruce-fir stand, 13% in the juvenile-thinned stand, and 29% in the juvenile pine stand. Expected recovery according to the watershed assessment guidebook (B.C. Ministry of Forests 1999) would have been zero, 25% and 50% (snow accumulation and melt are not considered separately in the guidebook), clearly an overestimate for each of the study stands respectively. The results show that juvenile stands affect peak snow accumulation at an earlier stage of development than they affect melt.
Snowmelt rates under forest cover relative to those in the open were found to be highly correlated with the square root of basal area which explained 79% of the variability among stands. Stand basal area provides an indication of canopy development and an indirect representation of beneath-canopy meteorological conditions and the energy reaching the snow surface.

Lysimeters used to continuously measure outflow at the base of the snowpack during 1995 showed that in the juvenile-thinned stand, snowmelt began earlier, accumulated more rapidly, and disappeared sooner than in either the clearcut and the juvenile-unthinned stand. The lysimeter data further showed that maximum melt rates were highest in the juvenile-thinned stand. The earlier onset of snowmelt and the more rapid accumulation of melt water outflow in the juvenile-thinned pine stand was thought to be a result of increased shortwave radiation at the snow surface in the thinned stand relative to the unthinned in combination with increased longwave radiation from the dark exposed stems relative to the more shaded stems in the unthinned stand and to their absence in the clearcut.

In the mature spruce-fir stand at Mayson Lake, below canopy wind speeds were reduced to zero and in the juvenile pine stands to one third of those in the clearcut. Snowpack temperatures were 2 °C colder, on average, in the mature spruce-fir stand than at the other sites prior to melt. The snowpack at all sites became isothermal on the same date. Once melt began, snowpack temperatures at 10 cm above the ground were highest in the juvenile-thinned stand followed by the clearcut and then the juvenile and mature stands. The air temperature above 0 °C and the temperature of the snowpack at 10 cm above the ground together explained 71 to 77% of the variability in daily snowmelt in the clearcut and juvenile stands.

Snowmelt Modelling

Several models were developed using the results of this research. The work has shown that simple ratios of snow accumulation, and of melt, under forest cover relative to the open may provide an ‘index’ to differences among stands, both juvenile and mature, where detailed stand
information is not available. Since these ratios are dimensionless their application is broad, restricted only by the stand characteristics they represent. Where stand characteristics are quantified, simple regression relationships between variables such as crown length and stand basal area can be used to predict FOSWE and FOMR for operational planning purposes.

A temperature-index model, incorporating both air temperature above 0 °C and snowpack temperature at 10 cm above the ground, worked well in the clearcut and juvenile stands. Inclusion of the snowpack base temperature improved daily estimates using this model by 14 to 21% (i.e. the standard error of the estimate (SEₚ) was reduced from 0.24 to 0.19 cm d⁻¹ and from 0.28 to 0.24 cm d⁻¹ in the juvenile-thinned and juvenile stands, respectively) when compared to the standard, single variable, air temperature model cited in the literature. The successful application of the temperature-index model at Mayson Lake was likely a result of both model calibration for the study conditions and because both the latent and sensible heat fluxes at these sites are small.

A simplified radiation budget model based on standard meteorological variables closely predicted both daily snowmelt and the accumulation of snowmelt over the season under diverse forest cover conditions. Standardised melt ratios were used to account for the influence of forest cover type on the radiation budget, producing good results. These ratios, if determined to be consistent for similar stands over a broader geographic area, would provide the opportunity to apply the radiation budget model operationally to predict snowmelt under changing forest cover conditions.

This research has also shown the importance of scale in snow accumulation and melt research and modelling. Scale considerations have been discussed in the literature based on modelled hydrologic processes. The field data collected as part of this work showed that snow accumulation and melt are influenced to a greater degree by forest cover at the stand scale (1 ha) rather than at the much smaller scale of the plots (0.005 ha) used in this study. In the models predicting FOSWE from crown length, precision increased substantially at the stand relative to the plot scale as shown by the SEₚ of 0.21 and 0.05 cm cm⁻¹, for each scale.
respectively. Similarly, at the stand scale the square root of basal area explained the variability in FOMR with a SE of 0.09 cm d\(^{-1}\) (cm d\(^{-1}\))\(^{-1}\) in comparison to 0.20 cm d\(^{-1}\) (cm d\(^{-1}\))\(^{-1}\) at the plot scale.

This thesis has provided new information on snow accumulation and melt in forest types common throughout south-central B.C., including the quantification of snow accumulation, meteorological conditions, and snowmelt in juvenile stands. Linkages have been shown between forest structure, meteorological conditions, and snow accumulation and melt. Relationships between forest inventory variables that reflect snow interception and energy available at the snowpack surface, such as crown length and basal area, will improve the assessment of snowpack changes associated with forest development. The knowledge gained through the quantification of snowmelt processes in this research will be useful in the development, calibration, and verification of melt models.

Several recommendations for further research follow from the work described in this thesis.

1. Snow accumulation, melt, and forest structure data from a broader geographic area, and from stands representing gaps in the current range of forest types studied, should be collected to further refine our understanding of the linkages among these variables.

2. Variables more reflective of both canopy surface area and tree distribution across the stand, e.g. canopy gap fraction, should be considered in further investigations to improve the prediction of SWE with varying canopy characteristics.

3. Lysimeter measurements should be undertaken, along with manual measurements, at Upper Penticton Creek and the data be considered in relation to the discharge at the streamflow gauges to link stand-level snow accumulation and melt processes to basin hydrology.
4. Investigation of energy fluxes to the snowpack under diverse forest cover should be continued, with particular attention to the radiation budget and albedo throughout the melt season.

5. Stand-level data should be incorporated into operational and research snowmelt models to validate assumptions and outputs and to broaden the application of local results.
LITERATURE CITED


http://www.elp.gov.bc.ca/wat/snow_bulletin/archive


Church, J.E., 1912. The conservation of snow - its dependence on forests and mountains. Scientific American Supplement LXXIV(1914):152-155.


APPENDIX I

Photos
Photo panel 1. The clearcut at Mayson Lake in summer (top) and winter (bottom), lysimeters, climate station, and snow course stations.
Photo panel 2. The juvenile-thinned pine stand at Mayson Lake in summer (top) and winter (bottom), lysimeters, climate station, and snow course stations.
Photo panel 3. The juvenile pine stand at Mayson Lake in summer (top) and winter (bottom), lysimeters, climate station, and snow course stations.
Photo panel 4. The mature spruce-fir stand at Mayson Lake, interior (top) and view from the road (bottom).
Photo panel 5. A snowmelt lysimeter and tipping bucket under construction at Mayson Lake (top) and the excavated lysimeter showing ice build-up in the mature spruce-fir stand (bottom).
Photo panel 6. The clearcut (top) and adjacent juvenile spruce-fir stand (bottom) at Upper Penticton Creek.
Photo panel 7. The mature pine stand interior (top) and canopy (bottom) at Upper Penticton Creek.
Photo panel 8. The mature spruce-fir stand at Upper Penticton Creek, view from the road (top) and view from the air (bottom).
APPENDIX II

Equations Used in Snowmelt Models
The energy budget model and its components were calculated using the following equations (from Gray and Prowse 1993 unless otherwise noted):

\[ Q_m = Q_n + Q_h + Q_e + Q_g + Q_a - \Delta U/\Delta t \]

where:
- \( Q_m \) = energy available for melt (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_n \) = net radiation (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_h \) = convective transport of sensible heat between the air and snowpack (pos. if from air to snow and neg. if from snow to air) (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_e \) = latent heat released through condensation of water vapour onto the snowpack or lost through evaporation (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_g \) = conduction of heat to the snowpack from the ground (MJ m\(^{-2}\) d\(^{-1}\))
- \( Q_a \) = advection of heat to the snowpack through rain (MJ m\(^{-2}\) d\(^{-1}\))
- \( \Delta U/\Delta t \) = rate of change of internal energy in the volume per unit surface area per unit time (MJ m\(^{-2}\) d\(^{-1}\))

and where \( U \) was assumed to be small relative to the other energy balance components and was omitted.

Once the amount of energy available for snowmelt was calculated, the amount of melt water (SWE (m)) was estimated from (Pomeroy and Goodison 1997):

\[ SWE = Q_m / (\rho_w \cdot L_f \cdot B_i) \]

where:
- \( \rho_w \) = density of water (~1000 kg m\(^{-3}\))
- \( L_f \) = latent heat of fusion (0.335 MJ kg\(^{-1}\))
- \( B_i \) = thermal quality of snow (generally between 0.95 and 0.97)

\[ Q_n = S\downarrow - S\uparrow + L\downarrow - L\uparrow \]

where:
- \( S\downarrow \) = solar radiation arriving at the snow surface (MJ m\(^2\) d\(^{-1}\))
- \( S\uparrow \) = solar radiation reflected by the surface = \( S\downarrow(\alpha) \) (MJ m\(^2\) d\(^{-1}\))
- \( L\downarrow \) = longwave radiation arriving at the snow surface (MJ m\(^2\) d\(^{-1}\))
  \[ = c(\varepsilon_s \sigma T_s^4 0.0864) + (1-c)(\varepsilon_t \sigma T_t^4 0.0864) \]
  (after Campbell 1977)
- \( L\uparrow \) = longwave radiation leaving the snow surface (MJ m\(^2\) d\(^{-1}\))
  \[ = \varepsilon_s T_s^4 0.0864 \]
\( \alpha \) = albedo
\( c \) = canopy cover factor (from Chapter 4) = 1 in the open
\( \varepsilon_a \) = emissivity of the sky
\( \varepsilon_t \) = emissivity of the trees = 1 (Price and Petzold 1984)
\( \varepsilon_s \) = emissivity of the snow = 1 (Price and Petzold 1984)
\( \sigma \) = \( 5.67 \times 10^{-8} \) Wm\(^{-2}\)K\(^{-4}\)
\( T_a \) = air temperature (K)
\( T_t \) = tree temperature (K)
\( T_s \) = snow temperature (K)
\( \varepsilon_a \) = \((1-0.84(n))(0.72 + 0.005(T_a - 273)) + 0.84n\)

where: \( n \) = fractional cloud cover = \( 1 - S_g \text{measured} / S_g \text{maximum} \) (Spittlehouse and Black 1981)

and: \( S_g \text{maximum} = 1.7 + 0.21D \) \( (r^2 = 0.99; \text{SE} = 0.42 \text{MJ m}^2 \text{d}^{-1}) \) (Chapter 6)
\( D \) = day of the year between days 86 and 115

\[ Q_e = D_e u_z (e_a - e_s) \times 0.0864 \]

where: \( D_e = 8 \times 10^{-6} \) MJ m\(^{-3}\) mb\(^{-1}\)
\( u_z \) = average wind speed (m s\(^{-1}\))
\( e_a \) = vapour pressure of the air (mb) = RH(\( e_s \)) \( \exp(17.2969(T_a/T_s + 237.3)) \)
(Price and Petzold 1984)

\( e_s \) = saturation vapour pressure (mb) = 6.11 over snow

\[ Q_h = (D_h u_z (T_a - T_s)) \times 0.0864 \]

where: \( D_h = 1.68 \times 10^{-6} \) MJ m\(^{-3}\) °C
\( u_z \) = average wind speed (m s\(^{-1}\))
\( T_a \) = air temperature (°C)
\( T_s \) = temperature of the snow surface (°C)

\( Q_p \) for melting snowpack where rain doesn’t freeze = \( (4.2 \times (T_r - T_s) \times P)/1000 \)

where: \( T_r \) = temperature of the rain, generally taken as air temperature (°C)
\( T_s \) = temperature of the snow surface (°C)
\( P \) = rain (mm d\(^{-1}\))

\[ Q_g = (\lambda_g(T_{soil-d} - T_{soil-s}) / z) \times 0.0864 \]

where: \( \lambda_g \) = thermal conductivity of soil = 2 W m\(^{-1}\) °C\(^{-1}\)
\( T_{soil-d} \) = soil temperature at depth \( z \) (°C)
\( T_{soil-s} \) = soil surface temperature (°C)
\( z \) = soil depth of temperature measurement (m)