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Alpine Snow Modelling Using Geographic Information Systems

by

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ABSTRACT

Geographic Information Systems (GIS) and satellite remote sensing are now used extensively in analyses of natural environments. GIS allow for the collation of existing databases and the integration of new information from widely varying sources.

This thesis used Landsat Thematic Mapper (TM) satellite data, Digital Elevation Model (DEM) data, and various mapped data layers to predict snow depth and snow-water equivalent depth for a small mountain watershed using a series of stepwise, multiple, linear regression models. The SPANS GIS integrated the multi-source data sets and provided the ability to model the regression results.

The best snow model produced a coefficient of determination or adjusted R^2 of 0.6370. The independent variables of elevation, incidence, tree height, and principal component four of the TM data could explain approximately 64% of the variation in snow depth. This result improved upon the best previous snow model result in the Marmot Creek Basin watershed by 6%.

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This thesis is dedicated to Elfriede

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LIST OF ACRONYMS

Academic Computing Services = ACS
Advanced Very High Resolution Radiometer = AVHRR
Alpine Snow Cover Analysis System = ASCAS
Digital Elevation Model = DEM
Earth Resources Technology Satellite = ERTS
Equi - Temperature = ET
File Transfer Protocol = FTP
Geographic Analysis and Display System = GADS
Geographic Information System = GIS
Geostationary Operational Environmental Satellite = GOES
Global Positioning System = GPS
Ground Control Points = GCP
High Resolution Visible = HRV
mean sea level = msl
Melt - Freeze = MF
Multispectral Scanner = MSS
National Oceanic and Atmospheric Administration = NOAA
National Topographic Series = NTS
Normalized Difference Snow Index = NDSI
Normalized Difference Vegetation Index = NDVI
personal communication = pers. comm.
Principal Component Analysis = PCA
Root Mean Square = RMS
Snow Geographic Information System = SGIS
Snowmelt-Runoff Models = SRM
Snow-Water Equivalent = SWE
Statistical Package for the Social Sciences = SPSS
Synthetic Aperture Radar = SAR
Systeme Probatoire d'Observation de la Terre = SPOT
Temperature - Gradient = TG
Thematic Mapper = TM
Triangular Irregular Network = TIN
Universal Transverse Mercator = UTM

CHAPTER 1

INTRODUCTION

1.1 Introduction

Snow is composed of ice crystals, chiefly in complex branched hexagonal form, and often agglomerated into snowflakes which may reach several inches in diameter (Linsley et al., 1982). In North America, studies of snow are thought to have originated in New York State during the early 1800s. The analysis of the role of snow in the hydrological balance has shown rapid progress in the last few years. Recent studies (Rango, 1992; Marks et al., 1992; Carroll, 1994) have used technological innovations such as satellite remote sensing and Global Positioning Systems (GPS) for snow studies. This is indicative of the movement towards increasingly automated snow research procedures in place of the traditional field based methods.

In the 1960s and 1970s new trends arose in the ways that mapped data were being used for different types of resource assessment and land evaluation. These trends led to the development of Geographic Information Systems (GIS) (Maguire et al., 1991). GIS are used in wide ranging types of research from city planning to environmental studies. GIS and satellite remote sensing are increasingly being used for evaluation and analysis of many different types of natural systems (Johnson and Paine, 1991; Elachi, 1994; Epp, 1994; Forsythe et al., 1995). Some applications provide solutions to environmental problems while others are used in a resource monitoring capacity.

Snow studies in mountainous areas provide an excellent opportunity to utilize GIS and remote sensing. The majority of precipitation in alpine environments occurs as snowfall (Golding and Swanson, 1986; Linsley et al., 1982); however, the actual role that snow plays in the water balance has not been determined precisely. This can be attributed to the difficulty in assessing the snowpack variation of high mountain basins which directly impacts the hydrologic regime. Snow studies often are limited by the high cost involved in the logistics of the study, especially if it involves extensive amounts of field work. These high costs can be offset through the use of GIS and satellite remote sensing which offer a more cost-effective alternative to manual measurement techniques.

This thesis used the SPANS GIS (Intera-Tydac, 1993) and the PCI Easi/Pace Image Analysis Package (PCI, 1991) to develop a series of stepwise, multiple, linear regression models for predicting snow depth and snow-water equivalent depth in a small mountain watershed. LANDSAT Thematic Mapper (TM) data, a dense grid Digital Elevation Model (DEM), and various mapped data layers were combined with historical snow data. The SPANS GIS was the integrating platform for the multi-source data sets and provided the ability to model the regression results into an interpretable map form or to export the results as digital data to be used for applications such as snow runoff models.

The recent pressure on hydrologic resources caused by rapid population growth and resource development increases the need for accurate measurement of Snow-Water Equivalent (SWE) in alpine regions (Elder et al., 1991). Snow and SWE are also important in agricultural areas where the water from snowfall has implications for crop productivity. In the past, snow studies were entirely field based as it was necessary to measure physically each snow characteristic that was to be studied. In the future, studies of snow will rely increasingly on automation and new technology. While manual measurement and field observations may not be abandoned totally, they will certainly have a reduced role due to innovations and technical advancements in snow studies using GIS and remote sensing techniques.

There are worldwide applications of GIS and remote sensing in snow related studies. In Canada, some snow applications that utilize GIS have included avalanche studies (Forsythe et al., 1995) and snow models (Granberg and Irwin, 1991). In Austria, new advances have been made recently in snow research involving the use of satellite sensors as well as sensors on board the space shuttle to collect various types of snow data. These new data are being utilized in the areas of snowpack research and glacier monitoring (Rott and Nagler, 1993). Rott et al. (1993) also have used these techniques in remote areas of the Antarctic to look at the signatures obtained from firn fields on glaciers. Rango and Peterson (1980) have many examples of satellites being used in snow cover mapping and runoff forecasting. The areas for these studies range from central Arizona to Norway to New Zealand. The difference in reflective properties between snow and other surfaces is normally quite large, thus making it possible to distinguish and map these areas within a catchment (Winther, 1992).

1.2 Objectives

The overall objective of this research was to develop a series of stepwise, multiple, linear regression models to determine the variation in snow depth, SWE depth, and snow density in a small mountain watershed. The models were based on variables derived from satellite data, Digital Elevation Model (DEM) data, and data derived from existing map information sources. These multi-source data were integrated and organized within a GIS framework and then combined with historical snow data for the regression analyses. The results of the regression models were then entered into the GIS and modelled. In order to achieve this objective a number of tasks were completed:

1) geometrically registered remote sensing and topographic data sets were prepared
2) the necessary snow data were assembled and the coordinates digitized for each sampling site
3) the GIS was used to integrate the multi-source data and to derive additional information from some of these data

4) field work was undertaken to quantify and verify some of the GIS inputs

Many observers feel that the full potential of both GIS and remote sensing can be best achieved if the technologies are integrated (Jensen, 1986). The advantages of using GIS include:

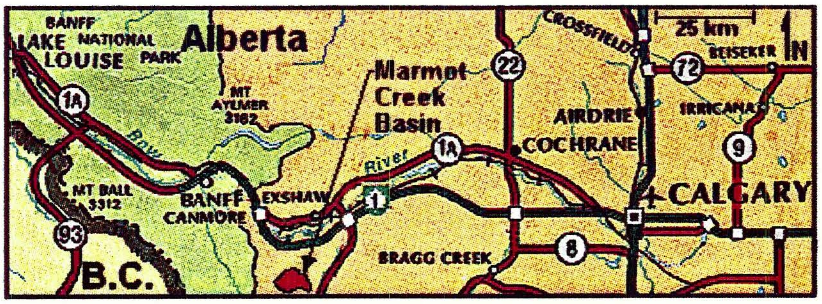
- GIS are designed to accept, organize, statistically analyze, and display diverse types of spatial data that are digitally referenced to a common coordinate system of a particular projection and scale (Avery and Berlin, 1992)
- GIS can be utilized according to user-defined specifications; the researcher can define the parameters for the study and add or delete information
- GIS can accept large volumes of spatial data from a variety of sources (Jensen, 1986)

The ultimate goal of this research is the development of a stepwise, multiple, linear regression model that can be used in any representative mountain watershed. This empirical model will predict snowpack properties in any alpine environment where land cover features and topography can be determined through the use of satellite imagery, DEM data, and GIS.

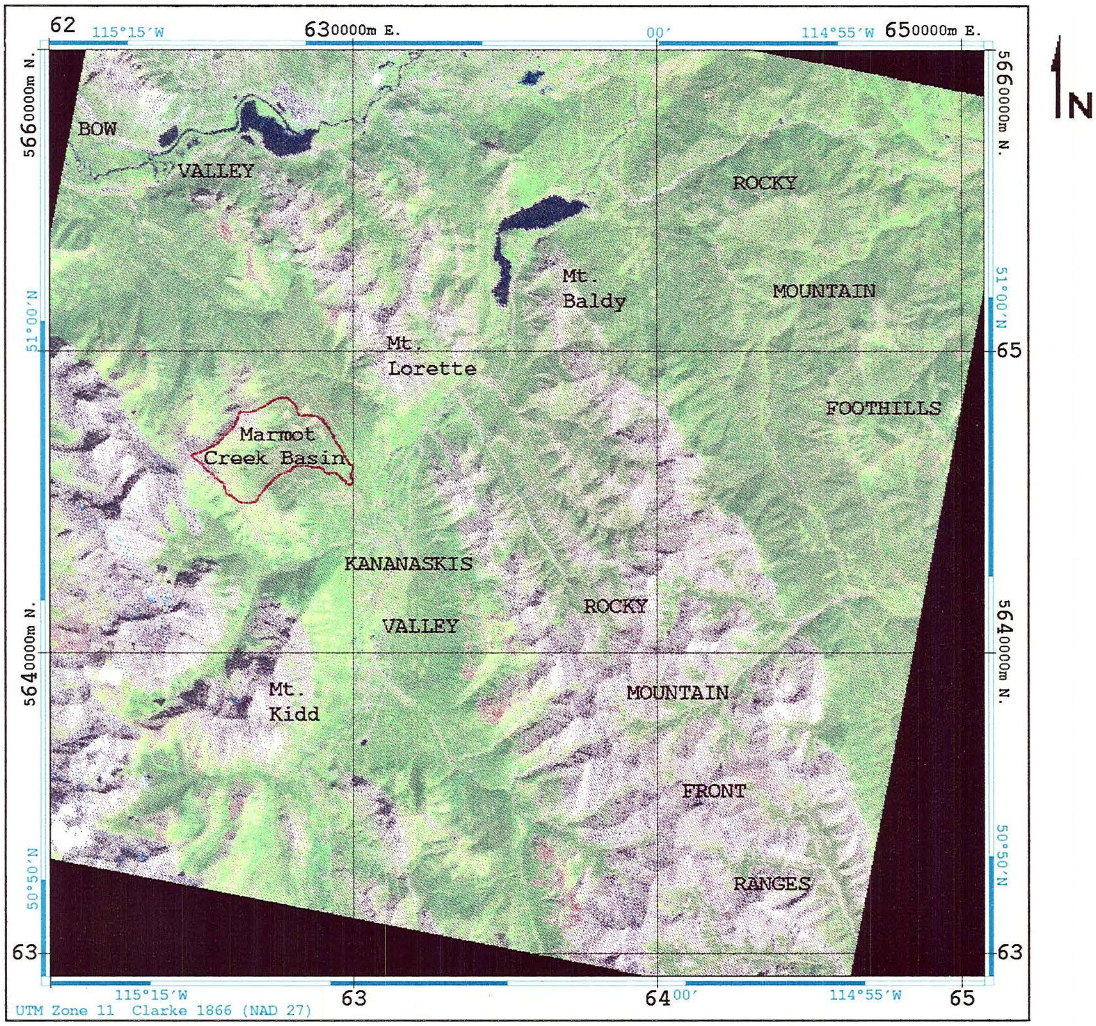
1.3 Study Area

The study area chosen was Marmot Creek Basin which is located in the Kananaskis Valley of southwestern Alberta, Canada. It is approximately 80 km west of Calgary, Alberta, and is roughly centred at:

50° 57' North Latitude
115° 09' West Longitude (Figure 1)



Area Overview



Satellite Image Composite: LANDSAT TM Bands 3,4,5
Scale 1:250000

Figure 1: The Marmot Creek Basin Study Area

This area was chosen because of its variable terrain and the availability of snow data, satellite imagery, topographic data, airphotos, and well documented vegetation maps.

It is a high relief area ranging in elevation from 1585 m to 2805 m above mean sea level (msl) and is approximately 9.4 km^2 in area. This basin is one of the oldest research basins in western Canada (Storr and Ferguson, 1972) and is just east of the Continental Divide. An average slope of 39 percent causes numerous access problems (Storr and Ferguson, 1972) or at least caused numerous problems prior to the development of the Nakiska Ski Area at Mount Allan. The basin has been heavily glaciated in the past which has resulted in rugged and variable terrain. Ground cover consists mainly of glacial deposits (till and glaciofluvial material) and postglacial deposits (talus, scree, and alluvium) with outcroppings of bedrock at higher elevations and along stream channels (Hillman and Golding, 1981).

The measurement of precipitation and other hydrometeorlogical variables began in August 1962 and for the most part was discontinued after 1980. The basin has (or had) the distinction of being the most heavily instrumented experimental basin in Canada (Swanson et al., 1986). The general aspect of the basin is easterly and forest covers the basin up to the treeline which ranges between 2135 m and 2285 m. The main tree types are lodgepole pine in the lower reaches and mature spruce at higher elevations up to the treeline.

1.3.1 Scale of the Study

The amount of data that are available for any study directly affects the nature of the analyses that can be undertaken. This study was to have looked at snowpack variation in the entire 9.4 km^2 area of Marmot Creek Basin. Historical literature on snow collection in the basin describes snow surveys that were conducted in all catchment zones of the basin including alpine and sub-alpine. The alpine zone data could not be located to be included in the analyses for this study. Technicians at the Northern Forestry Research Centre in Edmonton, Alberta (R. Hurdle, pers. comm.) and at the Atmospheric Environment Service in Saskatoon, Saskatchewan and Downsview, Ontario (B. Goodison, pers. comm.) were unable to locate and retrieve these snow data. Therefore the scale of this study was limited to the sub-alpine or forested areas of the watershed for which snow data were available.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Classical scholars such as Plato and Aristotle were the first individuals to identify precipitation as having some input to the flow of streams. The hydrologic cycle was not fully understood by these early scholars but they did make progress toward understanding at least a portion of the cycle (Linsley et al., 1982). The development of a more complete understanding of the cycling of water in the environment has occurred. Research programs have been initiated to try and improve existing knowledge of the components of the hydrologic system. Snow and associated attributes, such as snow-water equivalent, play a vital but as yet not completely understood role in the hydrologic system. This chapter examines snow and processes that affect the snowpack, the history of snow surveying, and snow research including regression modelling of snowpack attributes.

2.2 Snow and Snowpack Dynamics

When a parcel of air is cooled to saturation, water molecules will start to condense on water droplets if the water droplets exist. Each cm^3 of air may contain between 10 and 10000 condensation nuclei (D.J. Smith, pers. comm.). Droplets only exist if there is a contaminant (condensation nuclei) but will not automatically freeze. Freezing will only occur if the droplets contain a freezing nuclei. These are much rarer than condensation nuclei. In one cm^3 of air there will only be ten at -10°C. The colder the air is, the greater the probability of finding active freezing nuclei. When the temperature is -10°C, only one in one million droplets freeze; at -30°C, one in one thousand freeze while at -40°C, all droplets freeze spontaneously.

Generally, large intricate snow crystals form at relatively warm cloud temperatures where an ample supply of moisture is available. Smaller crystals form where temperatures are lower and the air holds less moisture. These hexagonal, crystal shapes can be very small stars, needles, or columns. The crystal structures are explained by four intrinsic axes. Three A-axes extend outward from a C-axis (Figure 2). The A-axes form plates while the C-axis forms columns or needles. Temperature and the amount of moisture available determine which of these types occur. Snowfall can be described by the most frequent crystal types (Figure 3). Snowflakes are formed by a coagulation of snow crystals in warm, moist conditions. The largest are most commonly formed of stellar crystals. On collision between crystals, adhesion can result from:

- interlocking
- riming
- vapour deposition
- sintering

Interlocking is simply the crystals physically joining together. Riming involves the

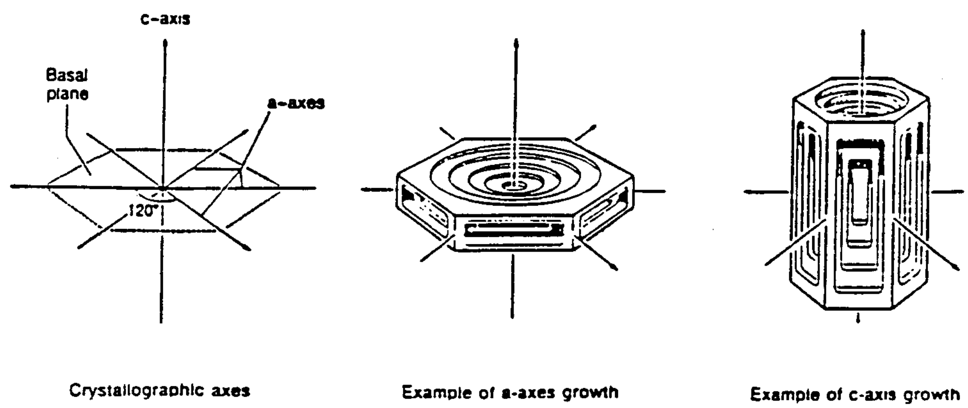
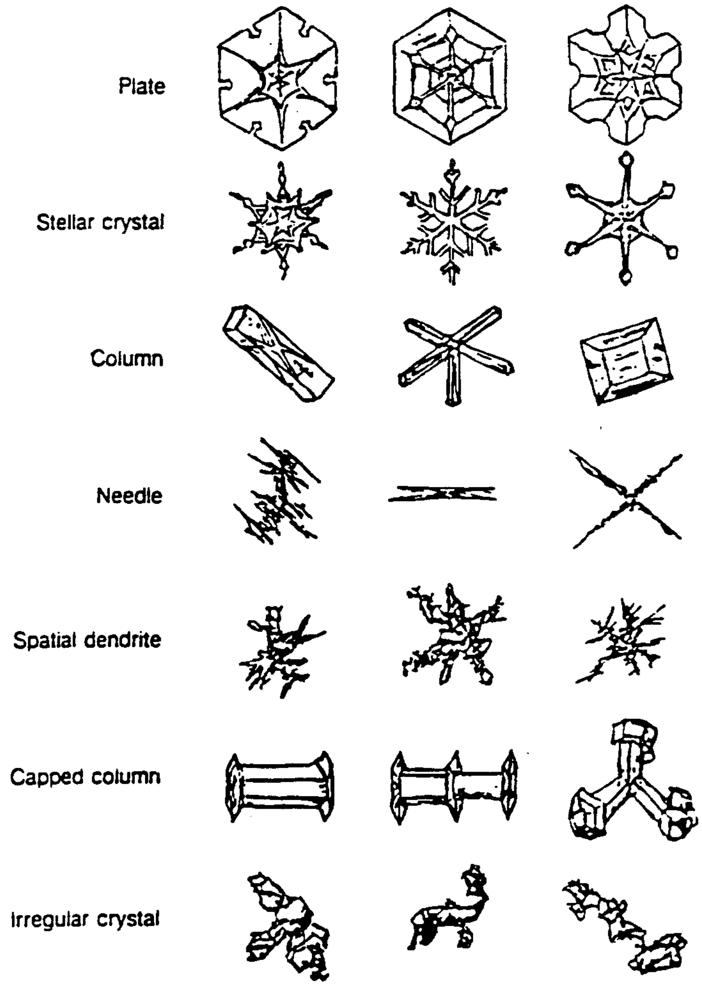


Figure 2: Crystallographic Axes of Snow and Ice Crystals
If the growth rate along the a-axes exceeds that along the c-axis, the crystals tend toward a plate-like structure. If c-axis growth dominates, the crystals assume a column-like appearance.
(source: after La Chapelle, 1969)



Type of Crystal	Temperature Range at Formation °C
Thin hexagonal plates	0 to −3
Needles	−3 to −5
Hollow prismatic columns	−5 to −8
Hexagonal plates	−8 to −12
Stellars and dendrites	−12 to −16
Hexagonal plates	−16 to −25
Hollow prisms	−25 to −50

Figure 3: Types of Snow Crystals and Temperature Range (source: after La Chapelle, 1969)

collision of the ice crystals with super-cooled water droplets, while vapour deposition occurs when water vapour is directly deposited on to the ice crystals. Sintering is an evaporation process where water molecules from one part of a snowflake are evaporated and condensed on another part of the snowflake (D.J. Smith, pers. comm.). Aggregation to form snowflakes ceases at approximately -20°C. Newly fallen snow has an average density of 0.1 g/cm^3 but changes take place after it reaches the surface (Linsley et al., 1982). Snow cover comprises the ground accumulation of snow, ice pellets, various forms of frost, glaze, liquid water, and various pollutants. Its structure is complex since it is made up of strata of varied composition, each determined by the producing storm, and subsequent weather (McKay, 1968).

Forest canopies, wind erosion and deposition (horizontal transport), sublimation, melting, crust formation, settling, crystal metamorphosis, and condensation all may modify the snowpack in significant ways (Timoney et al., 1992). McKay (1968) states that the greatest modification of snow cover results from the action of wind. Wind transports loose snow in a manner analogous to the movement of sediment by stream flow in a river channel, causing erosion of the snow cover and the formation of drifts and banks. Wind does play a significant role in the redistribution of snow in any watershed but metamorphosis also plays a large role. Investigations of the snow cover energy balance and snowmelt in remote alpine watersheds require detailed monitoring of the surface climate. Snow metamorphism, melting, and runoff are controlled by the magnitude of energy available to drive these processes, and these energy fluxes are determined by the combination of local meteorological inputs of precipitation and energy (Marks et al., 1992). The three types of snow metamorphism are:

a) Temperature - Gradient (TG)
- occurs in response to a strong temperature gradient

b) Equi - Temperature (ET)
- occurs because of the tendency of snow to simplify its form

c) Melt - Freeze (MF)
- occurs when snowpack temperatures reach approximately 0°C, analogous to fluctuations of freeze-thaw cycles

(La Chapelle, 1969)

TG reflects energy transfer processes through the snowpack. The temperature near the ground is generally higher than the temperature near the snowpack surface. Water vapour in the warmer part of the snowpack is transferred upward and since the colder upper region cannot hold as much vapour, crystal growth begins. ET occurs because the curvature of an ice surface influences the amount of water vapour that can be supported in the air above that surface. More vapour is supported over a convex surface than a flat or concave surface. MF is a general agglomeration of grains. It occurs due to alternating melt and freeze cycles in the snowpack. Dry snow is affected by TG and ET metamorphism, while wet snow is affected by MF metamorphosis. Generally, ET is dominant when snow is new. ET is a general rounding of the snow grains. TG occurs when energy transfer is happening in the snowpack. It is thought to be the dominant process in early winter (D.J. Smith, pers. comm.). MF occurs at the end of the snow season. It is thought to take place due to smaller grains having slightly lower melting temperatures than larger grains. Initially there is a strong structure but as the snowpack ages and ripens the structure becomes progressively weaker.

Metamorphism of the snowpack over the season affects the characteristics of the pack. Thermal properties as well as changes in conductivity and permeability occur. These changes have effects on the water content and density of the pack. Due to metamorphism, channels may be developed in the pack that move liquid water towards the surface-snow contact which affects the rate at which water may be released from the pack. This has implications for the yield from the snowpack especially if the ground was relatively dry when freezing took place. These types of losses from the snowpack cannot be determined precisely yet due to local variations in ground coverage and in snowpack characteristics.

Generally there are three features of the snowpack that are monitored in field based snow studies. These are snow depth, snow-water equivalent depth, and snow density. Snow depth is just the actual depth measurement from the top of the snowpack to the intersection with the ground surface. The snow-water equivalent is a measure of the amount of water that would occur in the same column of snow if it were melted and then measured. Generally these measurements are obtained by weighing the snow column in the field to determine the snow-water equivalent value. The density of the snowpack is a ratio of the snow-water equivalent depth to the actual snow depth.

Energy exchange between the snowpack, sun, and the earth is the controlling factor for snowmelt. Snow density increases with time due to settling and compaction. Ripe snow is snow that is saturated and isothermal at 0°C (Linsley et al., 1982). Isothermal implies a constant temperature throughout the snowpack (Dunne and Leopold, 1978). Ripe snow holds all the liquid water it can against gravity. Additional heat produces runoff. Energy for snowmelt is derived from:

- net solar radiation
- net longwave radiation exchange
- inductive and convective transfer of sensible heat to and from overlying air
- condensation of water vapour from overlying air
- conduction from underlying soil
- heat supplied by rainfall

Some non-precipitated forms of snow and ice are rime and hoar frost. Rime occurs on the downwind side of objects. Super-cooled water droplets freeze in a dull white, non-crystalline form. Hoar frost is a bright sparkling crystalline growth that occurs on and below the snow surface. It can be thought of as the snow equivalent of dew.

2.3 Snow Surveying

One of the earliest snow surveys was completed in 1834. The exact methodology used is uncertain but it is known that John B. Jervis, the chief engineer for a canal project in New York State, was concerned with the availability of water for the canal system. He was one of the first individuals that recognized the exact role that snow played in the hydrologic system (Harrington, 1953). The data collected were certainly not without some inherent error but suited their intended purpose which was to estimate water available for reservoirs. Charles Mixer in 1900 is generally recognized as having fathered today's sophisticated snow surveys (Kirk, 1977). James Church was also an early pioneer and is recognized for having developed the Mount Rose Sampler for collecting snow samples in the early 1900s. It was used to extract snow samples and consisted of 10 foot steel tubing sections that could be connected together. Modifications of this original design have occurred but the basic concept remains the same today. Snow tubes were first used in New York State in 1912 (Harrington, 1953). Snow stakes came into widespread use in the late 1940s in order to try and correlate snow measurements with data collected from snow tubes.

Snow gauging techniques were first developed in 1934. Since that time many researchers have worked to try and solve the problems in standardizing wind shields, gauge design, calibration, placement, and wind correction (Marks et al., 1992). From 1933 to 1948, improvements in snow measuring and monitoring techniques included such important items as the first use of helicopters on snow surveys, the development of new types of snow tubes and cutters, the design and testing of heated snow survey measurement gauges, the emergence of over-snow vehicles, the development of radioactive systems for measuring snowpack water content, and the new evolving language of snow hydrology and related equipment (Henderson, 1982). McKay (1968) states that it is generally very difficult to obtain adequate precision in areal water equivalent of snow cover because of the heterogeneity of the cover, and the limitations of the instruments. There is no completely satisfactory system for areal measurement, although statistical procedures and photogrammetry are useful in selected instances.

In thirty years, from 1949 to 1979, snow surveying changed from manual data gathering and forecasting to the electronic age (Shafer et al., 1989). Prior to the development of satellites, aerial photography had been used for determining the extent of snow cover in some studies (Henderson, 1982). Beginning in the early 1970s, the use of remotely sensed satellite imagery for data collection began. The early studies were primarily concerned with the use of the digital data for land cover classification, however, snow-related aspects of satellite remote sensing also came into effect during this time (Rango, 1992). Today we see the widespread use of sophisticated instrumentation such as satellites, passive microwave radar, GPS, and GIS in the study of the snowpack and its properties. The most recent studies using satellite technology (Rango, 1992; Winther, 1992; Marks et al., 1992; Carroll, 1994) have integrated many newly emerging methods and technological innovations for snow studies.

The properties of snowfall and snow cover are highly dynamic. Their physical characteristics change continuously in response to changing atmospheric conditions and gradients of temperature and vapour pressure. Thus, snow surveys are usually made at regular intervals to obtain an index of changes in the characteristics of the snow cover (Dunne and Leopold, 1978). Snow surveying can take many forms which include but are not limited to:

- 24 hour snow ruler - these are used at first line climatological stations; they assume a snow density of 0.1 g/cm^3
- snow board - separates new from old snow; there is a problem of the new snow compacting the old snow underneath in measuring total depth
- threads - these are buried and dug down to; they allow for determination of the amount of snow since the threads were laid down
- snow stakes - usually white and placed in the ground; depth is determined from marks on the stakes
- snow gauge - snow is melted to its water equivalent; there are wind problems associated with these gauges
- snow corers - extract snow cores; snow depth and snow-water equivalent depth can be determined
- rammsonde - these determine planes in the snow pack

Snow point measurements are the classical way to obtain high precision information on snow depth, SWE, snow density, and snow temperatures. They are very efficient and reliable especially in small basins or in simple terrain where a few points are representative of the whole area. Some disadvantages are that they can be time consuming and often delayed by bad weather conditions (particularly in mountain areas), costs may be considerable when repeated snow surveys are required (Lang, 1986), and there are problems of interpolation in the areas between snow point measurements. Surveying advances such as the development of GPS have helped to locate more precisely the coordinates of study sites (Marks et al., 1992). While manual data collection continues in some areas, the use of remote data collection has been underway for some time. Automated snow recording gauges such as snow pillows do not require that snow be measured after each storm event. The weight of the snow on the pillow is recorded by a computer attached to it. Satellite data is now also being used to map the extent of snow cover. The U.S. government is making National Oceanic and Atmospheric Administration (NOAA) satellite snow data available at no cost through anonymous File Transfer Protocol (FTP) on computer networks.

For many years snow surveys, usually in the form of point measurements on snow stake grids, were made near the end of the snow accumulation season, but are now usually made monthly or more often during the accumulation season. Daily observations from snow pillows are also used (Linsley et al., 1982). Performance trials have demonstrated that, realistically, acoustic sensors can be used to measure snow depth at a site, under a variety of conditions with a Root Mean Square (RMS) error of +/- 2.5 cm (Goodison et al., 1988). Bergman (1989) has developed an acoustic snow depth sensor that will help in the determination of SWE data that are already being collected at telemetred sites. This will lead to a better understanding of the water resources in the snowpack.

The most used ground based method for measuring snow cover is point measurement for areal analysis. Snow rulers or snow stakes are pushed into the snow to determine the depth. In remote regions, snow stakes or vertical poles in the snow are used. The problem with each of these is that SWE can not be measured. Snow pillows offer the advantage of being able to measure SWE but are very costly to setup and maintain. Snow survey techniques applied over a grid allow for the measurement of depth and SWE. A graduated hollow tube is used to push into the pack and extract a core for depth and SWE determination (Dunne and Leopold, 1978).

Satellite surveys of snow cover extent are the only remote sensing methods currently employed where it is not necessary to ground truth the satellite observations. In all other cases ground data are still being used to determine the accuracy of the satellite data. Radar and passive microwave data are currently being used to assess SWE over large and small areas. The passive data has had the most success so far when compared to ground observations of SWE over relatively flat prairie environments. Both radar and passive data have signal problems in mountainous terrain due to vegetation cover and relief (F. Thirkettle, pers. comm.). In these areas, techniques such as regression analysis which relate snow characteristics to easily observable satellite spectral signatures and DEM variables may need to be employed. These models may then provide another method to calibrate remotely sensed snow observations.

2.3.1 Problems with Measuring Snowpack

In a high mountain environment the influence of certain topographic variables can vary greatly. Elevation is one of the variables that has been identified as having a positive effect on snow depth (Cote, 1984; Golding and Swanson, 1986). Generally, as elevation increases so does snow depth. Other factors can also influence snow accumulation and the snowpack. Features such as chinooks, prevailing wind direction (Granberg and Irwin, 1991; Lapen, 1991), temperature inversions, solar radiation receipt, snow blowover, precipitation variability, and other factors such as sublimation and vegetative differences can influence snow depth in a basin. Bernier (1986) sees slope aspect as a variable that is of little importance in mid-winter, but of crucial importance in peak melt season with regards to the snowpack. Classification of a basin by slope, exposure, and elevation would be useful in establishing a snow course to measure snow data (Bernier, 1986). Studies of windy alpine environments indicate that there are problems with wind during snow deposition. Gauge placement is important in that wind can significantly alter gauge catch in rugged, high elevation regions (Marks et al., 1992). Deflation in windswept areas must be taken into account so as to obtain an unbiased estimate of snowpack characteristics.

Large variations in shortwave snow albedo due to surface contamination and various states of snow metamorphosis create serious problems for making high quality estimates of the snow covered area. This can lead to misclassification and makes mono-spectral satellite registered estimates of snow covered areas a difficult task. Better knowledge of temporal and spatial variability of albedo for both snow covered areas and snow free areas would be useful for a more accurate interpretation of satellite images, especially late in the melting season (Winther, 1992).

2.4 Snow Research, GIS, and Remote Sensing

2.4.1 Snow Research

Early snow studies were usually small scale and thus the scope of most projects was limited. The cost and time involved in doing snow research in the past was an obstacle to large scale snow studies (Linsley et al., 1982). Ground or field based studies usually involved a considerable investment in time and money to gain insight into the snow characteristics of a study area. Remote sensing techniques may offer an alternative to this but the accuracy of some methods has yet to be proven without the collection of ancillary ground based information. New technology is constantly being developed which leads to the problem of keeping up with these changes and trying to integrate them into projects that have already been started with alternative methods. Until remote sensing information on snow can be reliably and accurately collected ancillary ground information will need to be collected and utilized.

Recently the use of remotely sensed satellite data and GPS have come into focus for snow studies. The use of GIS has added an additional element. Granberg and Irwin (1991) have integrated the study of snow into a GIS environment. Marks et al. (1992) have integrated GPS into their study of a small mountain watershed in the Sierra Nevadas of California. Many different scales of study have been undertaken in widely varying areas. Golding (1974) modelled snow-water equivalent depth in a 9.4 km^2 research basin in the Canadian Rockies (Marmot Creek Basin which is used in this study). Dey and Sharma (1992) examined snow cover for a 162 000 km^2 area in the Himalayas of India and Pakistan. Rango (1992) focused on global applications of a Snowmelt Runoff Model (SRM). In almost all cases so far the need for ground measurements is still a necessity. However, future studies of snow are going to rely increasingly on automation and new technology.

Previous snow studies (Cote, 1984; Dickinson and Theakson, 1984; Golding, 1974; Golding and Swanson, 1986; Granberg and Irwin, 1991; Storr and Ferguson, 1972) have tried to determine the relationship between snow depth (or snow-water equivalent depth) and topographic and land cover variables. Research has also been initiated to determine snow-water equivalent depth and snow accumulation patterns from passive-microwave data (Giovinetto et al., 1991; Thirkettle et al., 1991). Synthetic Aperture Radar (SAR) has also been used for studies of snow and glaciers (Rott and Nagler, 1992).

2.4.2 Satellite Remote Sensing and Snow

In 1972, the first Earth Resources Technology Satellite (ERTS) was launched. This satellite later became known as LANDSAT 1. With the advent of this new technology, the science of satellite remote sensing started to evolve. In total, there have now been five LANDSAT satellites launched into orbit. There have also been other satellites launched including the Systeme Probatoire d'Observation de la Terre (SPOT) satellite in 1986. One of the main goals of the LANDSAT and SPOT research programs has been to use the resulting digital data for land cover classification. The satellite's capability to provide real-time data with synoptic and repetitive coverage gives significant advantages over traditional methods (Kushwaha, 1990). The main satellites involved in the remote sensing of snow are LANDSAT, SPOT, NOAA, and Geostationary Operational Environmental Satellite (GOES). The sensors on these satellites collect a wide range of digital data, some of which are useful in snow studies.

Kirk (1977) states that satellites orbiting the earth now map snow cover and, although depth and moisture content cannot yet be detected by this means, what they tell about the extent of snow has proven extremely accurate both in mountainous terrain and across flat land. Gray and Male (1981) state that ground based data will still be needed for calibration and verification and for filling in gaps in the satellite data set. These statements show that change has occurred in the remote sensing of snow. SWE can now be determined in fairly level prairie environments. Passive microwave data from the United States Nimbus series of satellites are processed and maps are prepared outlining the SWE depth. Ground observations of SWE have shown the maps to be accurate within ten mm. Thirkettle et al. (1991) have used passive microwave data to estimate SWE over snow covered areas of Alberta. Using their Geographic Analysis and Display System (GADS), maps can be produced within six hours of the time of the satellite passing over an area.

Traditional methods are still used today. These methods are a lot more costly than the data that is provided by satellite remote sensing but they provide a necessary and excellent source of data that can be used to verify and help improve land cover classifications derived from satellite digital data. Investigative fieldwork, airphoto interpretation techniques, and existing topographic and land cover maps can all be used. The validity (with respect to time period and accuracy) of maps and airphotos must be considered as well as the scale in comparison with the spatial resolution of the satellite data. Jensen (1986) states that the ideal or perfect remote sensing system has yet to be developed. With this in mind it is important to note the error that may result in the collection process of digital satellite data. Until errors such as noise and distortion can be completely removed from satellite systems, it will be necessary to have the traditional approaches with which to compare the satellite data. The advantages of satellite data are that they offer significant financial savings over manual data collection in the field and repetitive complete coverages can be obtained depending on research requirements.

Land cover classification from satellite imagery allows for both land cover classification at a single moment in time and for the delineation of changing land cover features from one time period to the next. The scale of the classification can vary from the global to the very localized. Loveland et al.(1991) used an Advanced Very High Resolution Radiometer (AVHRR) with a spatial resolution of 1 km to determine land cover characteristics in the conterminous United States. Kushwaha (1990) used LANDSAT false colour composites to determine forest types and change in a 12186 km^2 area in Western India. Dixon and Mack (1991) used a study area in Manitoba of 20.7 km^2 to discriminate crops through a combination of SAR and TM data.

Information from satellite sensors, which register surface reflective characteristics, is commonly used to describe remote areas such as snow covered mountainous terrain (Winther, 1992). Spatial and spectral resolution make the LANDSAT Thematic Mapper useful for detailed studies of snow (Winther, 1992). Winter TM satellite scenes have been used by Eyton (1989) and Skoye and Eyton

(1992) to map snow covered terrain in prairie environments. Holroyd et al. (1989) examined the usefulness of three different types of satellite data for snow cover mapping. LANDSAT TM, GOES, and NOAA AVHRR were all found to have differing strengths and weaknesses. Chang and Tsang (1992) have used a neural network approach to classify snow cover with some success from microwave satellite measurements. The advantage of this new technique is that it requires no assumptions (ie: normality) about the parametric nature of the distributions of the data to be classified. The disadvantage is that there is no equation where the importance of the different independent variables is known.

2.4.3 Remote Sensing in Mountainous Environments

The evaluation of any problem in mountainous environments presents a variety of obstacles not encountered in less rugged terrain. The complex interrelationships between geomorphic, climatic, and land cover variables cannot be interpreted easily. Research projects which are to be undertaken in remote locations with limited access must be considered carefully before they are initiated. Franklin et al. (1990) state clearly that in mountain areas a whole range of digital operations on remote sensing data are far more accurate with the incorporation of DEM data. Connery (1992) achieved an increase in classification accuracy of over 8% when DEM data were incorporated into the classification and tested through discriminant analysis.

Radiometry is highly variable in mountain areas. Radiation at any specific site can be a combination of direct solar radiation and reflected radiation from other areas in a mountain valley. This may lead to problems in determining the contribution from varying source areas. However, elevation, slope, and aspect can all be determined from DEM data which helps to alleviate some of these problems (McDermid, 1993). Hall and Foster (1994) have used DEM data and a winter TM image to map snow by elevation zone in Glacier National Park, Montana. A Normalized Difference Snow Index (NDSI) was derived using TM bands 2 and 5 (2-5/2+5). It was noted that DEM data registered to the TM data refined the accuracy of the snow mapping algorithm used and improved the determination of snow covered areas in this mountainous environment. One challenge that was noted in this study was the inability to determine snow cover in heavily forested areas with a dense tree canopy.

2.5 Snow Studies in Marmot Creek Basin

Annual precipitation in the basin is approximately 900 mm, of which 75 percent falls as snow. Average outflow from the basin is approximately half of this amount or 450 mm. Originally, the basin was established as an experimental watershed to determine the effect of forest clearing practices on stream flow (Golding and Swanson, 1986). It was for this reason that in the fall of 1974 approximately 50 percent of the forested portion of the Cabin Creek sub-basin of

Marmot Creek Basin (Figure 4) was clearcut in five separate blocks, which ranged in area from 8 to 13 hectares (Figure 5). An intensive snow survey was undertaken in 1969 to determine snow accumulation patterns on the forested part of Marmot Creek Basin before and after clearcutting treatment. Snow depth and snow-water equivalent measurements were taken in the last part of March using a 5x10 chain grid of numbered stakes (Water Survey of Canada, 1974). These surveys were developed in order to determine if there were snow accumulation differences in clearcut areas and areas adjacent to them. The results showed that there were increased amounts of snow in clearcut areas which could be attributed mostly to the lack of interception by forest cover. Golding (1973a) mapped snow cover in the basin using LANDSAT Multispectral Scanner (MSS) satellite imagery. The results were mixed due to problems with cloud cover and the 18 day return period of LANDSAT 1.

In a 1972 study using multiple regression models, the highest explanation of the variance in snow-water equivalent was 58% (Golding, 1972). This study used powers (ie: squares and cubes) of basic variables such as aspect and elevation as the independent variables. Squaring or cubing was used to transform the data and provided for a more "normal" distribution of the variables in the data set. Golding (1974) in his paper on the correlation of snowpack with topography found a high correlation between SWE depth and elevation. Previously, highly significant correlations were obtained when SWE depth was correlated with elevation

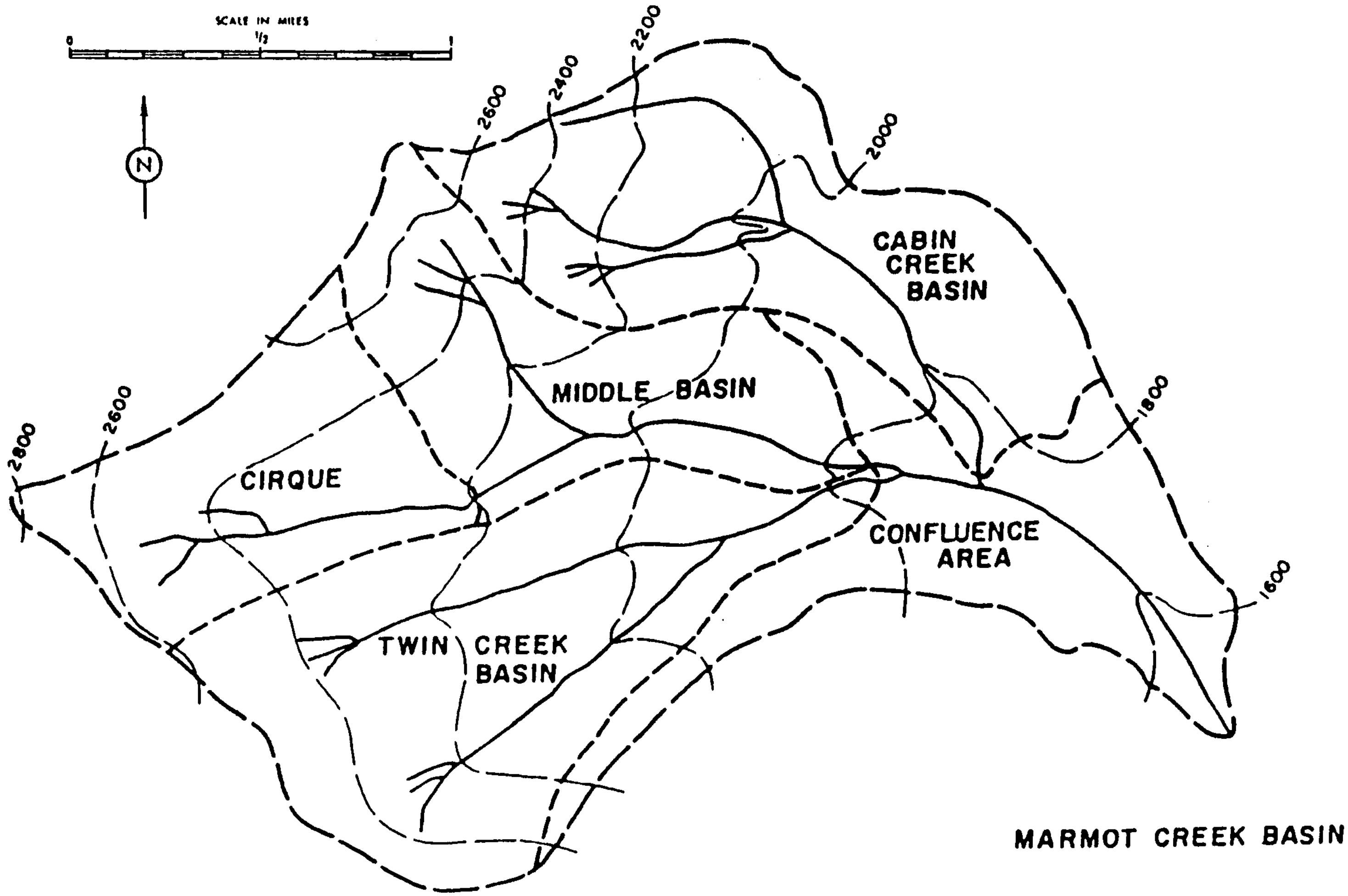


Figure 4: The Sub-basins of Marmot Creek Basin (source: Dickinson, 1982)

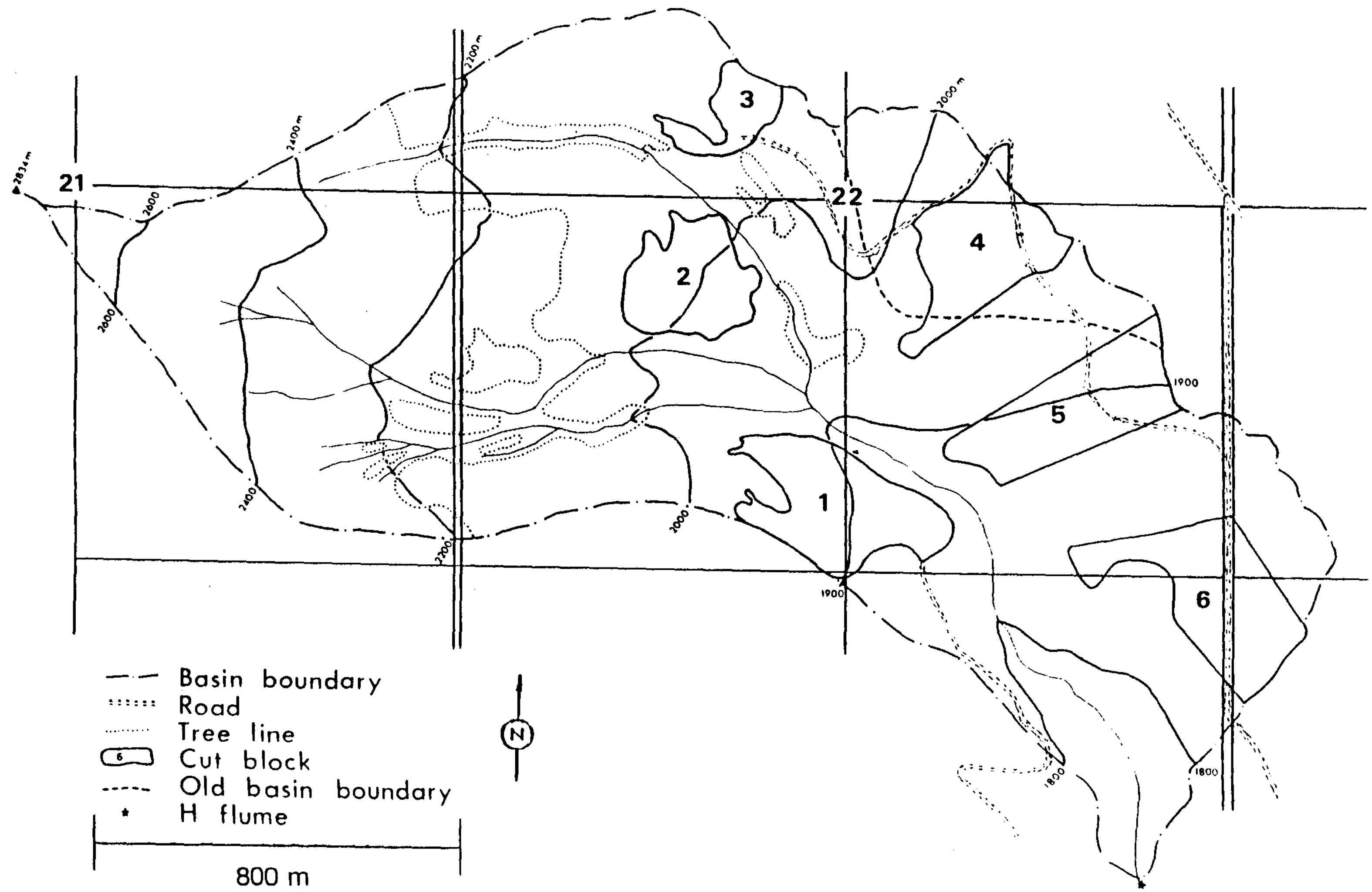


Figure 5: Cabin Creek Sub-basin Clearcut Blocks (source: Swanson et al., 1986)

and weighted by forest stand density. For April 1966, this correlation was 0.91 (Golding, 1970). SWE depth at maximum pack (approximately March 20) was correlated with eight combinations of the variables of elevation, relative topographic position, aspect, slope, and stand density (Golding, 1974). Some of these variables were squared and/or cubed. The results showed that 48 percent of the variation in snow accumulation could be accounted for using a combination of these variables in a multiple regression model. It was thus concluded that the variables having the greatest effect on the snow accumulation in Marmot Creek Basin were elevation, relative topographic position, aspect, slope, and forest density. Relative topographic positions were determined based on local topographic features of the basin. The categories used were:

1 - on ridge top
2 - in valley bottom
3 - on major slope
4 - on minor slope
5 - on flat or gentle slope (Golding, 1974)

Golding and Swanson (1986) have noted an increase in SWE depth in clearcut areas of the Cabin Creek sub-basin of Marmot. They have ruled out redistribution from adjacent areas and interpret the increase in SWE depth as being due to the elimination of interception from forest cover. Storr (1973) has noted that southeast and northwest winds predominate during snowfall. The focus here was on the wind variable in the redistribution of snow. While winds are generally light during snowfall, in-between periods can be characterized by strong winds, especially at upper levels in the basin. Artificial clearings (which optimize snow-water equivalent depths) should therefore be oriented southwest to northeast and should become progressively smaller with increasing elevation to maximize snow accumulation (Storr, 1973).

2.5.1 Nakiska at Mount Allan

The development of Nakiska for the 1988 Winter Olympics alpine skiing events was not met with enthusiasm by all parties concerned with the development. There were squabbles between various levels of government and also confrontations between environmentalists, wildlife biologists, and developers (who proposed the site venue at Nakiska). The decision to build at Nakiska was seen by many as an entirely political move. Despite extensive monitoring of Marmot Creek Basin which showed a lack of quality snow for downhill skiing and generally high winds, the decision to build was made in 1984. Horejsi (1986) notes that in reality, the decision (in favour of Mount Allan) had already been made by the Government of Alberta in 1981. A coalition called Ski Action Alberta, composed of skiers and environmentalists was formed in opposition to the decision in favour of Mount Allan. They were primarily concerned with the lack of snow on the site (as documented by the studies in Marmot Creek Basin), the generally high winds and the inadequacy of artificial snow as a substitute for adequate amounts of natural snow. Geist (1987) points out that the climate and snow conditions at

Mount Allan had been subject to long-term studies by the Canadian Forestry Service. A more unlikely site for the 1988 Winter Olympics was hard to imagine (Geist, 1987).

2.6 Snow Models and Runoff Models

Snow models are inherently related to runoff models because of the role that snow plays in the hydrologic regime of most watersheds. Models are usually concerned with snow-water equivalent depth but can usually be adapted to snow depth. Elder et al. (1991) chose parameters of elevation, slope, and solar irradiance from DEM data for a regression model because these variables represent physically based parameters that affect accumulation and ablation of snow. These were the independent variables and measured SWE data at corresponding points were the dependent variable in the model.

No general rule can be given for snowmelt prediction but it has been recommended that attention should be given to the following factors which have been shown to influence the deposition and depletion of the snow cover:

- topography
- altitude
- exposure
- wind conditions (Lang, 1986)

There are generally two methods for the prediction of snowmelt. The first is the full energy balance method where factors and values are experimentally discovered.

High quality data are needed to use this method.

It employs the equation:

$$Q_M = Q_{NR} + Q_S + Q_L + Q_P + Q_G \qquad (1)$$

where:
Q_M = heat used for melt or gained from refreezing of meltwater
Q_{NR} = net radiation
Q_S = sensible heat
Q_L = latent heat of condensation or evaporation
Q_P = heat provided by liquid precipitation
Q_G = heat from heat conduction in the snowpack

The second is the degree-day model. This is a very site specific method. It takes the positive degrees of mean daily air temperature to compute the corresponding melt rate.

2.6.1 GIS Snow Models

A GIS can be defined as: a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes (Burrough, 1986). Increasingly, in the future, GIS will play a role in snow studies. Elder et al. (1991) state that the use of a Geographic Information System will be helpful in future applications for a snow study in the Sierra Nevadas of California. The need to couple remote sensing techniques into such investigations was also recognized. This shows that indeed some investigations are still being done without the use of remote sensing or GIS. If larger studies are to be undertaken then these techniques must be integrated into future models. Extending databases both spatially and temporally will take some time, but satellite remote sensing data are improving the situation (Dey et al., 1992). Baumgartner and Apfl (1993) describe an Alpine Snow Cover Analysis System (ASCAS) which allows for the quantification of snow cover variation. The ASCAS integrates satellite remote sensing, GIS, database management, snowmelt runoff modelling, and the visualization of results. GIS based snow models could also be integrated into such a system to better quantify the amount of water available for the snowmelt component.

A Snow Geographic Information System (SGIS) has been developed to examine the feasibility of winter travel in Quebec (Granberg and Irwin, 1991). The SGIS employs weather and terrain data to predict spatial variations in snow cover properties. Topographic and vegetation coverages have been digitized and incorporated into the system. These coverages have been obtained at a 15 m resolution using air photo interpretation and photogrammetric techniques. The study integrated snow survey data with land cover variables to assess conditions throughout the snow season. GPS technology was also used to locate observation points in the study area. This methodology combined with the use of technologies such as GPS further develops and adds value to the use of GIS in snow related studies.

GPS can now be used to pinpoint locations with sub-metre accuracy. This makes the use of GPS an attractive alternative to traditional surveying methods. GPS receivers are lightweight and compact and are well suited for use in areas with remote access. Snow surveys in alpine watersheds are thus a perfect application for this technology. Marks et al. (1992) have used GPS in their study area in California's Sierra Nevadas to locate snow survey points precisely. Real-time location in the physical world "eliminates" the necessity of carrying bulky survey equipment into the study site.

2.6.2 Snow Runoff Models

There are traditional ground based methods and newly emerging remote sensing techniques for measuring snowpack characteristics. Although there is a good correlation between snow survey data and seasonal runoff, it is now recognized that reliable water supply forecasts cannot be made from snow surveys alone (Linsley et al., 1982). The application of snow survey data to the preparation of water supply forecasts is appealing because of the rather simple relation envisioned (Linsley et al., 1982). However, other factors such as groundwater storage need to be factored in because of their influence on the hydrologic regime. It must also be recognized that the snowpack is harder to quantify at higher elevations due to the lack of measuring stations.

The types of data which satellites can provide for hydrological models include snow cover, snow-water equivalent, cloud cover, precipitation, and evapotranspiration data (Kite, 1989). They also provide data for land cover classification which has proven useful (Kite and Kouwen, 1992) in watershed modelling. Rango (1992) notes that the SRM has experienced wide application since satellite observations of snow cover began. Many countries are using this model primarily in mountain snowmelt basins. The model is a relatively simple degree-day runoff model that is being looked at in terms of global climate change. Snow cover depletion curves derived from satellite imagery are used and interpolated into the SRM. The SRM also requires daily input of temperature and precipitation variables from climatological stations and the area of the basin covered by snow derived from remote sensing observations. A degree-day factor is used where degree-day values are compared with the daily decrease of snow-water equivalent which can be measured by conventional ground based observations (Rango, 1992).

Linear regression models assume that basin discharge, the dependent variable, increases by a constant amount with a unit increase in the value of basin snow cover area, the independent variable (Dey et al., 1992). The problem here is that the assumption of linearity usually does not hold true due to limits that the independent variable imposes on the dependent variable. Using procedures such as logarithms, squares, or cubes on the original data can help to solve this problem (Golding, 1972). Alternative models include lumped hydrological models which can be improved by computing the rainfall-runoff and snowmelt processes separately for different land cover classes (Kite and Kouwen, 1992). This requires the delineation of these classes through satellite classification which would bring another dimension to the hydrologic model. Division of larger catchments into sub-basins allows for the surface runoff peaks in these smaller areas to be distinguished as sharp peaks and incorporated into optimized parameters for the model. The model is run at different times of the year to determine the contribution of each unit in the basin to the runoff at those times.

In all cases of forecasting snowmelt runoff and particularly in large areas with poor ground information, the possibilities of using satellite snow cover information should be taken into consideration.

This can be argued for the following reasons:

- they may complement and improve the existing ground survey information, but cannot replace them completely
- in those remote areas where ground survey data are not available, satellite data are often the only source of information on the snow cover; simple as well as more sophisticated methods are available to make use of satellite information
- the methods for snow cover estimation on the basis of a simulation model have to be further developed (Lang, 1986)

Satellite observations of the snow line have been determined in mountain areas (Kirk, 1977; Gray and Male, 1981). These observations are quite simple in that it is a question of whether snow is present or not. Complex uses of passive microwave satellite data have been attempted to try and determine SWE in mountainous areas. These have not had much success however due to the signal interference that occurs in mountainous regions.

Snowmelt determines the distribution of runoff in mountainous environments. Unsteady, spatially varied flow is the contribution of snowmelt to stream flow. The snowmelt hydrograph represents an integrated number of processes.

These are:

- the melt process
- translation and storage of the melt product in the snowpack
- transfer to the measuring station

Some mechanisms for delays in runoff include storage in snow, storage in the ground, and storage in channels (Linsley et al., 1982). There is a regular diurnal cycle of lows and highs in runoff. The diurnal cycles represent lag effects of two to three hours between receipt of radiation and snowmelt. Further lag results from snowmelt stored in the snowpack. Snowmelt rarely produces a sharp sudden discharge (L. Nkemdirim, pers. comm.). This is because melt rates for snow cover are never terribly high, lapse rates affect different parts of basins, and when the highest summer temperatures are reached most basins are already snow free. Runoff peaks usually occur in the early evening with lows occurring just before noon. The volume of runoff depends on the:

1) water equivalent of the snow cover
2) water absorbability of a river basin or its physical characteristics such as slope gradient, depressions, and soil type
3) evaporation of meltwater during the flood period

If factor 1 is high and 2 and 3 are low then runoff will be high.

2.7 Regression Analysis

Regression analysis is a heavily used tool in quantitative geographical research and is an all encompassing term for many different types of predictive equation models. These include simple linear, stepwise, and multiple regression models to name a few. The technique is mostly applied to variables that can potentially take any value within some continuous range (Ferguson, 1977). Regression methods are used to fit models for a dependent variable as a function of one or more independent variables (Weisberg, 1980). Ebdon (1987) says regression is a way of measuring the dependence of one variable on another. The range of the regression coefficient is from plus one to minus one. A perfect positive linear relationship is plus one, while a perfect negative relationship is minus one. Zero implies no relationship. Ebdon (1987) identifies two practical considerations for regression analysis in Geography:

- the relationship between most geographical variables is not perfect
- the relationship between many geographical variables is not linear

The multiple regression equation is of the general form:

$$Y = B_0 + B_1X_1 + B_2X_2 + ... + B_nX_n \tag{2}$$

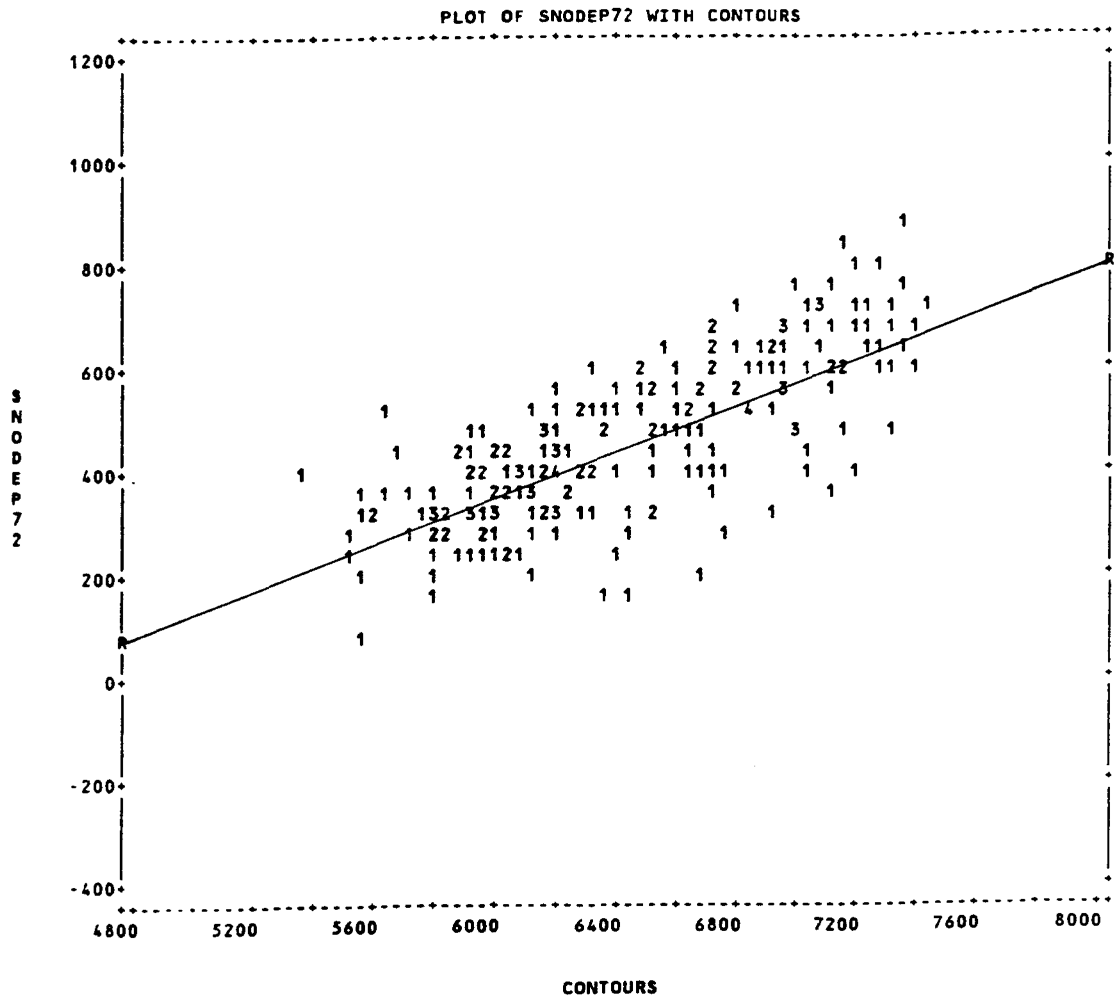
where:
Y = dependent variable
B_0 = constant
B_1 = beta value for independent variable one
X_1 = value of independent variable one
B_2 = beta value for independent variable two

X_2 = value of independent variable two
B_n = beta value for independent variable n
X_n = value of independent variable n

The number of independent variables that are significant determines how many coefficients are in the equation. Regression can be used for prediction and to explain the relationship between the variables. A positive relationship implies that as one variable goes up so does the other. A negative relationship implies that as one variable goes up the other goes down. The average relationship between the two variables is represented by a best fit line (Figure 6). This line minimizes the sum of the squared deviations of the points from the line and is thus the least squares, best fit line. The data portrayed are snow depth for 1972 (snodep72) and elevation (CONTOURS in Figure 6) in Marmot Creek Basin. There is a strong relationship between these two variables as can be seen by the correlation value of 0.75942. The R^2 of 0.57672 means that almost 58% of the variation in snow depth can be accounted for in a simple linear regression model by elevation. Elevation and SWE depth (which is closely related to snow depth) have been shown to be highly correlated (Golding, 1970). In performing a regression analysis there are several assumptions and conditions that must be met concerning the variables being analyzed. These include the following:

- that each x and y value is observed without measurement error (analysis will be biased if this is not true)
- the relationship between x and y is linear
- the distribution of the residuals has a mean of zero
- the variance of the residuals must be independent of the value of x
- the residuals must be independent of each other
- the distribution of x and y should be normal

(Ebdon, 1987)



229 cases plotted. Regression statistics of SNODEP72 on CONTOURS:
Correlation .75942 R Squared .57672 S.E. of Est 99.24238 2-tailed Sig. .0000
Intercept(S.E.) -1021.5452(84.32776) Slope(S.E.) .22955(.01305)

Figure 6: Regression Best Fit Line

Kennedy (1985) states that it is extremely convenient to assume that errors are distributed normally, but there exists little justification for this assumption. When faced with non-normality one can employ robust estimators or transform the data to create transformed errors that are closer to being normally distributed. The coefficient of determination, or R^2, is a measure of the amount of variation in the dependent variable that is explained by the independent variable(s). The adjusted R^2 is the actual statistic that is now used for determining the amount of explanation in a model. It takes into account the degrees of freedom for the model. It is necessary to use the adjusted R^2 because adding extra regressors will always cause the R^2 to rise but this addition in explanation may not be statistically significant (Kennedy, 1985).

2.7.1 Stepwise Regression

Stepwise regression is a multiple regression technique that looks for the best combination of independent variables that can explain the variation in a dependent variable. Yeates (1974) states a stepwise, multiple, linear regression is really a search procedure, for the technique enters each variable, one at a time, into the regression equation in the order of its contribution to the total variance, the greatest contributor being entered first. Thus, out of any number of independent variables, the technique "searches out" the greatest contributors to the total variance and effectively rank orders them. In essence then, the procedure selects the best regression equation.

The usual significance tests in a stepwise, multiple regression problem are approximate at best (Sokal and Rohlf, 1981). This is because in testing a large number of possible combinations of predictor variables, unplanned tests are carried out. The addition and deletion of variables in the model are not specified and are limited only by the probability values chosen for the analysis. Probabilities are conventionally determined for performing planned tests. Thus, the probability to enter (P-to-enter) and probability to remove (P-to-remove) values should not be interpreted as conventional levels of significance (Sokal and Rohlf, 1981). The standard for P-to-enter is usually 0.05 while the P-to-remove value is 0.10. It can then be stated that with a large number of predictor variables only a relatively small number of combinations of variables out of the total possible are actually tested by the program. It is therefore possible that the best solution may not be discovered. One cannot assume that the subset of variables found by a stepwise regression program necessarily corresponds to the most important set of variables (Sokal and Rohlf, 1981). The only way to be certain is to use an all-possible-subsets regression, but with many independent variables this could be prohibitively expensive in computation time. Variables left out of the predictor set are not necessarily unimportant but may simply be correlated with other variables in the predictor set. Rock (1988) states that professional statisticians take widely varying attitudes towards this procedure, ranging from tacit acceptance to outright hostility!

2.8 Summary

This chapter reviewed the past and present developments in snow surveying, snow research and snow modelling. Field based snow research procedures are now being supplemented or replaced by automated techniques and remote sensing technology. GIS are increasingly being used to integrate and build databases used for snow modelling. Regression procedures have been used with some success in previous studies incorporating snow, land cover, and topographic variables. The best result previously obtained in the Marmot Creek Basin watershed had a coefficient of determination or unadjusted R^2 of 0.58.

CHAPTER 3

METHODOLOGY

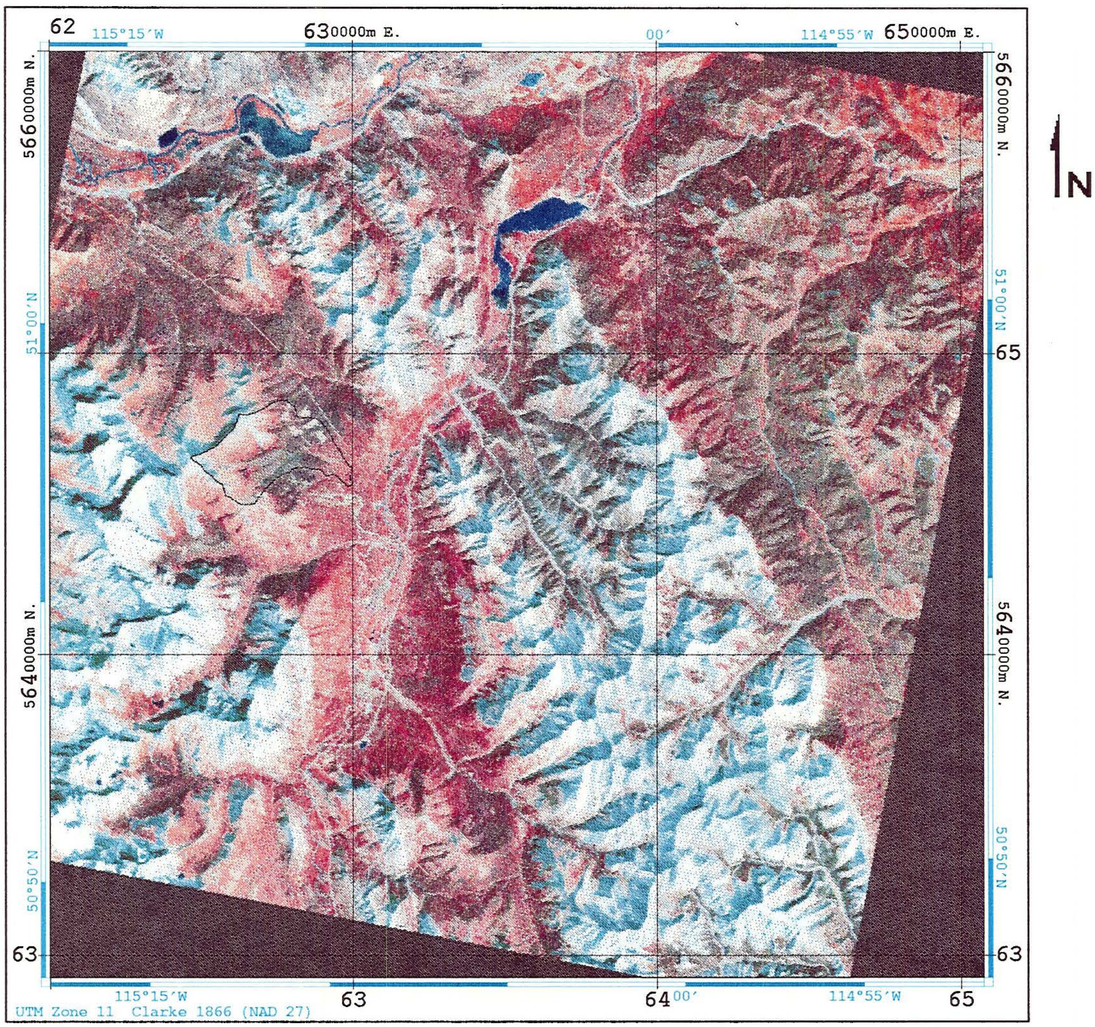
3.1 Introduction

The construction of the data set for the predictive snow depth, snow-water equivalent depth, and snow density stepwise regression models that were determined for Marmot Creek Basin is outlined in this chapter. The research required a progression of stages in order to integrate all of the multi-source data sets. The manipulation, verification, and analysis of the data along with the development of the final data set for the multiple regression models are all described below.

3.2 Data Acquisition

3.2.1 Satellite Imagery

Two satellite images were obtained for this study; a 1984 LANDSAT TM image (Figure 7) and a 1991 SPOT High Resolution Visible (HRV) image (Figure 8). The images were obtained from the University of Calgary at no charge. They were available through the Academic Computing Services (ACS) campus AIX (Unix) network. The TM image data were acquired on August 8, 1984, with a sun



LANDSAT TM Bands 2,3,4

(Equalization Enhancement: UTM Projection)

1:250 000 Scale

Figure 7: 1984 LANDSAT Thematic Mapper (TM) Image

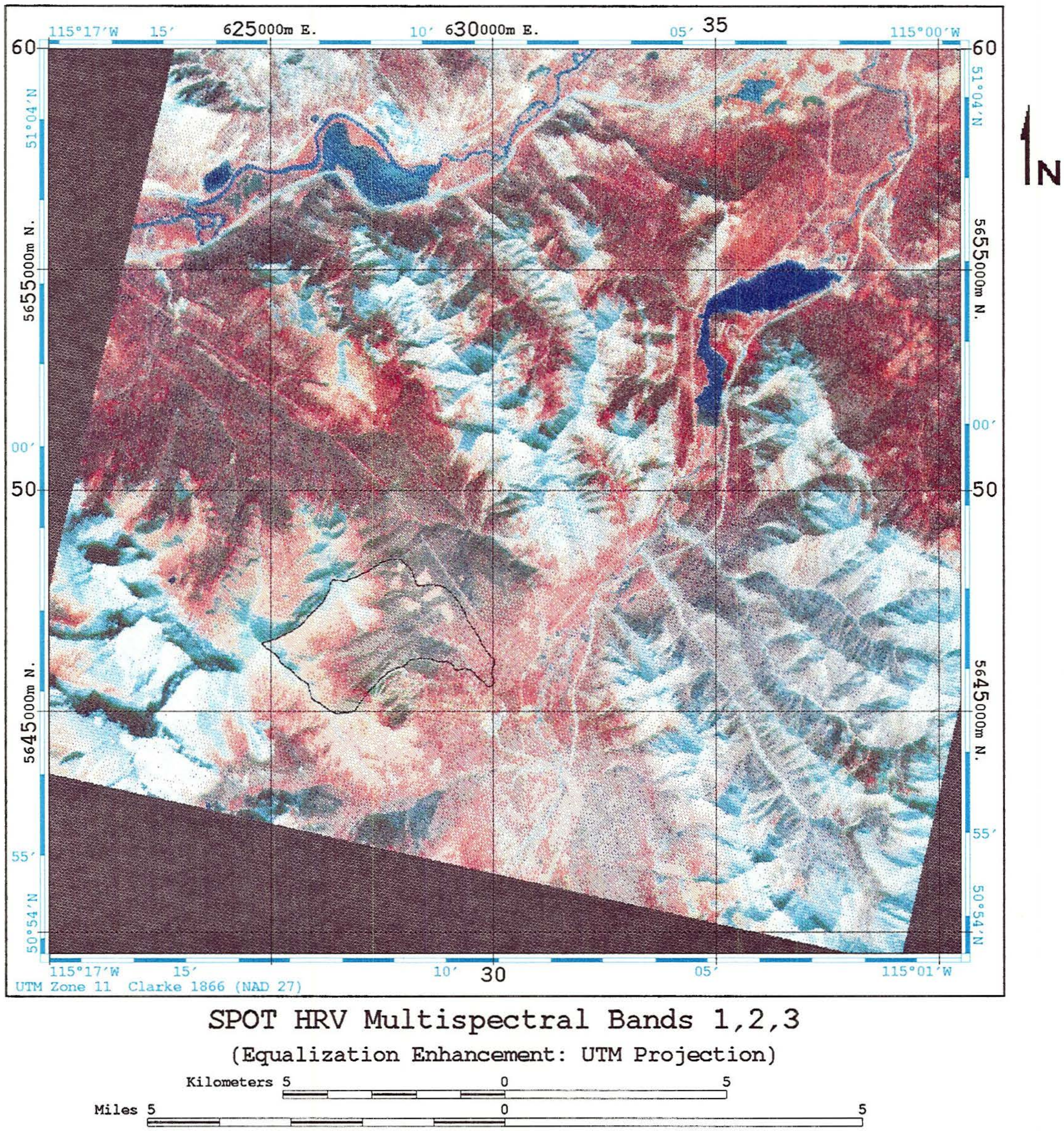


Figure 8: 1991 SPOT High Resolution Visible (HRV) Multispectral Image

elevation of 49.3° and azimuth of 138.1° while the SPOT image data were obtained on August 21, 1991 with a sun elevation of 50.3° and azimuth of 162.3°. The data contained in the images covered the lower reaches of the Kananaskis Valley where the study area is located. The LANDSAT TM data have a spatial resolution of 30 m over six bands (bands 1 to 5, 7) ranging from 0.45 um to 2.35 um. An additional band (band 6) has a spatial resolution of 120 m and covers the 10.4 um to 12.5 um range (Lillesand and Kiefer, 1987). Table 1 describes the characteristics of TM data. The SPOT HRV multispectral image ranges from green (0.50 um to 0.59 um) to near-infrared (0.79 um to 0.89 um) with a spatial resolution of 20 m.

3.2.2 Digital Elevation Data

Originally a DEM for the Marmot Creek Basin area was to be obtained from the Alberta government mapping branch. These types of DEM have a spatial resolution of 25 m and generally the accuracy of this type of DEM is within plus or minus 4 m. This did not occur however due to financial limitations and an alternative procedure was employed. A DEM was developed by digitizing the contours from an elevation map (Figure 9). The contour interval on this map is 100 feet or 30.48 m. No error term was given for this map but it is similar to a 1:50000 National Topographic Series (NTS) map sheet (Canada Map Office, 1986). These map sheets are accurate to within one half of a contour line (Wilson, 1990) or approximately 15 m.

Table 1: Characteristics of LANDSAT Thematic Mapper (TM) Spectral Bands (source: Lillesand and Kiefer, 1987)

Band	Wavelength (um)	Nominal Spectral Location	Principal Applications
1	0.45 - 0.52	Blue	Designed for water body penetration, making it useful for coastal water mapping. Also useful for soil/vegetation discrimination, forest type mapping, and cultural feature identification.
2	0.52 - 0.60	Green	Designed to measure green reflectance peak of vegetation for vegetation discrimination and vigour assessment. Also useful for cultural feature identification.
3	0.63 - 0.69	Red	Designed to sense in a chlorophyll absorption region aiding in plant species differentiation. Also useful for cultural feature identification.
4	0.76 - 0.90	Near-infrared	Useful for determining vegetation types, vigour, and biomass content, for delineating water bodies, and for soil moisture discrimination.
5	1.55 - 1.75	Mid-infrared	Indicative of vegetation moisture content and soil moisture. Also useful for differentiation of snow from clouds.
6	10.4 - 12.5	Thermal Infrared	Useful in vegetation stress analysis, soil moisture discrimination, and thermal mapping applications.
7	2.08 - 2.35	Mid-infrared	Useful for discrimination of mineral and rock types. Also sensitive to vegetation moisture content.

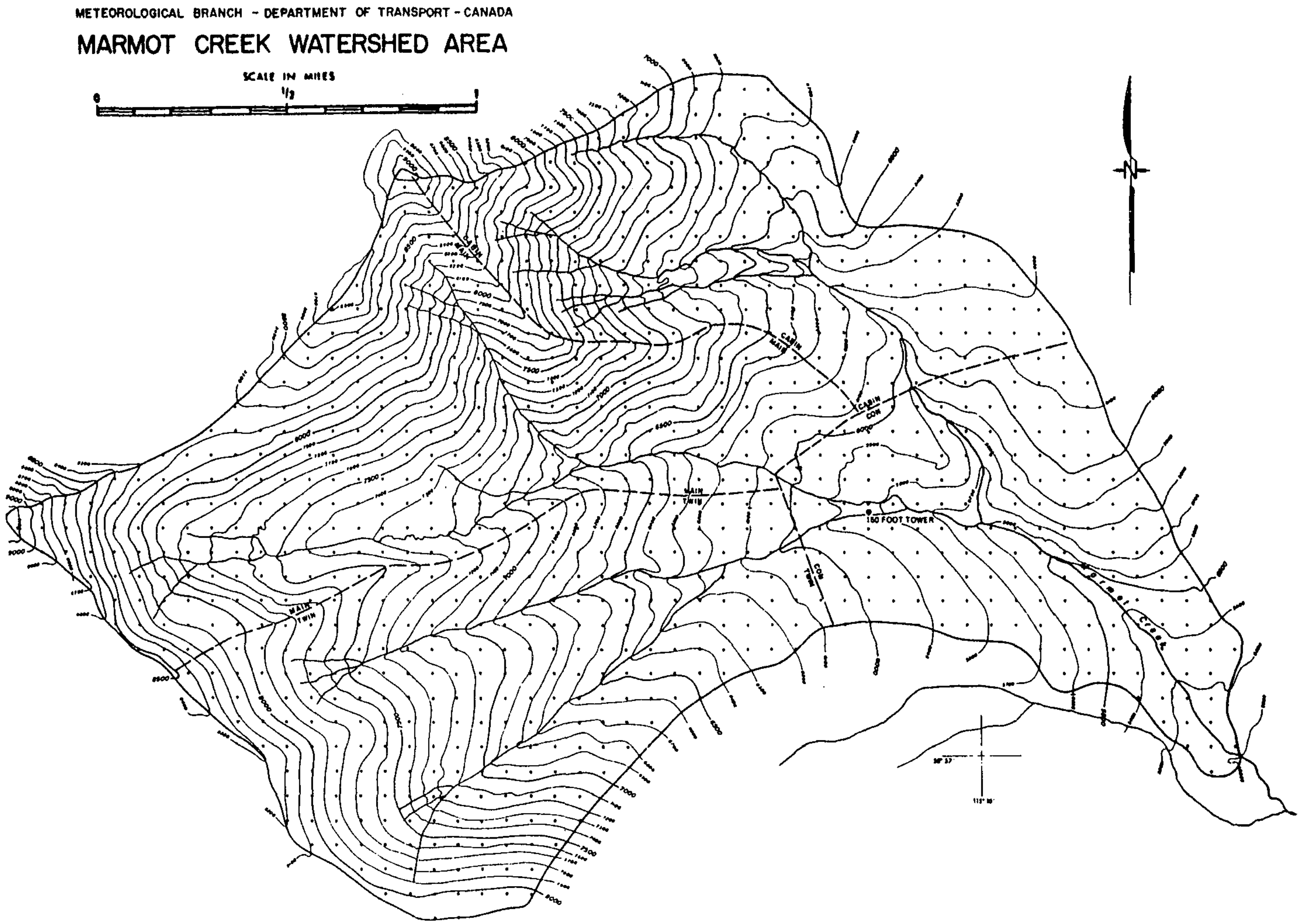


Figure 9: Topographic Map of Marmot Creek Basin (source: Ferguson et al., 1971)

3.2.3 Additional Map Data

There have been many different studies in the Marmot Creek Basin area and the literature on these studies is extensive (Bernier, 1986; Dickinson, 1982; Golding, 1973a; Golding, 1972; Storr, 1973; Swanson et al., 1986). Maps were obtained which showed tree height, crown density, insolation, and streams (Alberta Forest Service, 1979; Ferguson et al., 1971). The data were in polygon and line format and were entered through digitizing procedures into the database. Maps showing the amount of insolation striking the surface of the basin were derived for different times of the year using a three-dimensional model (Ferguson et al, 1971). The insolation map for March 21 (Figure 10) coincides approximately with maximum snowpack in the basin. All of the insolation maps are theoretical in that a clear sky was assumed. Therefore, the insolation values are constant for the dates that the maps portray. During melt periods, greater ablation rates can be expected in areas with higher insolation values.

3.2.4 Snow Data

A large amount of snow data have been collected in Marmot Creek Basin. Unfortunately the documentation that describes the procedures used and the data that were collected is not easy to find or obtain. Some of the data that were collected cannot be located as stated previously. Snow course survey data were

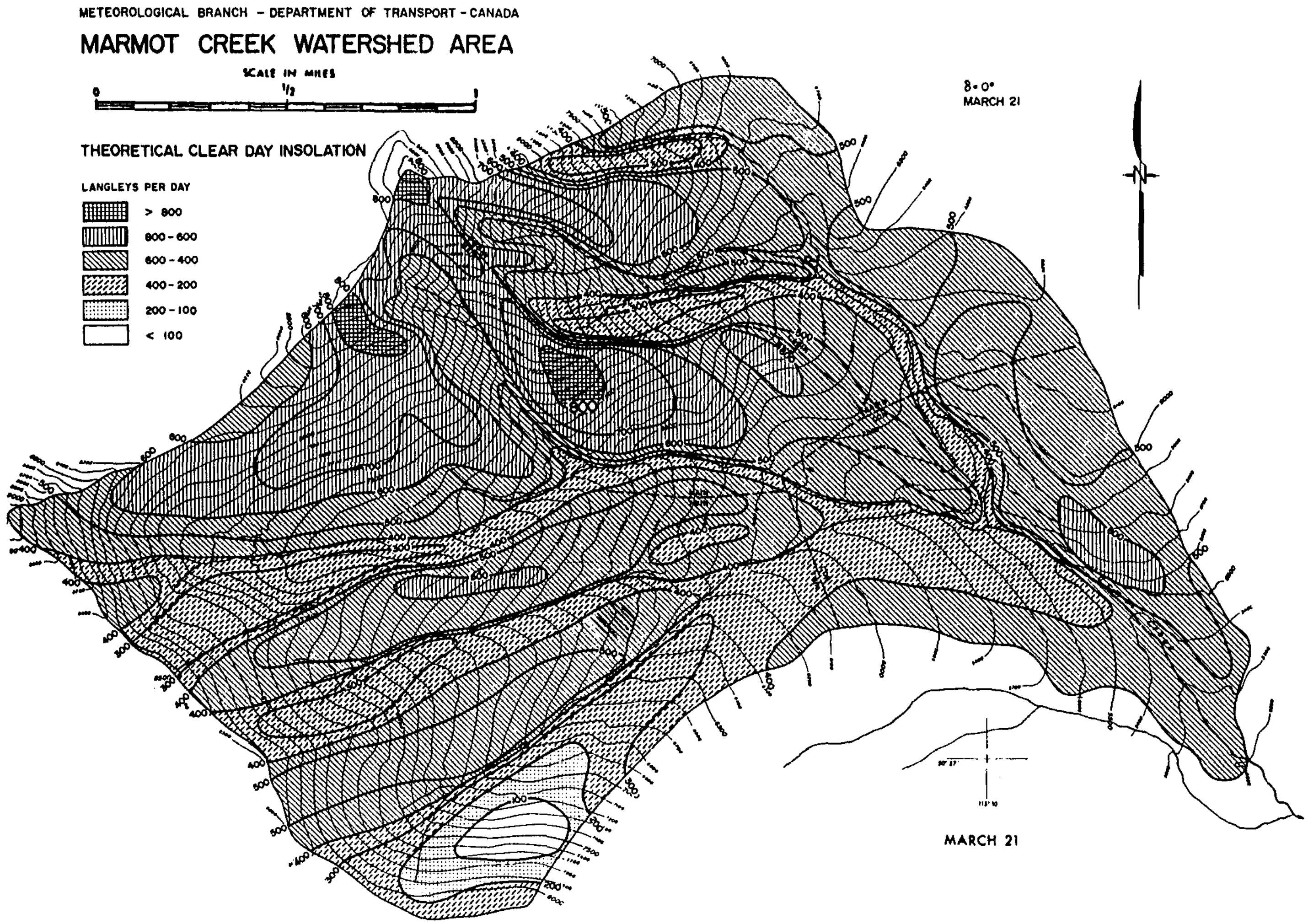


Figure 10: March 21 Theoretical Clear Sky Insolation (source: Ferguson et al., 1971)

obtained in spreadsheet format from the Northern Forestry Research Centre in Edmonton consisting of data collected on twenty snow courses in the basin.

Snow point survey data were obtained in digital form from Dr. D.L. Golding of the Faculty of Forestry, University of British Columbia. The data consists of annual snow surveys that were usually conducted in the third week of March from 1969 to 1980. There are 290 grid points for the intensive snow survey which was undertaken in forested portions of the basin. There were some years where data were erratically collected and these were examined to determine their suitability for the analyses. This included determining the amount of missing data as a percentage of the total (Table 2). If greater than 60% of the data were missing the data for that year were not used. There were also years where no survey took place during that time period.

A set of snow depth data also exists for snow pillows which were setup at various sites throughout the basin along with measurements taken at six total station sites. Total stations measure variables such as wind speed and direction, incoming insolation, temperature, and relative humidity.

Two different snow course maps and a map of the intensive snow survey data (Figures 11 to 13) were obtained from the literature on the basin. The snow course maps were supposed to show the same twenty snow course locations.

Table 2: Number and Percentage of Missing Values for All Regressions (total number of snow points = 290)

YEAR	SNOW DEPTH	SNOW-WATER EQUIVALENT DEPTH	SNOW DENSITY
1969	100 (34.5%)	100 (34.5%)	100 (34.5%)
1970	44 (15.2%)	44 (15.2%)	44 (15.2%)
1971	56 (19.3%)	33 (11.4%)	56 (19.3%)
1972	60 (20.7%)	60 (20.7%)	60 (20.7%)
1973	64 (22.1%)	64 (22.1%)	64 (22.1%)
1975	38 (13.1%)	38 (13.1%)	38 (13.1%)
1976	22 (7.6%)	22 (7.6%)	22 (7.6%)
1977	135 (46.6%)	135 (46.6%)	135 (46.6%)
1978	27 (9.3%)	18 (6.2%)	27 (9.3%)
1980	154 (53.1%)	154 (53.1%)	154 (53.1%)
1981	155 (53.4%)	155 (53.4%)	155 (53.4%)

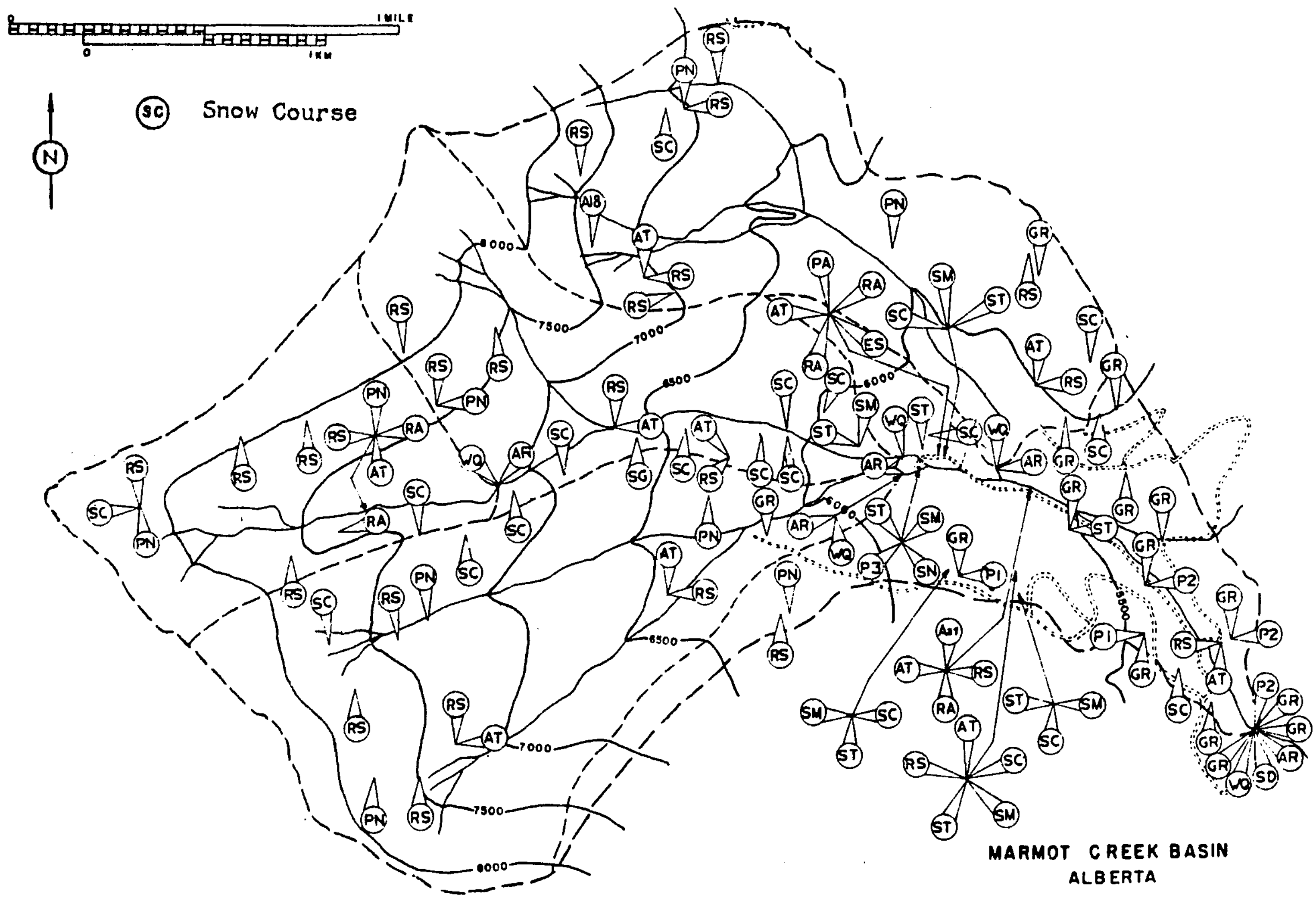


Figure 11: Snow Course Map 1
(source: Northern Forestry Research Centre, Edmonton, Alberta)

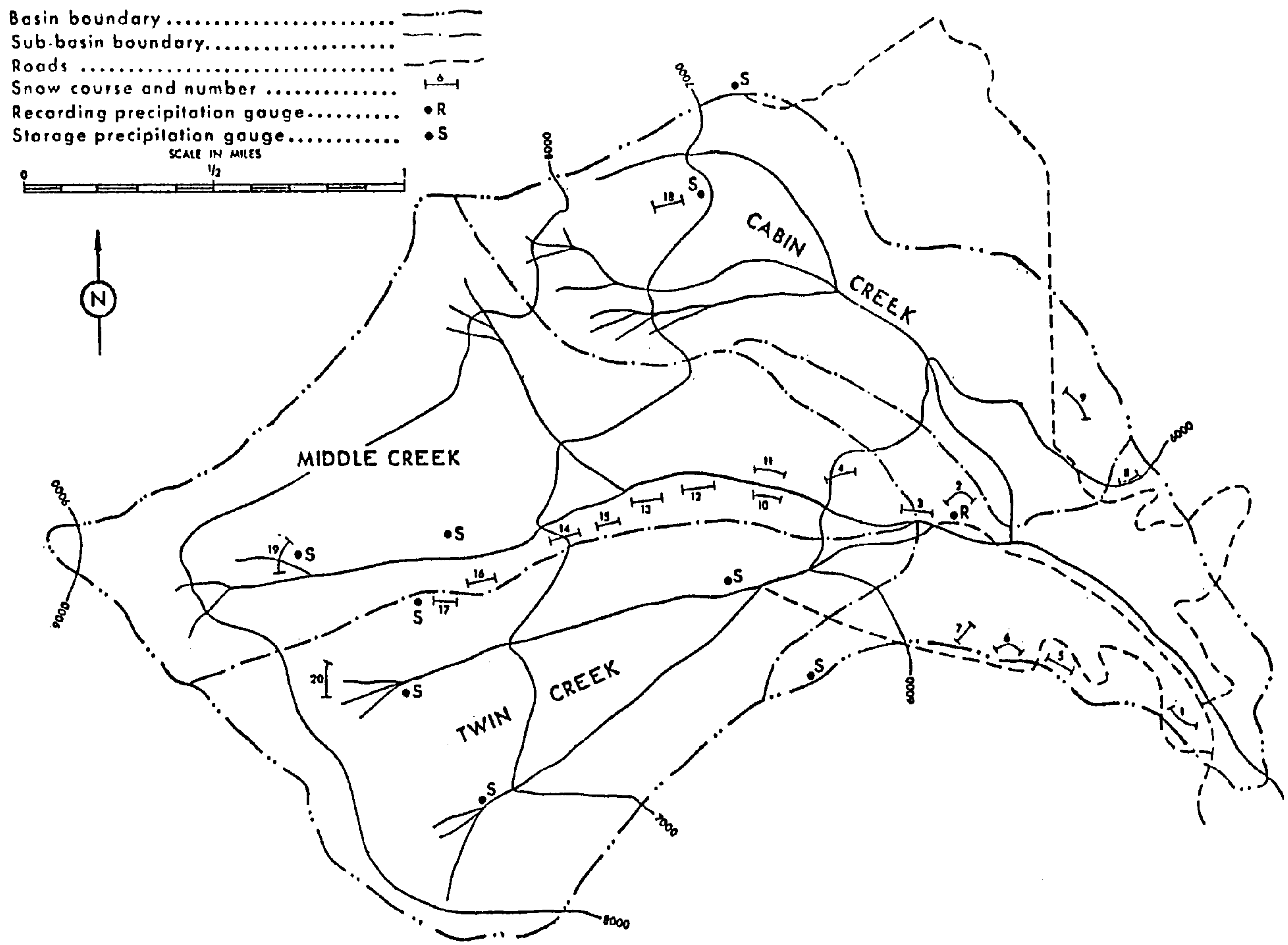


Figure 12: Snow Course Map 2
(source: Golding, 1968)

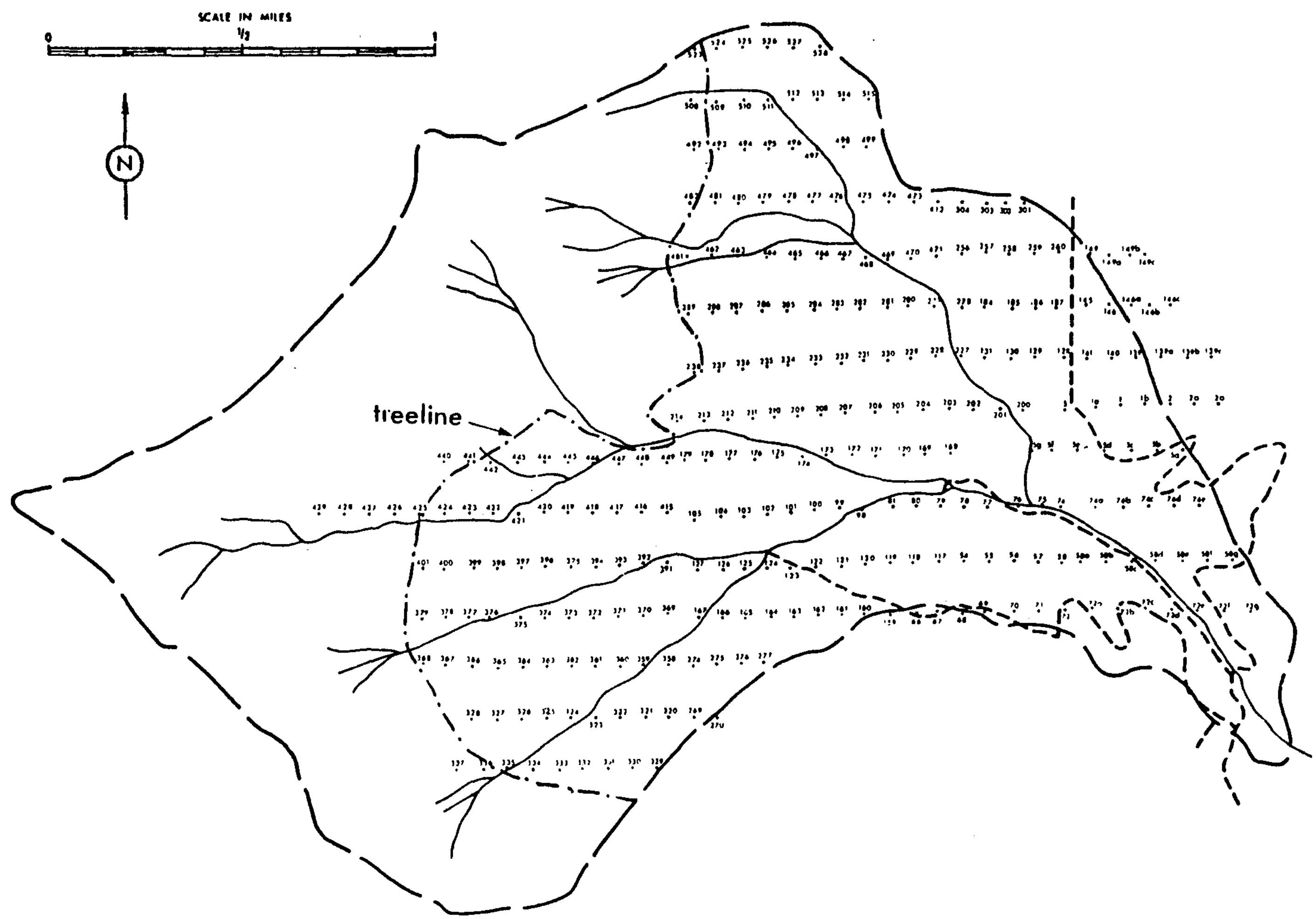


Figure 13: Intensive Snow Survey Points
(source: Golding, 1973b)

This was not the case, however, as some of the snow courses with the same number were located in different areas on the maps. This problem could not be satisfactorily resolved and thus the snow course maps and data were dropped from the analyses. Bernier (1986) mentions alpine snow stake data but, as stated previously, these could not be obtained. In the end it was decided to use the data for which both good records and good maps could be found. Thus only the snow point data were used.

3.2.5 Field Work

Field work was originally undertaken in July 1992 to verify variables for a land cover classification scheme. Information that was collected included topographic data and land cover information (Appendix A). It was not possible to collect all of the information on the field sheet at the time the field work was performed. Items such as the Universal Transverse Mercator (UTM) coordinates and the expected class for land cover classification were not recorded. To assist with the field work, two sets of airphotos were obtained and these were used to try and delineate unique land cover units. The airphotos were from 1972 and from 1984 which is similar to the period of the snow data. Sites were located using a grid overlay on the airphotos from 1984. These were 1:20000 colour airphotos that allowed ground features such as trails and roads to be readily identified.

To ensure that an unbiased representation of the study area was obtained, a random selection procedure was employed to identify field sites (Williams, 1984). Eighty sites were selected (at random) throughout the entire basin and visited during the field season. A GPS would have made locating the field sites in the basin easier but there were still no major problems in getting to any site due to the previous investigations that had been completed in the study area. An extensive network of trails exists in this basin from previous field studies.

3.3 Data Processing and GIS Integration

3.3.1 Satellite Image Geocorrection and Processing

The PCI Easi/Pace Image Analysis System (PCI, 1991) was used for the image processing techniques described here. It was first necessary to view the entire satellite image for both the TM and SPOT scenes to determine the pixel coordinates for the Marmot Creek Basin study area. Subscenes of approximately 1024 x 1024 pixels were then extracted from the images. These subscene sizes were selected because they allowed for a small amount of data to be used (eight megabytes for TM, three megabytes for SPOT) but they still allowed for large enough image samples to use for geocorrection procedures.

Geocorrection procedures were performed in order to register the satellite data with the Universal Transverse Mercator (UTM) grid system. This was done for the TM data with a resulting RMS error of under 0.25 pixels (X: 0.232 Y: 0.205) for 15 Ground Control Points (GCP). This corresponds to a maximum error of approximately 6 m to 7 m in any compass direction. The GCP were obtained from the National Topographic Series 82 J and 82 O 1:50000 map sheets (Canada Map Office, 1986). The SPOT image data were also registered to the UTM projection with a RMS error of under 0.3 pixels (X: 0.280 Y: 0.275) which corresponds to approximately 5 m to 6 m in any compass direction. Both registration procedures were completed using a bilinear resampling algorithm (PCI, 1991). The bilinear procedure calculates a weighted average using the four nearest pixel values to determine the resultant individual pixel value. Resampling of the images to a 25 m size would have been performed had a 25 m DEM been obtained. This would have involved using the image-to-image tie down procedure (PCI, 1991). Similar registration and resampling procedures are outlined by Dixon and Mack (1991) where they combined SAR and TM data for an improved classification and O'Leary et al. (1991) where LANDSAT TM and LANDSAT MSS data were resampled to 50 m pixels. Ehlers (1991) discusses image fusion in detail. The TM image and the SPOT image were resampled to their original dimensions (30 m and 20 m pixels respectively) so as to retain as much of the raw image spectral information as possible.

The analysis of satellite data in mountain environments is complicated by topographic and slope effects. Cloud cover and fog in the atmosphere can also affect spectral signatures. Procedures and algorithms for correction of these effects are discussed in Schanzer (1991), Lavreau (1991), and De Hann et al. (1991). These procedures were not utilized here since the images are cloud free in the study area.

Three techniques that had proven useful in previous studies incorporating satellite data were used to derive additional information from the TM image. First, Principal Component Analysis (PCA) was shown by Walsh et al. (1990) to provide useful information for defining resource characteristics in a mountainous environment. PCA transforms the TM bands into statistically independent axes which account for the variance in the TM data set in a more succinct manner. The PCA was produced using the entire set of seven TM bands (Appendix B). Second, a Normalized Difference Vegetation Index (NDVI), as a measure of biomass, has proven to be useful in the classification of vegetation patterns in mountainous environments in the past (Wheate and Franklin, 1991). In the present study a NDVI was produced using a combination of TM bands 3 and 4 (4-3/4+3). Third, Near Infrared Chromaticity which is an index of visible spectral response versus infrared spectral response was used by Franklin and Raske (1994) to look at the differences between damaged and undamaged stands of trees. In the present study, Near Infrared Chromaticity was calculated using TM bands 2, 3, and 4 (4/(2+3+4)).

3.3.2 SPANS GIS Study Area Definition

The setup of the SPANS study area for the present research involved the definition of the map projection to be used and delineation of the extents for the study area (Intera-Tydac, 1993). LANDSAT TM band 1 was used to specify that the study area projection would be UTM. The data had previously been corrected to the UTM projection and Zone 11 (120°W to 114°W) was specified in the setup procedure. Next, the extents or limits of the study area had to be defined. Therefore a window was cut out of the satellite image that encompassed Marmot Creek Basin. Following these procedures it was then possible to query the database for properly georeferenced coordinates for any point in the basin. This was extremely useful because only one coordinate or no coordinates were given on most of the map information used in this study. SPANS was used to determine additional coordinates to attach to the maps for registration purposes. The registration procedure involved digitizing latitude/longitude coordinate pairs so the maps could be referenced spatially in the database. This insured that all of the data sets were georeferenced for the same projection that was originally setup from the TM data.

3.3.3 GIS Data Integration and Processing

All of the TM and SPOT satellite band data and additional derived information (PCA, NDVI, Near- Infrared Chromaticity) were imported into the study area database using the raster import option of SPANS. Headers for the data had to be created (Intera-Tydac, 1993) before the data could be properly georeferenced. After import, the raster data were enquadded (ie: placed in quadtree format) to map form using the raster to map function. Quadtrees are the data structure that SPANS uses to minimize the storage requirements of large databases that contain many pixels of the same value or class. The quadtree method assumes a matrix structure that is square and subdivides the image successively into four equal quarters until one pixel level is reached (Wilson, 1990). Each block within a given data set is tested for homogeneity; if the block is homogeneous then it is classified as such; if not, it is subdivided into quarters and retested until the specified quadtree level is reached. The first three TM bands were combined to see if a combination of TM data would be a good predictor in the regression models.

The DEM was created through the following procedure. Elevation map contours were digitized as lines using SPANS TYDIG (Intera-Tydac, 1993) and had the appropriate elevation values attached to them. They were then exported as vectors from the TYDIG digitizing package and subsequently imported into the study area. Further processing was still necessary however because a DEM can only be interpolated in SPANS from point data. Therefore the vectors were exported as lines in a latitude/longitude format. The SPANS utility, arc2pnt, was then used to convert the line data to point data. These point data were then re-imported into the study area for further processing. The Transform/Data Types/Points to Map/Contouring procedure was used to develop a DEM (Figure 14). This technique uses a Triangular Irregular Network (TIN) to calculate the surface (Intera-Tydac, 1993). A non-linear interpolation method was employed. This interpolation procedure creates a continuous surface where the values are smooth and derivatives will also be continuous. Non-linear interpolation should be used with caution as point data sets containing inaccurate data may produce unreliable interpolated surfaces (Intera-Tydac, 1993). The quadtree level used was nine which approximates a 17 m pixel. Other variables were calculated using the DEM data and various SPANS modules. These included ten different variations of an angle of incidence calculation, surface illumination, slope aspect, slope percent, and slope angle.

Tree height, crown density, and insolation maps were digitized and imported into the study area following the same procedures that were used for the DEM. Contouring was used to try and derive the same map information that were digitized. Streams were imported as vector data. It was then decided to perform a buffer operation on this data set. Buffers in 10 m increments were specified and calculated around all major streams to provide an additional independent variable in the regression models.

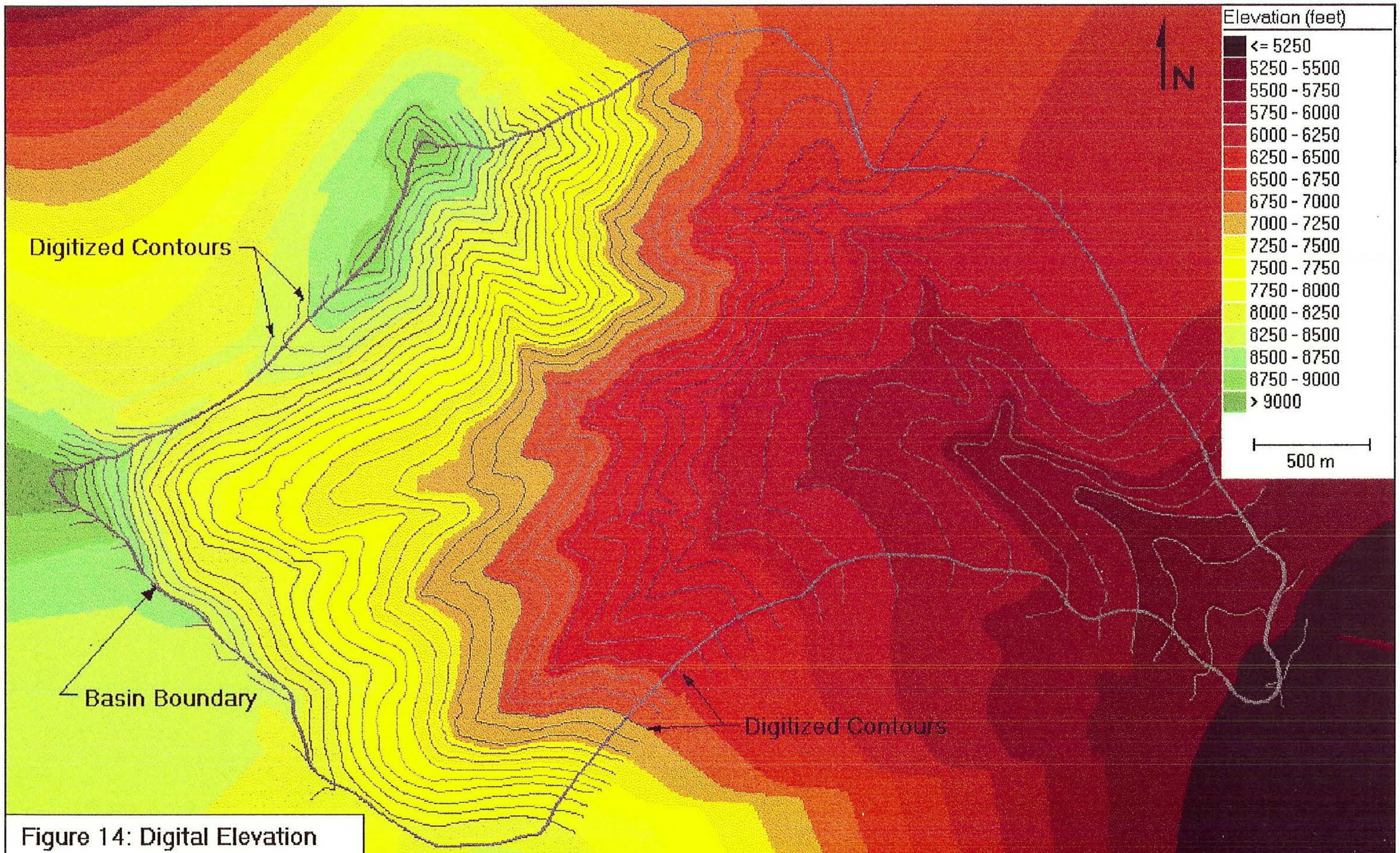


Figure 14: Digital Elevation Model Data (reclassified)

Note: data interpolated beyond the digitized contours are spurious

The distance between snow point observation sites on Figure 13 is 100 m. Since the snow data were the limiting factor in this study it was decided to perform a 150 m buffer operation on the snow data. The value of 150 m was chosen because it allowed interpolation into areas where snow points were not located and did not extend the data more than 50% of the distance between successive snow observations. The area for the 150 m buffer around the snow points as determined by the GIS was 7.25 km^2 (Figure 15).

3.3.4 Data Manipulation and Integration Challenges

Some data integration problems were encountered when entering the different data sets. Using some of the imported data sets to derive additional information was not met with success in all cases.

Digital elevation models (DEM) were to be utilized to determine topographic variation using a program called GEOM. This program was originally developed at the University of Saskatchewan for the extraction of geomorphometric variables from DEM data (Smith and Martz, 1989; Lapen, 1991). The variables that are derived include: slope aspect, slope gradient, profile curvature, contour curvature, and elevation. A problem was encountered when the DEM data had to be converted to IDRISI GIS format (Eastman, 1990). The 16-bit DEM created by SPANS was incompatible with the IDRISI file format utilized by GEOM. Various

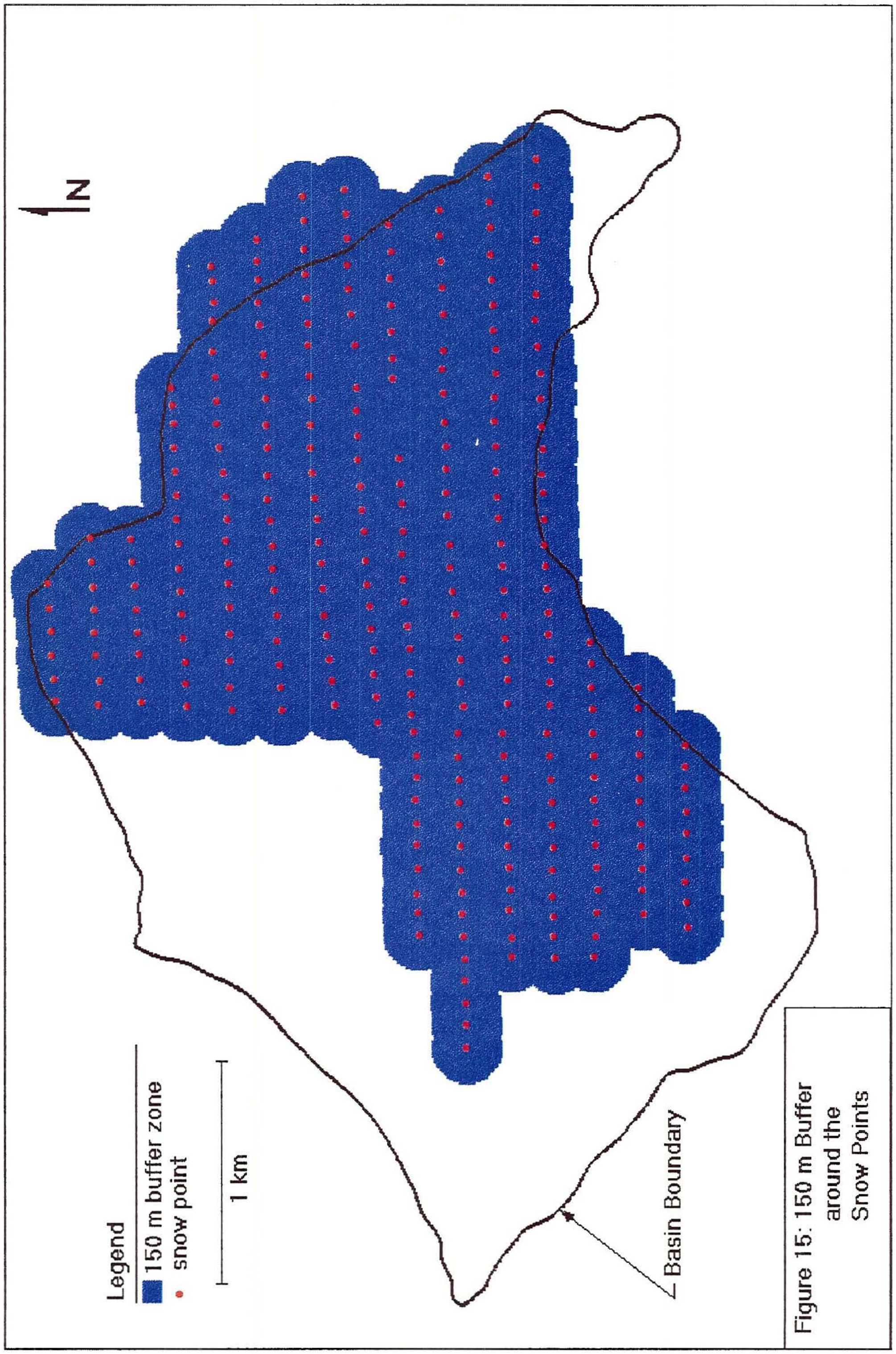


Figure 15: 150 m Buffer around the Snow Points

methods were attempted to try and input the data into GEOM but all were unsuccessful in the end. The main problem was that the IDRISI file could only be 8-bit data. This data can have a range of values from 0 to 256 compared with 16-bit data which can have a maximum class of 32767 (Intera-Tydac, 1993). The DEM could have been reclassed into 256 levels but this would then have altered the original interpolated surface and not used the entire range of values in the DEM data. It was then decided not to use the GEOM program. This was very unfortunate because the contour curvature and profile curvature variables have been shown to be useful in a previous snow study that looked at snow distribution in a rolling agricultural area (Lapen, 1991).

Interpolation with the contouring module of SPANS for the digitized insolation maps also proved to be unsuccessful although not for the same reasons. The problem here was that all of the insolation maps had areas where there existed sparse line data. The TIN procedure then had to interpolate from wide ranging data points with the results being incorrect interpolations and holes in the data. Therefore the insolation data were abandoned.

When the SPOT data were imported into the study area database it was found that the image data did not match up very closely with the base TM data. Errors of two pixels or 34 m were encountered in a west-east direction. The reason for this is unclear but the RMS error in registering both images independently to the UTM projection certainly played a role and the fact that when imported the 20 m SPOT image data were resampled by the GIS to a projection based on the 30 m TM image data may also have had an influence. Had the study area not been so small and the point measurements so specific these errors could probably have been ignored. It was decided though to remove the SPOT data from the analyses. Joria et al. (1991) have compared the use of TM and SPOT imagery and found that TM data provided an increase of 4% in a supervised classification result and an increase of 8% in an unsupervised classification result over SPOT data. The TM data set also contains more information (seven bands) than the SPOT (three bands). Also TM bands 2, 3, 4 approximate the information in SPOT bands 1, 2, 3.

3.3.5 GIS Variable Extraction and Snow Data Integration

In total, there were thirty two map data layers in the study area database. These were the independent variable set for the regression analyses (Table 3). The values for each layer of data were appended to the digitized snow point locations and exported out of SPANS for the stepwise regression analyses. This was accomplished using the Model/Points/Append Class operation of SPANS. Each point had a unique identifier attached to it so it could be referenced to the snow data which were in a separate file.

Table 3: Independent Variable Data Set

INDEPENDENT VARIABLE	DESCRIPTION
TM10	TM band 1 image data
TM20	TM band 2 image data
TM30	TM band 3 image data
TM40	TM band 4 image data
TM50	TM band 5 image data
TM60	TM band 6 image data
TM70	TM band 7 image data
OVERTM13	overlay of TM bands 1-3
NDVI	normalized difference vegetation index
CHROME	near-infrared chromaticity
CONTOURS	elevation (interpolated from the DEM)
SLOPEANG	slope angle (calculated from the DEM)
SLOPEPCT	slope percent (calculated from the DEM)
ASPECT	slope aspect (calculated from the DEM)
ILLUM	surface illumination (calculated from the DEM, shows shadows at different times of the day; in this study 12 noon was used)
CROWDEN	tree crown density (interpolated from digitized crown density contours)
HEIGHT	tree height (interpolated from digitized tree height contours)
STREAMS	10 m incremental buffer zones from streams
INCID90	angle of incidence, zenith angle = 90° (ie: the dawn or dusk sun)

Table 3:	continued.
INDEPENDENT VARIABLE	**DESCRIPTION**
INCID80	angle of incidence, zenith angle = 80°
INCID70	angle of incidence, zenith angle = 70°
INCID60	angle of incidence, zenith angle = 60°
INCID50	angle of incidence, zenith angle = 50°
INCID40	angle of incidence, zenith angle = 40°
INCID30	angle of incidence, zenith angle = 30°
INCID20	angle of incidence, zenith angle = 20°
INCID10	angle of incidence, zenith angle = 10°
INCID0	angle of incidence, zenith angle = 0° (ie: right above the surface)
PCA1	principal component one of the TM data (loads on TM bands 1,4,5
PCA2	principal component two of the TM data (loads on TM band 7
PCA3	principal component three of the TM data (loads on TM band 1
PCA4	principal component four of the TM data (loads on TM bands 3,4

The snow point data were manually entered into the Quattro Pro spreadsheet package (Borland, 1992). While the data were originally obtained in digital format it was easier to print out the raw data and extract the necessary information from hard copy. Then the correct information could be extracted from irregularly spaced columns. It was also easier to identify gaps in the data record. The dependent variable data set consists of snow depth, snow-water equivalent depth, and snow density for the years 1969 to 1973, 1975 to 1978, 1980, and 1981 (Table 4). The snow depth and snow-water equivalent depth measurements were recorded in inches for the all of the study years (D.L. Golding, pers. comm.). The values for the years 1969 through 1977 were recorded as whole numbers (ie: 145 would actually be 14.5 inches), thereafter values were recorded to the decimal place.

The dependent and independent variable data files were combined using Quattro Pro and sorted according to the snow point identifier. The final data file for the regression analyses comprised 290 rows x 67 columns, where row 1 contained the column headings and column 67 was a control column to delineate the end of each row in the export file.

Table 4: Dependent Variable Data Set
- the snow depth and snow-water equivalent depth measurements were recorded in inches for the all of the study years

SNOW VARIABLE	**DESCRIPTION**
snodep69	snow depth for 1969
snowat69	snow-water equivalent depth for 1969
snoden69	snow density for 1969
snodep70	snow depth for 1970
snowat70	snow-water equivalent depth for 1970
snoden70	snow density for 1970
snodep71	snow depth for 1971
snowat71	snow-water equivalent depth for 1971
snoden71	snow density for 1971
snodep72	snow depth for 1972
snowat72	snow-water equivalent depth for 1972
snoden72	snow density for 1972
snodep73	snow depth for 1973
snowat73	snow-water equivalent depth for 1973
snoden73	snow density for 1973
snodep75	snow depth for 1975
snowat75	snow-water equivalent depth for 1975
snoden75	snow density for 1975
snodep76	snow depth for 1976
snowat76	snow-water equivalent depth for 1976
snoden76	snow density for 1976

Table 4:	continued.
SNOW VARIABLE	**DESCRIPTION**
snodep77	snow depth for 1977
snowat77	snow-water equivalent depth for 1977
snoden77	snow density for 1977
snodep78	snow depth for 1978
snowat78	snow-water equivalent depth for 1978
snoden78	snow density for 1978
snodep80	snow depth for 1980
snowat80	snow-water equivalent depth for 1980
snoden80	snow density for 1980
snodep81	snow depth for 1981
snowat81	snow-water equivalent depth for 1981
snoden81	snow density for 1981

3.4 Summary

This chapter described the data acquisition and processing components of this thesis. In addition, the procedures for the setup and definition of the study area database were outlined. Data processing and integration methodologies and difficulties were specified. The procedures for extracting the independent variable data with the GIS and integration with the snow data were also set forth.

CHAPTER 4

ANALYSIS AND RESULTS

4.1 Introduction

The results of the stepwise, multiple, linear regression models are presented in this chapter. The procedures for entering the data, determining and analyzing the results, and modelling the regression equations in the SPANS GIS are outlined.

4.2 SPSS Statistical Analysis

The data file prepared in Quattro Pro was exported in Microsoft Excel format and subsequently imported into a Statistical Package for the Social Sciences (SPSS) command file (Norusis, 1985) for the statistical analyses. Initially the data were run through a multiple regression procedure that was not stepwise. The previously mentioned problem of adjusted R^2 and degrees of freedom made it necessary to opt for a stepwise regression procedure (Kennedy, 1985). The straight multiple regression procedure entered 30 of 32 variables into the equations. This resulted in models where the equations were unwieldy and independent variables that were not really making a contribution to the models were included.

The stepwise procedure was run in a command file where all of the regressions were run in one batch. The advantages of using the Unix-based SPSS became very apparent here. The processing went quickly and the summarized results are presented in Table 5. Multicollinearity occurs where independent variables are highly correlated with each other. In all of the analyses the variable of OVERTM13 (ie: TM bands 1, 2, 3 added together) was found to be multicollinear (Kennedy, 1985). Therefore it was removed from the data set used for the analyses. The variables of SLOPEANG (slope angle) and INCID0 (incidence with 0° zenith angle) were also multicollinear in a number of cases so they were not included in the SPSS regression runs.

The P-to-enter (0.05) and P-to-remove (0.10) values were defaulted in the stepwise regression procedures. When the limits were reached no further variables were entered into or removed from the analyses. Missing values (coded as -99) were excluded from the regression runs. Their role is discussed in Chapter 5.

4.3 Results of the Regressions

A summary of the results of these regressions showing which independent variables were significant, and in how many instances is presented in Table 6. Sokal and Rohlf (1981) state that one should not lose sight of the fact that the purpose of stepwise, multiple, regression analysis is simply to find the smallest set

Table 5: Adjusted R^2 Values for All Regressions (expressed in % explanation) - independent variables contributing to the model are presented for snow depth and snow-water equivalent depth

YEAR	**SNOW DEPTH**	**SNOW-WATER EQUIVALENT DEPTH**	**SNOW DENSITY**
1969	32.61% CONTOURS (25.63%) PCA2 (4.15%) INCID30 (1.75%) HEIGHT (1.08%)	17.24% CONTOURS (8.77%) PCA2 (2.24%) STREAMS (2.35%) ASPECT (1.42%) HEIGHT (2.36%)	10.17%
1970	40.26% CONTOURS (28.47%) INCID90 (6.77%) SLOPEPCT (2.02%) NDVI (1.28%) TM60 (1.72%)	28.33% CONTOURS (19.04%) INCID90 (4.67%) NDVI (1.46%) TM60 (3.16%)	3.48%
1971	48.37% CONTOURS (39.31%) INCID50 (6.87%) HEIGHT (0.82%) PCA2 (0.68%) CROWDEN (0.69%)	42.89% CONTOURS (37.17%) INCID40 (4.16%) HEIGHT (1.56%)	4.88%
1972	63.70% CONTOURS (57.49%) INCID90 (4.09%) HEIGHT (0.59%) PCA4 (1.53%)	58.14% CONTOURS (55.77%) INCID90 (1.66%) TM70 (0.71%)	5.42%
1973	51.04% CONTOURS (39.85%) INCID50 (9.50%) PCA2 (0.94%) CHROME (0.75%)	38.02% CONTOURS (29.73%) INCID30 (8.29%)	6.10%

Table 5:	continued.		
YEAR	**SNOW DEPTH**	**SNOW-WATER EQUIVALENT DEPTH**	**SNOW DENSITY**
1975	37.02% CONTOURS (27.36%) INCID90 (5.48%) NDVI (3.01%) HEIGHT (1.17%)	25.86% CONTOURS (17.43%) INCID90 (4.40%) NDVI (3.10%) HEIGHT (0.93%)	no analysis
1976	48.37% CONTOURS (42.13%) INCID60 (4.83%) NDVI (0.65%) TM60 (0.76%)	47.44% CONTOURS (38.27%) INCID90 (5.92%) CROWDEN (0.98%) HEIGHT (0.93%) ASPECT (0.70%) PCA2 (0.64%)	9.02%
1977	41.94% CONTOURS (27.71%) INCID90 (6.11%) TM70 (5.99%) HEIGHT (2.13%)	31.41% CONTOURS (22.35%) INCID90 (3.55%) TM70 (3.97%) HEIGHT (1.54%)	no analysis
1978	44.08% CONTOURS (38.07%) TM50 (2.47%) INCID80 (2.51%) HEIGHT (1.03%)	33.12% CONTOURS (29.00%) NDVI (3.04%) INCID90 (1.08%)	7.63%
1980	42.43% CONTOURS (34.15%) INCID50 (8.28%)	39.72% CONTOURS (33.26%) INCID50 (6.46%)	11.95%
1981	32.88% CONTOURS (28.53%) INCID80 (4.35%)	35.41% CONTOURS (33.98%) INCID60 (1.43%)	11.59%

Table 6: Significant Independent Variables in the Snow Models (Only snow depth (snodep##) and snow-water equivalent depth (snowat##) are presented; where ## represents the year)

INDEPENDENT VARIABLE	**MODEL(S) WHERE VARIABLE WAS SIGNIFICANT AND ORDER OF SIGNIFICANCE IN THE MODEL: (#) = order of significance**
TM10 (TM band 1)	none
TM20 (TM band 2)	none
TM30 (TM band 3)	none
TM40 (TM band 4)	none
TM50 (TM band 5)	snodep78(2)
TM60 (TM band 6)	snodep70(5), snowat70(4), snodep76(4)
TM70 (TM band 7)	snowat72(3), snodep77(3), snowat77(3)
OVERTM13 (overlay of TM bands 1-3)	none, multicollinear in all models (excluded)
NDVI (normalized difference vegetation index)	snodep70(4), snowat70(3), snodep75(3), snowat75(3), snodep76(3), snowat78(2)
CHROME (near-infrared chromaticity)	snodep73(4)
CONTOURS (elevation)	for all models (1)
SLOPEANG (slope angle)	none, multicollinear in 15 of 22 models (excluded)

Table 6:	continued.
INDEPENDENT VARIABLE	**MODEL(S) WHERE VARIABLE WAS SIGNIFICANT AND ORDER OF SIGNIFICANCE IN THE MODEL: (#) = order of significance**
SLOPEPCT (slope percent)	snodep70(3)
ASPECT (slope aspect)	snowat69(4), snowat76(5)
ILLUM (surface illumination)	none
CROWDEN (tree crown density)	snodep71(5), snowat76(3)
HEIGHT (tree height)	snodep69(4), snowat69(5), snodep71(3), snowat71(3), snodep72(3), snodep75(4), snowat75(4), snowat76(4), snodep77(4), snowat77(4), snodep78(4)
STREAMS (10 m incremental buffer zones from streams)	snowat69(3)
INCID90 (angle of incidence, zenith angle = 90°)	snodep70(2), snowat70(2), snodep72(2), snowat72(2), snodep75(2), snowat75(2), snowat76(2), snodep77(2), snowat77(2), snowat78(3)
INCID80 (angle of incidence, zenith angle = 80°)	snodep78(3), snodep81(2)
INCID70 (angle of incidence, zenith angle = 70°)	none
INCID60 (angle of incidence, zenith angle = 60°)	snodep76(2), snowat81(2)

Table 6:	continued.
INDEPENDENT VARIABLE	**MODEL(S) WHERE VARIABLE WAS SIGNIFICANT AND ORDER OF SIGNIFICANCE IN THE MODEL: (#) = order of significance**
INCID50 (angle of incidence, zenith angle = 50°)	snodep71(2), snodep73(2), snodep80(2), snowat80(2)
INCID40 (angle of incidence, zenith angle = 40°)	snowat71(2)
INCID30 (angle of incidence, zenith angle = 30°)	snodep69(3), snowat73(2)
INCID20 (angle of incidence, zenith angle = 20°)	none
INCID10 (angle of incidence, zenith angle = 10°)	none
INCID0 (angle of incidence, zenith angle = 0°)	none, multicollinear in 7 of 22 models (excluded)
PCA1 (principal component one of the TM data)	none
PCA2 (principal component two of the TM data)	snodep69(2), snowat69(2), snodep71(4), snodep73(3), snowat76(6)
PCA3 (principal component three of the TM data)	none
PCA4 (principal component four of the TM data)	snodep72(4)

of predictor variables that still does an adequate job of predicting the value of the dependent variable, in this case snow depth, snow-water equivalent depth, or snow density. It can be seen in the table that some of the variables were useful in all models (eg: CONTOURS) while others were not useful in any instances (eg: ILLUM).

The best snow model that was produced had a coefficient of determination or adjusted R^2 of 0.6370. In this case for 1972 (snodep72), the independent variables of elevation (CONTOURS), incidence (INCID90), tree height (HEIGHT), and principal component four (PCA4) of the TM data explained approximately 64% of the variation in snow depth. PCA4 loads heavily on the red and near-infrared portion of the spectrum (Appendix B, Eigenvectors of covariance matrix and Table 1). The equation was:

$$\text{snodep72} = -568.503764 + 0.228866\,(\text{CONTOURS}) + 1.005163\,(\text{INCID90}) - 5.384195\,(\text{HEIGHT}) - 3.717428\,(\text{PCA4}) \qquad (3)$$

This result improves upon the best previous snow result in the basin using a stepwise, multiple regression procedure by 6%. The snow-water equivalent high result was approximately 58% while snow density had a top result of approximately 12%. Snow density had not been examined in any type of regression analysis in the basin before and with these disappointing results (Table 5) will not be examined here. Density is more likely to be different due to melting and wind compaction processes that affect different areas in the basin (Linsley et al., 1982).

In a simple, linear regression, positive residuals are those data points that lie above the least squares, best fit regression line, while negative residuals are those that lie below the line. Their sum equals zero. The coefficient of determination or R^2 is a measure of the total variation in the data which is accounted for by the regression (Ebdon, 1987). Complementary goodness-of-fit tests look at the variation which is not accounted for by the regression. In the case of snow depth for 1972 approximately 36% of the variance in snow depth cannot be explained by the model. It is probable that some other variables can provide the extra explanation and a discussion of what these may be is presented in Chapter 5.

The variables of elevation, incidence (mostly with a 90° zenith angle), tree height, NDVI, and principal component two of the TM data seem to explain most of the variation in snow depth and snow-water equivalent depth in the analyses (Table 6). This can be stated due to the number of times that these independent variables were significant in the series of snow models. Principal component two loads heavily on TM band 7 (Appendix B) which was significant in three of the analyses as well. The general increase in the snowpack with elevation is a well documented fact but the other variables have not been examined as closely.

Incidence, which is closely related to slope aspect, was the second best regressor in the analyses. Snow depths were higher in the areas where less insolation occurred. This is a logical extension of the snowmelt and ablation processes discussed earlier. Twin sub-basin and Cabin sub-basin (Figure 4) have both been treated with tree cutting procedures. The influence this had on the snow cover has been documented in the literature (Golding, 1973b; Hillman and Golding, 1981). Generally the clearcut areas had more snow cover than the surrounding forest areas at the same elevation. The clearcutting eliminated forest cover which could intercept some of the incoming snow before it reached the ground surface.

Forest fires have swept through the lower part of the basin. The lodgepole pine stands are generally the areas where the fire damage was extensive. Here, the trees are shorter than might normally be expected in the lower reaches of a watershed and the tree crown density is very high. Generally a negative relationship with tree height can be expected with elevation increase. It must be remembered that the data were confined to the forested portion of the basin where snow data were available. Extrapolation of the model beyond these areas is not possible without data to quantify the model. NDVI was quite useful in the analyses and had a negative relationship with snow variables. The relationship was negative because there is less cover (biomass) in more sparsely forested areas that could possibly intercept some of the incoming snow. This leads to a greater snowpack on the ground. The amount of biomass is greater at lower elevations and the forest fire caused a massive regeneration of new growth in the lower reaches of the basin. The crown density is also very high in the lower reaches which could cause additional interception of snow cover. Dense canopies have been shown to intercept more snow (Dunne and Leopold, 1978).

4.4 Regression Input into SPANS

Once the regression equations (Table 7) were determined it was possible to enter them back into SPANS using the modelling language. The regression equations were used by SPANS to create extrapolated snow surfaces for the basin. The equations used the beta coefficients (as determined by the regression analyses) to query pixel values in the map layers that were significant for calculating the snow surfaces. The snow depth result for 1972 (Figure 16) has some interesting features. The general trend is for an increase in snow depth with increasing elevation but some interesting patterns occur in light of the literature for snow studies in the basin. The clearcut areas of the Cabin sub-basin have higher snow depth values than the surrounding forest at the same elevation. This may be attributable to the lack of interception by forest cover (Golding and Swanson, 1986). There is no interception here and the tree height is zero. Principal component four highlights the red and near-infrared portions of the spectrum. These bands were designed to sense chlorophyll, biomass content, and vegetation type (Lillesand and Kiefer, 1987). Their negative coefficients in the equation also

Table 7: Regression Equations for Snow Depth and Snow-Water Equivalent Depth

SNOW MODEL	REGRESSION EQUATION
snodep69	-716.896474 + 0.092713 (CONTOURS) + 3.790974 (PCA2) + 0.761222 (INCID30) - 2.737900 (HEIGHT)
snowat69	-118.810614 + 0.015529 (CONTOURS) + 1.074890 (PCA2) - 0.256120 (STREAMS) - 0.063316 (ASPECT) - 1.162451 (HEIGHT)
snodep70	262.902177 + 0.104067 (CONTOURS) + 0.797848 (INCID90) - 0.261970 (SLOPEPCT) - 2.947015 (NDVI) - 4.589946 (TM60)
snowat70	155.764814 + 0.018576 (CONTOURS) + 0.162435 (INCID90) - 0.868687 (NDVI) - 1.504433 (TM60)
snodep71	-579.848195 + 0.121595 (CONTOURS) + 1.145146 (INCID50) - 4.333356 (HEIGHT) + 2.441166 (PCA2) - 1.694043 (CROWDEN)
snowat71	-196.643351 + 0.045405 (CONTOURS) + 0.419234 (INCID40) - 1.369332 (HEIGHT)
snodep72	-568.503764 + 0.228866 (CONTOURS) + 1.005163 (INCID90) - 5.384195 (HEIGHT) - 3.717428 (PCA4)
snowat72	-336.686578 + 0.068865 (CONTOURS) + 0.262278 (INCID90) + 0.699524 (TM70)
snodep73	-1471.233562 + 0.131320 (CONTOURS) + 1.552427 (INCID50) + 4.967897 (PCA2) + 1.614674 (CHROME)
snowat73	-168.836043 + 0.033257 (CONTOURS) + 0.562447 (INCID30)
snodep75	-148.983567 + 0.079127 (CONTOURS) + 0.954296 (INCID90) - 1.905817 (NDVI) - 2.547824 (HEIGHT)
snowat75	-28.045948 + 0.018471 (CONTOURS) + 0.265925 (INCID90) - 0.584909 (NDVI) - 0.707342 (HEIGHT)

Table 7:	continued.
SNOW MODEL	**REGRESSION EQUATION**
snodep76	57.457368 + 0.137756 (CONTOURS) + 0.955612 (INCID60) - 2.553826 (NDVI) - 3.807097 (TM60)
snowat76	-185.355820 + 0.040535 (CONTOURS) + 0.230707 (INCID90) - 0.508230 (CROWDEN) - 1.421395 (HEIGHT) - 0.059770 (ASPECT) + 0.460938 (PCA2)
snodep77	-500.822811 + 0.093071 (CONTOURS) + 1.096672 (INCID90) + 1.690638 (TM70) - 3.257969 (HEIGHT)
snowat77	-108.894974 + 0.020824 (CONTOURS) + 0.217756 (INCID90) + 0.349428 (TM70) - 0.0719588 (HEIGHT)
snodep78	-48.261717 + 0.010623 (CONTOURS) + 0.086345 (TM50) + 0.060894 (INCID80) - 0.245204 (HEIGHT)
snowat78	-7.430770 + 0.002485 (CONTOURS) - 0.059407 (NDVI) + 0.010039 (INCID90)
snodep80	-74.164892 + 0.015632 (CONTOURS) + 0.143887 (INCID50)
snowat80	-26.219897 + 0.004952 (CONTOURS) + 0.041210 (INCID50)
snodep81	-71.040872 + 0.013394 (CONTOURS) + 0.084253 (INCID80)
snowat81	-21.367038 + 0.003988 (CONTOURS) + 0.016556 (INCID60)

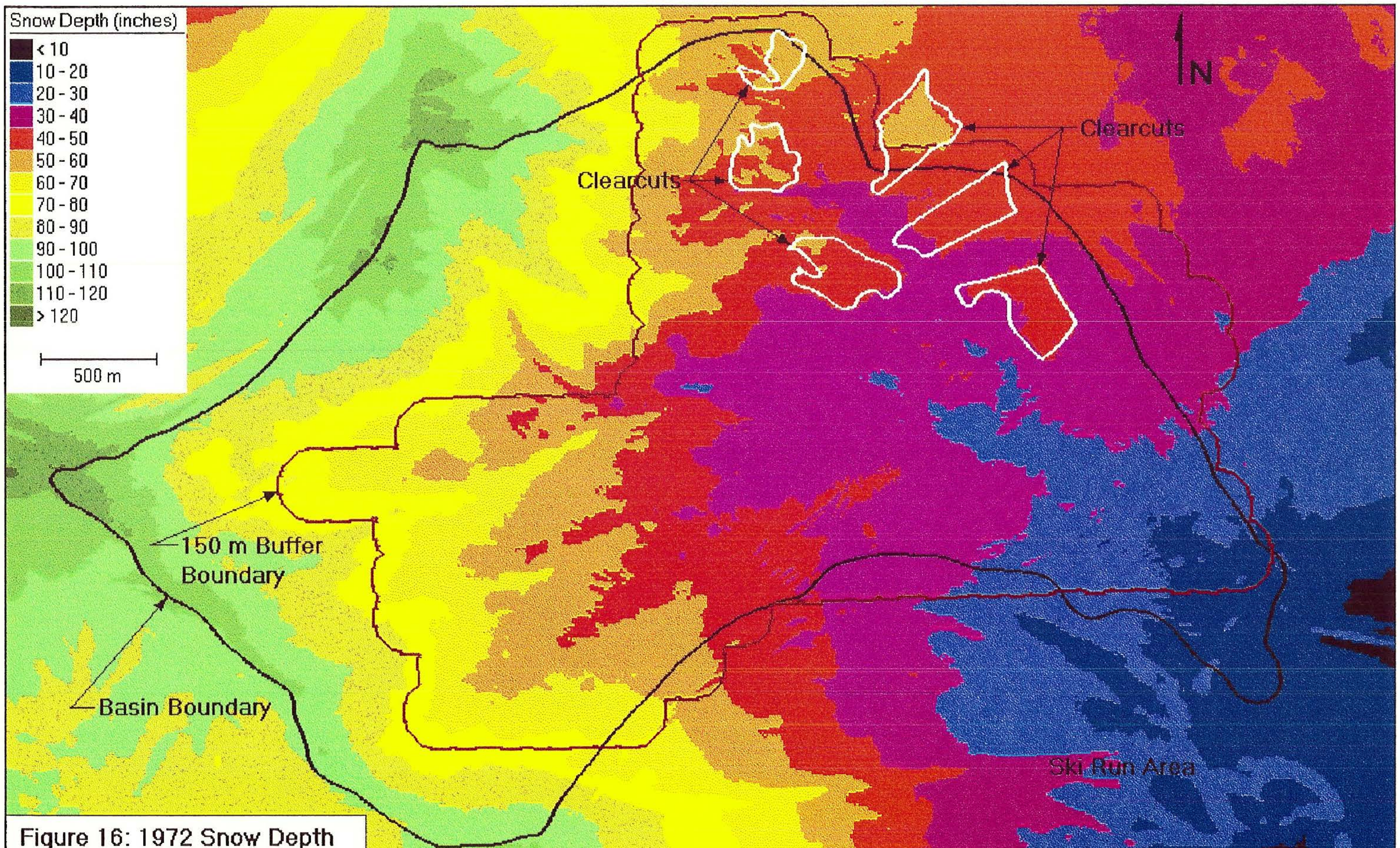


Figure 16: 1972 Snow Depth Regression Map

Note: this regression model explains 64% of the variation in snow depth for 1972 (adjusted $R^2 = 0.6370$), snow depths outside of the 150 m buffer cannot be validated due to DEM and snow data limits seem to be revealed. Clearcut areas have less biomass and more snow cover. This can be seen in the clearcut patterns where snow depths are generally higher than other areas at the same elevation.

It is also possible to determine the amount of water that is available from a snow-water equivalent map with SPANS by running an area analysis on each map. The area of each class or raw data value can be determined and summed to give an idea of how much water is in the basin. This is, however, limited by the amount of explanation provided by the model and its confidence limits.

When examining the results of the snow depth 1972 model it can be noted that higher snow values appear in clearcut areas including the ski slopes of Nakiska. Due to the limits of the DEM which is only realistically interpolated for Marmot Creek Basin and the limits of the snow data locations no information can be derived but it is interesting to note the higher snow values here than in the surrounding forest areas.

4.5 Summary

The most parsimonious stepwise, multiple, linear regression model was developed for snow depth in 1972. It provided the best explanation while using the fewest variables. If an independent variable did not provide the necessary increase in the goodness-of-fit it was not used in the model. Variables that were found to be multicollinear were excluded from the analyses. If an all-possible-subsets, stepwise, multiple, linear regression procedure had been used; there may have been a model produced that used a different combination of independent variables and provided an increased adjusted R^2 value.

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 Discussion

The stepwise, multiple, linear regression procedure produced a result that was better than any result for this research basin previously. The method was "automated" and remote, and found variables that were good predictors for snow cover. There may, however, be other variables that will produce a better result than the present set within the existing database.

Missing snow values are the unknown factors in these analyses. The number of missing values and the location of those values in the basin are key to the success of the models. If the missing values were concentrated in areas with low or high snow values it would adversely affect the models. This would not allow for the full variability of all the independent variables to be taken into account. Instead areas of concentration would be developed in the models that may or may not produce a model with a good explanation of the snow variation in the basin. The highest range of values for snow depth occurred in 1972 (Table 8). Whether a large range value is useful in the regression procedures requires further investigation in conjunction with the role of the missing data. It would have been useful to integrate alpine snow depth measurements into the analyses providing

Table 8: Snow Data Minimum and Maximum Values and Range for All Regressions

YEAR		SNOW DEPTH	SNOW-WATER EQUIVALENT DEPTH	SNOW DENSITY
1969	Minimum	130	24	0.125
	Maximum	630	210	0.429
	Range	500	186	0.304
1970		40	5	0.118
		540	140	0.444
		500	135	0.326
1971		110	20	0.123
		810	270	0.381
		700	250	0.258
1972		80	30	0.179
		870	265	0.414
		790	235	0.235
1973		65	5	0.069
		750	210	0.467
		685	205	0.398
1975		85	15	0.081
		550	150	0.367
		465	135	0.286
1976		120	20	0.057
		780	245	0.417
		660	225	0.360
1977		30	5	0.071
		450	115	0.383
		420	110	0.312
1978		4	1.5	0.069
		56	15	0.386
		52	13.5	0.317

Table 8:	continued.		
YEAR	**SNOW DEPTH**	**SNOW-WATER EQUIVALENT DEPTH**	**SNOW DENSITY**
1980	13.5 74 60.5	2 25.5 23.5	0.1163 0.3704 0.2541
1981	3 59 56	1 18.5 17.5	0.0690 0.5714 0.5024

the data could be obtained. Then the full gradation for snow depth at least could have been taken into account for the entire basin.

The TM satellite data were current in 1984. The snow data were collected three to fifteen years before this and modifications were made to the forest characteristics of the basin. If the basin had not been altered and if images could have been obtained for each year of the analyses then the results may have been improved upon. One half of the snow data were collected before extensive clearcutting in the basin and one half were collected after the clearcuts.

Previous snow models in Marmot Creek Basin were determined without the use of DEM or satellite imagery, with 0.58 (unadjusted R^2) or 58% being the largest amount of explained variation in SWE depth. The best case scenario for this thesis had 0.6370 (adjusted R^2) or 64% of the explained variation in snow depth that could be accounted for by the independent variables. The unadjusted R^2 value for comparison purposes was 0.6434. The best unadjusted R^2 value for SWE depth was 0.5869 which was still better than previous models.

Digitizing errors are compounded with further iterations of a data set. Error propagation is the process of producing even larger errors through the use of multiple sets of data, none of which are error free. Further iterations using these data produce larger amounts of error each time. The interpolated contours for the

DEM may have been generalized and errors resulting from this are carried forward in the analyses. The DEM may have been too coarse for the analyses that were performed on it to be very accurate. For every 100 foot rise in elevation on the original contour map the question is whether the interpolation procedure worked effectively and whether the DEM really represented the ground surface at each of the snow survey points. Some false flat spots could be noted in the DEM. These were a result of the interpolation procedure. The DEM was fairly coarse and flat spots where there really were not any may have led to misinterpretation in variables derived from the DEM. Perhaps this is why slope aspect and slope gradient which have been shown to be useful before (although in squared or cubed form, cf. Golding, 1974) were not very effective in these regression procedures. Error propagation could have led to false interpolation of values in some areas that could not be verified with field data. Image resampling can affect the accuracy of data. The 30 m resolution of the TM image was perhaps too coarse for the snow data set being utilized. It may have been better to include the SPOT image data with their spatial resolution of 20 m. The spatial resolution of a SPOT 20 m pixel as compared to a TM 30 m pixel would allow for more refined spectral signatures especially in transition areas of the images.

Possibilities exist for new ways of integrating data into this modelling procedure. Tree height determined from radar imagery is one of the possibilities. The use of GIS allows for the addition or deletion of any data set. Future models may have parameters that are very different from the present data set.

The question is: can GIS data integration techniques using multi-source data sets be useful in examining the dynamic process of snow accumulation? The results from this study are encouraging. Raw data and information derived from these data provided a better result than had previously been obtained in this area. This occurred even though the data were incomplete. If snow data had been available for the upper alpine zone of the basin it is hypothesized that the results would have been even more useful.

It may be interesting to model and map the regression equations for all of the analyses and compare the values to the original snow survey values. Individual pixel values and/or classes for the regression snow maps can be appended to the original point file and some comparative analysis could be performed.

5.2 Conclusion

Snow is a highly variable phenomenon and attempting to model its accumulation pattern in high mountain environments is especially difficult. A Geographic Information System (GIS) proved to be a valuable tool in the analysis and mapping of snow data. This thesis derived some encouraging results using remotely sensed and geomorphometric variables. Additional information provided from map sources also added to the models. The SPANS GIS was a very effective tool for integrating this large multivariate data set. The modelling capabilities in the GIS provided for the output of the snow models that were developed. In addition, the potential of integrating this data into other models, such as snow runoff models, was developed and refined.

Snow modelling using land cover variables from satellite imagery and topographic variables derived from digital elevation models was achieved with this research. The results of the regressions are encouraging and further research needs to be done in order to develop the relationships that have become apparent here. Baumgartner and Apfl (1993) describe the ASCAS system which integrates remote sensing and GIS techniques. One of the components of this system is the determination of snow cover variation. Snow cover is determined from satellite imagery and related to the amount of snowmelt runoff. This type of procedure could be enhanced with the addition of snow modelling techniques described in this thesis which could help to quantify the snow potential of basins.

Snow research must continue to look for ways to improve the modelling of snow depth and snow-water equivalent for widely ranging activities. Computer modelling is increasingly being used as an alternative to field based research. The time and cost involved in comprehensive studies in the field necessitates that alternative methods be developed. Snow modelling will allow for assessment of snowpack conditions in a timely and cost-effective manner. This will have implications for forestry as well as water management in hydroelectric and irrigation projects. If the amount of water that is available in mountain basins is known then planning decisions can be made based on that knowledge. The quantity of water that could potentially cause soil erosion after clearcutting would be known. Water supply estimates based on the snowpack would also be available to assess the potential for power generation and/or irrigation planning and management. Improvements in data quality and availability will continue. Satellite data are seen as being key to the further development of distributed hydrologic models with a snow component (Kite, 1989).

In the immediate future ground survey techniques will not be entirely replaced by remote sensing methods. Perhaps with further refinements and development of more reliable remote sensing techniques it will be possible to complete small and large scale studies without having to measure the snowpack in the field. Continued refinement of methods to collect snow data remotely must proceed if a cost-effective, timely, and reliable estimate of snow characteristics is to be obtained.

Information can be derived from the R^2 values obtained in the regression analyses and examination of which variables were the most effective overall can lead to the possible use of these variables in further research and in new regression procedures. Elimination of insignificant variables would seem to lend itself to developing a model through multiple, linear regression where the independent variables used are already known to be generally effective in explaining variation in the snowpack. If this is looked at, it can be said that elevation, a measure of incidence, principal component two of the TM data (which loads heavily on TM band 7), tree height, NDVI, and perhaps crown density, slope aspect and slope gradient would be the preferred independent inputs into a model.

5.3 Suggestions for Further Research

Appending snow modelling equation map results from the SPANS GIS to the original point data would allow the researcher to investigate the differences in observed and interpolated data. If the technique used by Golding (1974) of deriving powers of the variables had been utilized perhaps a better model could have been obtained. This definitely needs to be investigated further.

Autocorrelation measures whether there is correlation between absolute values of successive residuals. This indicates if the linear regression equation is the best possible equation for determining the relationship between the variables. A value close to plus one or minus one suggests the presence of a relationship between successive residuals. A complete absence of this relationship would give an autocorrelation value of zero (Ebdon, 1987). Spatial autocorrelation occurs when the presence, absence, or degree of a certain feature affects the presence, absence, or degree of the same feature in neighbouring units (Congalton, 1991). It is particularly important if an error in one place can be found to positively or negatively influence errors in surrounding locations (Congalton, 1991). The role of this process requires investigation in light of the data challenges that occurred with this thesis.

The exact variables that may account for the unexplained variation in this research are unclear. Lapen (1991) has shown that across slope and down slope curvature can be important when looking at snow distribution. The role of wind in redistribution of snow also needs to be examined further. The artificial clearings alter the data set but whether the impact is negative or positive on the regression procedure is unknown at this time.

REFERENCES

ALBERTA FOREST SERVICE. 1979. **Forest Inventory Map, TWP. 23, RGE. 9, W. 5, MER**. Alberta Energy and Natural Resources. Edmonton, Alberta.

AVERY, T.E. AND G.L. BERLIN. 1992. **Fundamentals of Remote Sensing and Airphoto Interpretation**. Macmillan Publishing Company. New York, New York. 472pp.

BARGE, B.L., R.G. HUMPHRIES, S.J. MAH, AND W.K. KUHNKE. 1979. **Rainfall Measurements by Weather Radar: Applications to Hydrology**. Water Resources Research. 15(6): 1380-1386.

BAUMGARTNER, M.F. 1990. **Snow Cover Mapping and Snowmelt Runoff Simulations on Microcomputers**. In Remote Sensing and the Earth's Environment, Proceedings of a Summer School held at Alpbach, Austria. July 26-August 4, 1990. (ESA SP-301, March 1990).

BAUMGARTNER, M.F. AND G. APFL. 1993. **Alpine Snow Cover Analysis System**. In Proceedings of the 6th AVHRR Data User's Meeting. Belgirate, Italy. June 29-July 2, 1993.

BAUMGARTNER, M.F., J. MARTINEC, AND K. SIEDEL. 1986. **Large-Area Deterministic Simulation of Natural Runoff from Snowmelt Based on Landsat MSS Data**. IEEE Transactions on Geoscience and Remote Sensing. Vol. GE-24. No. 6.

BAUMGARTNER, M.F., AND A. RANGO. 1991. **Snow Cover Mapping Using Microcomputer Image Processing Systems**. Nordic Hydrology. 22: 193-210.

BAUMGARTNER, M.F., K. SIEDEL, AND J. MARTINEC. 1987. **Toward Snowmelt Runoff Forecast Based on Multisensor Remote-Sensing Information**. IEEE Transactions on Geoscience and Remote Sensing. Vol. GE-25. No. 6.

BERGMAN, J.A. 1989. **An Evaluation of the Acoustic Snow Depth Sensor in a Deep Sierra Nevada Snowpack**. In Proceedings of the Western Snow Conference. 57th Annual Meeting. Colorado State University. Fort Collins, Colorado. April 18-20, 1989.

BERNIER, P.Y. 1986. **Extrapolating Snow Measurements on the Marmot Creek Experimental Basin**. Nordic Hydrology. 17: 83-92.

BORLAND. 1992. **Quattro Pro for Windows Manuals**. Borland International Inc. Scotts Valley, California.

BOWERS, W.W., S.E. FRANKLIN, J. HUDAK, AND G.J. McDERMID. 1994. **Forest Structural Damage Analysis Using Image Semivariance**. Canadian Journal of Remote Sensing. 20(1): 28-36.

BUNN, F.E., E.J. CARTY, AND S.D. PATERSON. 1991. **Easy Data Integration: Multi-Satellite, Airborne, and In-situ data with Geographic Analysis and Display System (GADS)**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

BURROUGH, P.A. 1986. **Principles of Geographical Information Systems for Land Resources Assessment**. Oxford University Press. Oxford, England. 194pp.

CANADA MAP OFFICE. 1986. **INDEX 2: Maps of the National Topographic System of Canada**. Surveys and Mapping Branch, Department of Energy, Mines, and Resources. Ottawa, Ontario.

CANADA SOIL SURVEY COMMITTEE, SUBCOMMITTEE ON SOIL CLASSIFICATION. 1978. **The Canadian System of Soil Classification**. Can. Dep. Agric. Publ. 1646. Supply and Services Canada. Ottawa, Ontario.

CANADIAN NATIONAL COMMITTEE FOR THE INTERNATIONAL HYDROLOGICAL DECADE AND THE UNIVERSITY OF NEW BRUNSWICK. 1968. **Snow Hydrology**. The Secretariat, Canadian National Committee for the International Hydrological Decade. Ottawa, Ontario. 82pp.

CARROLL, T.R. 1994. **Remote Sensing of Snow Cover in North America Using Airborne Gamma Radiation Data and AVHRR, GOES, and SSM/I Satellite Data**. In Proceedings of the 3rd Circumpolar Symposium on Remote Sensing of Arctic Environments. Fairbanks, Alaska. May 16-20, 1994.

CHANG, A.T.C. AND L. TSANG. 1992. **A Neural Network Approach to Inversion of Snow Water Equivalent from Passive Microwave Measurements**. Nordic Hydrology. 23: 173-182.

CHOW, V.T. 1964. **Handbook of Applied Hydrology**. McGraw-Hill Book Co. Toronto, Ontario.

COHEN, W.B. AND T.A. SPIES. 1991. **Image Spatial and Spectral Models for Estimating Conifer Forest Structural Attributes**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

COLBECK, S.C. (ed.). 1980. **Dynamics of Snow and Ice Masses**. Academic Press. Toronto, Ontario. 468pp.

CONESE, C. AND F. MASELLI. 1991. **Use of Multitemporal Information to Improve Classification Performance of TM Scenes in Complex Terrain.** ISPRS Journal of Photogrammetry and Remote Sensing. 46: 187-197.

CONGALTON, R.G. 1991. **A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data**. Remote Sensing of Environment. 37: 35-46.

CONNERY, D.R. 1992. **Avalanche Vegetation Classification Using Landsat Imagery and a Digital Elevation Model in southwestern Alberta.** Unpublished M.Sc. Thesis. Department of Geography. University of Calgary. Calgary, Alberta.

COTE, M. 1984. **Climate of Kananaskis**. Environment Canada, Atmospheric Environment Service. Edmonton, Alberta.

CURRIE, D.H., J.A. DECHKA, AND O. SAWICKI. 1991. **An Assessment of Results from a Forest Inventory and Reconnaissance System**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

DAVIES, T.D., M. TRANTER, AND H.G. JONES (eds.). 1991. **Seasonal Snowpacks, Processes of Compositional Change**. Springer-Verlag. New York, New York. Series G: Ecological Sciences. 28: 471pp.

DAVIS, J.C. 1986. **Statistics and Data Analysis in Geology (Second Edition)**. John Wiley and Sons Inc. Toronto, Ontario.

DAVIS, J.C. 1973. **Statistics and Data Analysis in Geology**. John Wiley and Sons Inc. Toronto, Ontario.

DE BROSIA, M. 1986. **Review of the Current and Potential Application of Modelling and Simulation in Environmental Assessment in Canada**. Canada, Department of Environment, Canadian Environmental Research Council (CEARC). Ottawa, Ontario.

DE HANN, J.F., J.W. HOVENIER, J.M.M. KOKKE, AND H.T.C. VAN STOKKOM. 1991. **Removal of Atmospheric Influences on Satellite-borne Imagery: A Radiative Transfer Approach**. Remote Sensing of Environment. 37: 1-21.

DEY, B. AND A.K. CHAKRAVARTI. 1976. **A Synoptic Climatological Analysis of Summer Dry Spells in the Canadian Prairies**. Great Plains Rocky Mountain Geog. A.A.G. 5(1): 30-46.

DEY, B., V.K. SHARMA, AND A. RANGO. 1992. **Linear or Nonlinear Covariance of Seasonal Snowmelt and Snow Cover in Western Himalayas**. Nordic Hydrology. 23: 183-192.

DICKINSON, W.T. 1982. **Distributed Watershed Models for the Marmot Basin**. In Proceedings of the Canadian Hydrology Symposium: 82. (Associate Committee on Hydrology, National Research Council of Canada). Fredericton, New Brunswick. June 14-15, 1982.

DICKINSON, W.T. AND F.H. THEAKSON. 1982. **Snow-Flume Modelling of Snow Accumulation in Forest Openings**. In Proceedings of the Canadian Hydrology Symposium: 82. (Associate Committee on Hydrology, National Research Council of Canada). Fredericton, New Brunswick. June 14-15, 1982.

DICKMAN, S. 1988. **Snow and Avalanche Research, all you ever wanted to know about snow**. Nature. Vol. 336 (Nov. 28/88): 330-31.

DIXON, R. AND A. MACK. 1991. **Crop Discrimination in the Carberry Area with Combined SAR and TM Data**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

DUNCAN, C.L. 1992. **Chemistry of Rime and Snow collected at a site in the Central Washington Cascades**. Environmental Science and Technology. Vol. 26 (Jan. 92).

DUNNE, T. AND L.B. LEOPOLD. 1978. **Water in Environmental Planning**. W.H. Freeman Co. New York, New York. 818pp.

DURY, D.H. 1966. **Essays in Geomorphology**. Heinemann Educational Books Ltd. London, England. 404pp.

EASTMAN, J.R. 1990. **IDRISI, A Grid-Based Geographic Analysis System**. Clark University. Graduate School of Geography. Worchester, Massachusetts. 362pp.

EBDON, D. 1987. **Statistics in Geography**. Basil Blackwell Ltd. Oxford, England. 232pp.

EHLERS, M. 1991. **Multisensor Image Fusion Techniques in Remote Sensing**. ISPRS Journal of Photogrammetry and Remote Sensing. 46: 19-30.

ELACHI, C. 1994. **Recent Advances in Spaceborne SAR Observation of the Earth's Surface**. In Proceedings of the 3rd Circumpolar Symposium on Remote Sensing of Arctic Environments. Fairbanks, Alaska. May 16-20, 1994.

ELDER, K., J. DOZIER, AND J. MICHAELSEN. 1991. **Snow Accumulation and Distribution in an Alpine Watershed**. Water Resources Research. 27(7): 1541-1552.

ENVIRONMENT CANADA, ATMOSPHERIC ENVIRONMENT SERVICE. 1982. **Canadian Climate Normals 1951-1980, Vol. 2 Temperature**. Atmospheric Environment Service, Department of the Environment. Ottawa, Ontario.

EPP, H. 1994. **The Utilization of Remote Sensing and Geographic Information Systems Technology for the Exploration of Kimberlite Deposits, Lac De Gras Area, Northwest Territories, Canada**. In Proceedings of the 3rd Circumpolar Symposium on Remote Sensing of Arctic Environments. Fairbanks, Alaska. May 16-20, 1994.

EYTON, J.R. 1989. **Low-Relief Topographic Enhancement in a Landsat Snow-Cover Scene**. Remote Sensing of Environment. 27: 105-118.

FERGUSON, H.L., H.F. CORK, R.L. ANDERSON, S. MASTORIS, and B. WEISMAN. 1971. **Theoretical Clear Sky Effective Insolation Over a Small Mountain Basin**. Climatological Studies No. 21. Environment Canada, Atmospheric Environment Service. Ottawa, Ontario.

FERGUSON, R. 1977. **Linear Regression in Geography**. Catmog #15, Concepts and Techniques in Modern Geography. Norwich, East Anglia, England. 43pp.

FOLKS, J.L. 1981. **Ideas of Statistics**. John Wiley and Sons. Toronto, Ontario. 368pp.

FORSYTHE, K.W., R.D. WHEATE, AND N.M. WATERS. 1995. (in press). **Classification and Mapping of Avalanche Slopes in Yoho National Park: An Assessment Using LANDSAT TM and Digital Elevation Data**. In Proceedings of the 17th Canadian Symposium on Remote Sensing. Saskatoon, Saskatchewan. June 13-15, 1995.

FRANKLIN, S.E., D.R. CONNERY, AND J.A. WILLIAMS. 1994. **Classification of Alpine Vegetation Using Landsat Thematic Mapper Spot HRV and DEM Data**. Canadian Journal of Remote Sensing. 20(1): 49-56.

FRANKLIN, S.E., G.D. LODWICK, AND R.D. WHEATE. 1990. **Research Related to Digital Remote Sensing of Mountain Areas at the University of Calgary**. Canadian Journal of Remote Sensing. 16(2): 50-54.

FRANKLIN, S.E. AND A.G. RASKE. 1994. **Satellite Remote Sensing of Spruce Budworm Forest Defoliation in Western Newfoundland**. Canadian Journal of Remote Sensing. 20(1): 37-48.

GARSTKA, W.U., L.D. LOVE, B.C. GOODELL, AND F.A. BERTLE. 1958. **Factors Affecting Snowmelt and Streamflow**. United States Department of the Interior, Bureau of Reclamation. Denver, Colorado. 189pp.

GEIST, V. 1987. **Bighorn Sheep and the Calgary Winter Olympics**. Probe Post. 9(4): 20-24.

GEMMEL, F.M., D.G. GOODENOUGH, C. KUSHIGBOR, J.F. MEUNIER, AND R. WIART. 1991. **Investigation of Remotely Sensed Data for Estimating Forest Stand Attributes**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

GIOVINETTO, M.B., N.M. WATERS, AND H. ZWALLY. 1991. **Satellite Passive-Microwave Observations and the Distribution of Net Surface Accumulation in the Interior of Greenland**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

GLYNN, J.E., T.R. CARROLL, P.B. HOLMAN, AND R.L. GRASTY. 1988. **An Airborne Gamma Ray Snow Survey of a Forest Covered Area with a Deep Snowpack**. Remote Sensing of Environment. 26: 149-160.

GOLDING, D.L. 1993. **Personal Communication**. Faculty of Forestry. University of British Columbia.

GOLDING, D.L. 1974. **The Correlation of Snowpack with Topography and Snowmelt Runoff on Marmot Creek Basin, Alberta**. Atmosphere. 12(1): 31-38.

GOLDING, D.L. 1973a. **Snow Cover and Water Equivalent Measurement by Remote Sensing**. Northern Forest Research Centre. Edmonton, Alberta.

GOLDING, D.L. 1973b. **Snowpack calibration on Marmot Creek to detect changes in accumulation pattern after forest-cover manipulation**. Proceedings of the Banff Symposia on The Role of Snow and Ice in Hydrology. Properties and Processes. UNESCO. Paris, France.

GOLDING, D.L. 1972. **Snow Accumulation as Influenced by Topography, and its Correlation with Annual and Seasonal Streamflow on Marmot Basin, Alberta**. Presented at the Sixth Annual Congress of the Canadian Meteorological Society. Edmonton, Alberta. May-June 1972.

GOLDING, D.L. 1970. **Research Results from Marmot Creek Experimental Watershed, Alberta, Canada**. IASH-UNESCO. Symposium on the results of research on representative and experimental basins. Wellington, New Zealand. December, 1970.

GOLDING, D.L. 1968. **Snow Measurement on Marmot Creek Experimental Watershed**. Forest Research Laboratory. Information Report A-X-18. Calgary, Alberta.

GOLDING, D.L. AND R.L. HARLAN. 1972. **Estimating Snow-Water Equivalent from Point-Density Measurements of Forest Stands**. Ecology. Vol. 53(4).

GOLDING, D.L. AND R.H. SWANSON. 1986. **Snow Distribution Patterns in Clearings and Adjacent Forest**. Water Resources Research. 22(13): 1931-1940.

GOODISON, B.E. 1994. **Personal Communication**. Atmospheric Environment Service, Environment Canada. Downsview, Ontario.

GOODISON, B.E., J.R. METCALFE, R.A. WILSON, AND K. JONES. 1988. **The Canadian Automatic Snow Depth Sensor: A Performance Update**. In Proceedings of the Western Snow Conference. 56th Annual Meeting. Kalispell, Montana. April 19-21, 1988.

GOODISON, B.E. AND A.E. WALKER. 1994. **Passive Microwave Remote Sensing of Snow Cover and Freshwater Ice in Canada.** In Proceedings of the 3rd Circumpolar Symposium on Remote Sensing of Arctic Environments. Fairbanks, Alaska. May 16-20, 1994.

GRANBERG, H.B. AND G.J. IRWIN. 1991. **Construction of a Digital Transect at Schefferville to Validate a Geographic Snow Information System.** In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

GRAY, D.M. AND D.H. MALE (eds). 1981. **HANDBOOK OF SNOW: Principles, Processes, Management & Use.** Pergamon Press. Toronto, Ontario. 776pp.

GREGOTSKI, M.E. AND E.F. LE DREW. 1991. **The Mapping of Net Surface Radiation Using LANDSAT TM Imagery.** In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

HALL, D.K. AND J.L. FOSTER. 1994. **Mapping Snow by Elevation Zone in Glacier National Park, Montana.** In Proceedings of the 3rd Circumpolar Symposium on Remote Sensing of Arctic Environments. Fairbanks, Alaska. May 16-20, 1994.

HALL, D.K. AND J. MARTINEC. 1985. **Remote Sensing of Ice and Snow.** Chapman and Hall Ltd. New York, New York. 189pp.

HANN, C.T. 1977. **Statistical Methods in Hydrology.** The Iowa State University Press. Ames, Iowa.

HARRINGTON, A.W. 1953. **Snow Surveys in the Northeast and Uses of Data.** In Proceedings of the Western Snow Conference. 21st Annual Meeting. Boise, Idaho. April 20-22, 1953.

HELMERS, A.E., D.E. DONLEY, AND H.J. STOCKWELL (eds.). 1953. **Proceedings of the Western Snow Conference.** 21st Annual Meeting. Boise, Idaho. April 20-22, 1953.

HENDERSON, T.J. 1982. **Western Snow Conference - The First Fifty Years.** In Proceedings of the Western Snow Conference. 50th Annual Meeting. Reno, Nevada. April 19-23, 1982.

HICKS, C.R. 1982. **Fundamental Concepts in the Design of Experiments (Third Edition).** Holt, Rinehart, and Winston. Toronto, Ontario.

HILLMAN, G.R. and D.L. GOLDING. 1981. **Forest Floor Characteristics of Marmot and Streeter Experimental Watersheds, Alberta**. Northern Forest Research Centre, Information Report NOR-X-234. Environment Canada, Canadian Forestry Service. Edmonton, Alberta.

HOLROYD, E.W., J.P. VERDIN, AND T.R. CAROLL. 1989. **Mapping Snow Cover with Satellite Imagery: Comparison of Results from Three Sensor Systems**. In Proceedings of the Western Snow Conference. 57th Annual Meeting. Fort Collins, Colorado. April 18-20, 1989.

HOREJSI, B. 1986. **Bighorn Sheep, Mount Allan, and the 1988 Winter Olympics: Political and Biological Realities**. In Proceedings of the Fifth Biennial Symposium, Northern Wild Sheep and Goat Council. Missoula, Montana. April 14-17, 1986.

HUDSON, R.O. 1986. **Rainfall-Runoff Relations**. Unpublished M.Sc. Thesis. Department of Geography. University of Calgary. Calgary, Alberta.

HURDLE, R. 1992. **Personal Communication**. Northern Forestry Research Centre. Edmonton, Alberta.

INTERA-TYDAC. 1993. **SPANS GIS Manuals**. Intera-Tydac Technologies Inc. Nepean, Ontario.

JENSEN, J.R. 1986. **Introductory Digital Image Processing**. Prentice-Hall. Englewood Cliffs, New Jersey. 379pp.

JOHNSON, V.A. AND S.H. PAINE. 1991. **Visualization and Analysis of Resource Conflicts Using a Geographic Information System: A Case Study**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

JORIA, P.E., S.C. AHEARN, AND M. CONNOR. 1991. **A Comparison of the SPOT and LANDSAT Thematic Mapper Satellite Systems for Detecting Gypsy Moth Defoliation in Michigan**. Photogrammetric Engineering and Remote Sensing. 57(12): 1605-1612.

JUSTICE, C.O. AND J.R.G. TOWNSHEND. 1981. **Integrating Ground Data with Remote Sensing**. In: Terrain Analysis and Remote Sensing. George Allan and Unwin Ltd. London, England. 38-58.

KEMPKA, R.G., B.S. MAURIZI, F.A. REID, R.C. ALTOP, AND J.W. DENTON. 1994. **Standardizing Reference Data Collection for Satellite Land Cover Mapping in Alaska**. GIS '94 Symposium. Vancouver, British Columbia.

KENNEDY, P. 1985. **A Guide to Econometrics (Second Edition)**. MIT Press. Cambridge, Massachusetts.

KIRK, R. 1977. **Snow.** William Morrow and Co. Inc. New York, New York. 319pp.

KITE, G. 1989. **Hydrologic Modelling with Remotely Sensed Data.** In Proceedings of the Western Snow Conference. 57th Annual Meeting. Fort Collins, Colorado. April 18-20, 1989.

KITE, G.W. AND N. KOUWEN. 1992. **Watershed Modelling Using Land Classifications**. Water Resources Research. 28(12): 3193-3200.

KRAIJENHOFF, D.A. AND J.R. MOLL. 1986. **River Flow Modelling and Forecasting**. D. Reidel Publishing Co. Hingham, Massachusetts. 372pp.

KUSHWAHA, S.P.S. 1990. **Forest Type Mapping and Change Detection from Satellite Imagery**. ISPRS Journal of Photogrammetry and Remote Sensing. 45: 175-181.

LA CHAPELLE, E.R. 1969. **Field Guide to Snow Crystals**. University of Washington Press. Seattle, Washington. 101pp.

LANG, H. 1986. **Forecasting Meltwater Runoff**. In: River Flow Modelling and Forecasting. D. Reidel Publishing Co. Hingham, Massachusetts. 372pp.

LAPEN, D.R. 1991. **Modelling the Redistribution of Snow in a Prairie Agricultural Landscape using Digital Terrain and Spatial Entropy Analysis**. Unpublished M.Sc. Thesis. Department of Geography. University of Saskatchewan. Saskatoon, Saskatchewan.

LAVREAU, J. 1991. **De-Hazing Landsat Thematic Mapper Images**. Photogrammetric Engineering and Remote Sensing. 57(10): 1297-1302.

LECONTE, R., C. ANCTIL, T.J. PULTZ, AND B. BRISCO. 1991. **Field Determination of Snow Density and Liquid Water Content Using Portable Dielectric Probes**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

LILLESAND, T.M. AND R.W. KIEFER. 1987. **Remote Sensing and Image Interpretation (Second Edition)**. John Wiley and Sons. Toronto, Ontario. 721pp.

LINSLEY, R.K., M.A. KOHLER, AND J.L.H. PAULHUS. 1982. **Hydrology for Engineers**. McGraw-Hill Book Co. Montreal, Quebec. 508pp.

LITTLE, T.M. AND F.J. HILLS. 1978. **Agricultural Experimentation**. John Wiley and Sons. Toronto, Ontario.

LOVELAND, T.R., J.W. MERCHANT, D.O. OHLEN, AND J.F. BROWN. 1991. **Development of a Land-Cover Characteristics Database for the Conterminous U.S.** Photogrammetric Engineering and Remote Sensing. 57(11): 1453-1463.

MAGUIRE, D.J., M.F. GOODCHILD, AND O.W. RHIND. 1991. **Geographical Information Systems**. Longman Scientific and Technical. London, England.

MARKS, D., J. DOZIER, AND R.E. DAVIS. 1992. **Climate and Energy Exchange at the Snow Surface in the Alpine Region of the Sierra Nevada, 1. Meteorological Measurements and Monitoring**. Water Resources Research. 28(11): 3029-3042.

MATHER, P.M. 1976. **Computational Methods of Multivariate Analysis in Physical Geography**. John Wiley and Sons. Toronto, Ontario. 532pp.

McDERMID, G.J. 1993. **Spatial, Spectral, and Geomorphometric Variables for the Remote Sensing of Slope Processes**. Unpublished M.Sc. Thesis. Department of Geography. University of Calgary. Calgary, Alberta.

McGHEE, J.W. 1985. **Introductory Statistics**. West Publishing Co. New York, New York.

McKAY, G.A. 1968. **Problems of Measuring and Evaluating Snowcover**. In: Snow Hydrology. The Secretariat, Canadian National Committee for the International Hydrological Decade. Ottawa, Ontario. 82pp.

MUSSAKOWSKI, R. AND N.F. TROWELL. 1991. **Lineament Analysis of Digital Elevation Data and a Comparison with LANDSAT Thematic Mapper and SPOT Panchromatic Data, Thunder Bay, Ontario Area**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

NAIMAN, A., R. ROSENFELD, AND G. ZIRKEL. 1972. **Understanding Statistics**. McGraw Hill Inc. New York, New York. 235pp.

NATIONAL HYDROLOGY RESEARCH INSTITUTE. 1980. **Glide and Creep Processes in Mountain Snowpacks**. Saskatoon, Saskatchewan. Paper No. 6. 66pp.

NIEMANN, K.O., R.G. PILON, AND R.J. WIART. 1991. **Generalized Forest Mapping Using Multitemporal LANDSAT TM Imagery: Providing Inputs into Geographic Information Systems.** In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

NKEMDIRIM, L. 1993. **Personal Communication**. Department of Geography. University of Calgary. Calgary, Alberta.

NORUSIS, M.J. 1985. **SPSS-X Advanced Statistics Guide**. SPSS Inc. 505pp.

NOSSIN, J.J. 1991. **Slope Visibility and Shadows in Side-look SPOT Imagery.** ISPRS Journal of Photogrammetry and Remote Sensing. 46: 133-146.

PALYLYK, C.L., P.H. CROWN, AND D.J. SAUCHYN. 1991. **Temporal Monitoring of Agricultural Soil Erosion Risk Through Integrated LANDSAT and GIS.** In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

PCI. 1991. **Pace Image Analysis Manuals version 5.1**. PCI Inc. Richmond Hill, Ontario.

PEDDLE, D.R. AND S.E. FRANKLIN. 1991. **Belief Theory for Multisource Data Modelling of Complex Environmental Phenomena**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

PIKE, R.J. 1988. **The Geometric Signature: Quantifying Landslide Terrain Types From Digital Elevation Models**, Mathematical Geology. Vol.20(5): 491-511.

PRESTON, E.B. 1993. **Remote Sensing, GIS Technologies Support Sea Ice Motion Monitoring**. GIS World. January 1993: 36-39.

RANGO, A. 1992. **Worldwide Testing of the Snowmelt Runoff Model with Applications for Predicting the Effects of Climate Change**. Nordic Hydrology. 23: 155-172.

RANGO, A. AND R. PETERSON (eds.). 1980. **Operational Applications of Satellite Snowcover Observations**. NASA Scientific and Technical Information Office. Houston, Texas. Conference Publication 2116. 301pp.

ROCK, N.M.S. 1988. **Numerical Geology**. Springer-Verlag. New York, New York. 427pp.

ROSENHOLM, D.G. 1993. **Land Use and Vegetation Mapping by Satellite - Some Experiences Gained by SSC Satellitbild in 1987-1993**. Presented at the International Symposium "Operationalization of Remote Sensing". ITC, Enschede, The Netherlands. April 19-23, 1993.

ROTT, H. AND R.E. DAVIS. 1993. **Multifrequency and Polarmetric SAR Observations on Alpine Glaciers**. Annals of Glaciology. 17: 98-104.

ROTT, H., H. MILLER, K. STURM, AND W. RACK. 1993. **Application of ERS-1 SAR and Scatterometer Data for Studies of the Antarctic Ice Sheet**. In Proceedings Second ERS-1 Symposium - Space at the Service of our Environment. Hamburg, Germany. October 11-14, 1993. (ESA SP-361, January, 1994).

ROTT, H. AND T. NAGLER. 1993. **Capabilities of ERS-1 SAR for Snow and Glacier Monitoring in Alpine Areas**. In Proceedings Second ERS-1 Symposium - Space at the Service of our Environment. Hamburg, Germany. October 11-14, 1993. (ESA SP-361, January, 1994).

ROTT, H. AND T. NAGLER. 1992. **Snow and Glacier Investigations by ERS-1 SAR - First Results**. In Proceedings First ERS-1 Symposium - Space at the Service of our Environment. Cannes, France. November 4-6, 1992. (ESA SP-359, March, 1993).

ROTT, H., K. STURM, AND H. MILLER. 1993. **Active and Passive Microwave Signatures of Antarctic Firn by Means of Field Measurements and Satellite Data**. Annals of Glaciology. 17: 337-343.

ROTT, H., K. STURM, AND H. MILLER. 1992. **Signatures of Antarctic Firn by Means of ERS-1 AMI and by Field Measurements**. In Proceedings First ERS-1 Symposium - Space at the Service of our Environment. Cannes, France. November 4-6, 1992. (ESA SP-359, March, 1993).

SCHANZER, D.L. 1991. **Spatial and Spectral Integration: Illustrated for Identification of Cloud, Haze, and Other Targets in LANDSAT TM Data.** In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

SHAFER, B. (ed.)., R.T. DAVIS, AND J.R. MEIMAN. 1982. **Proceedings of the Western Snow Conference.** 50th Annual Meeting. Reno, Nevada. April 19-23, 1982.

SHAFER, B. (ed.)., J.K. MARRON, AND C. TROENDLE. 1989. **Proceedings of the Western Snow Conference.** 57th Annual Meeting. Fort Collins, Colorado. April 18-20, 1989.

SHAFER, B. (ed.)., J.K. MARRON, AND C. TROENDLE. 1988. **Proceedings of the Western Snow Conference.** 56th Annual Meeting. Kalispell, Montana. April 19-21, 1988.

SKOYE, K.R. AND J.R. EYTON. 1992. **Digital Analysis of Low-Relief Topography in a Landsat Snow-Cover Scene in South-Central Alberta.** Canadian Journal of Remote Sensing. 18(3): 143-149.

SMITH, D.G. AND L.W. MARTZ. 1989. **Soil Erosion Hazards in Saskatchewan: An Assessment Using the USLE and WEQ.** Department of Geography Resource Paper. University of Saskatchewan. Saskatoon, Saskatchewan. 47pp.

SMITH, D.J. 1989. **Personal Communication.** Department of Geography. University of Saskatchewan. Saskatoon, Saskatchewan.

SOKAL, R.R. AND F.J. ROHLF. 1981. **Biometry (Second Edition).** W.H. Freeman and Co. New York, New York.

STORR, D. 1973. **Wind-Snow Relations at Marmot Creek, Alberta.** Canadian Journal of Forest Resources. 3: 479-485.

STORR, D. 1972. **Estimating Effective Net Radiation for a Mountainous Watershed.** Boundary-Layer Meteorology. 3: 3-14.

STORR, D. AND H.L. FERGUSON. 1972. **The Distribution of Precipitation in Some Mountainous Canadian Watersheds.** In Proceedings of the Symposium on Distribution of Precipitation in Mountainous Areas. Geilo, Norway. July 31 - August 5, 1972. World Meteorological Organization. Geneva, Switzerland.

SWANSON, R.H., D.L. GOLDING, R.L. ROTHWELL, and P.Y. BERNIER. 1986. **Hydrologic Effects of Clear-Cutting on Marmot Creek and Streeter Watersheds, Alberta.** Northern Forest Research Centre. Information Report NOR-X-278. Environment Canada, Canadian Forestry Service. Edmonton, Alberta.

TABACHNIK, B.G. AND L.S. FIDELL. 1989. **Using Multivariate Analysis**. Harper Collins. New York, New York.

THIRKETTLE, F. 1993. **Personal Communication**. Ph.D. Associates Inc. Calgary, Alberta.

THIRKETTLE, F., A. WALKER, B. GOODISON, AND D. GRAHAM. 1991. **Canadian Prairie Snow Cover Maps from Near Real-Time Passive Microwave Data: From Satellite Data To User Information**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

TIMONEY, K., G.P. KERSHAW, AND D. OLESEN. 1992. **Late Winter Snow-Landscape Relationships in the Subarctic Near Hoarfrost River, Great Slave Lake, Northwest Territories, Canada**. Water Resources Research. 28(7): 1991-1998.

WALKER, A.E. AND B. GOODISON. 1991. **Monitoring Snow Cover in the Boreal Forest Region of the Canadian Prairies Using Passive Microwave Data**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

WALSH, S.J., J.W. COOPER, I.E. VON ESSEN, AND K.R. GALLAGER, 1990. **Image Enhancement of Landsat Thematic Mapper Data and GIS Data Integration for Evaluation of Resource Characteristics**. Photogrammetric Engineering and Remote Sensing. 56(8): 1135-1141.

WATER SURVEY OF CANADA. 1969-1980. **Compilation of Hydrometeorological Record Marmot Creek Basin**. Volumes 5-16. Water Survey of Canada, Department of the Environment. Calgary, Alberta.

WEISBERG, S. 1980. **Applied Linear Regression**. John Wiley and Sons. New York, New York.

WHEATE, R.D. AND S.E. FRANKLIN. 1991. **Principal Component Transformation of Satellite Imagery in Mountain Areas**. In Proceedings of the 14th Canadian Symposium on Remote Sensing. Calgary, Alberta. May 6-10, 1991.

WILLIAMS, D.L. 1991. **A Comparison of Spectral Reflectance Properties at the Needle, Branch, and Canopy Level for Selected Conifer Species**. Remote Sensing of Environment. 35: 79-93.

WILLIAMS, R.G.B. 1986. **Intermediate Statistics for Geographers and Earth Scientists**. Macmillan Publishers Ltd. London, England. 712pp.

WILLIAMS, R.G.B. 1984. **Introduction to Statistics for Geographers and Earth Scientists**. Macmillan Publishers Ltd. London, England. 349pp.

WILSON, B.A. 1990. **DEM Data into a Spectral Classification**. Unpublished M.Sc. Thesis. Department of Geography. University of Calgary. Calgary, Alberta.

WINTHER, J. 1992. **Landsat Thematic Mapper (TM) Derived Reflectance from a Mountainous Watershed during the Snow Melt Season**. Nordic Hydrology. 23: 273-290.

YEATES, M. 1974. **An Introduction to Quantitative Analysis in Human Geography**. McGraw Hill. Toronto, Ontario.

APPENDICES

APPENDIX A

Field Sheet for Marmot Creek Basin

Date: July ____, 1992. Time:______ Observer:______________ Weather:______________

Site no:_____ UTM Coords:__________E __________N Expected Class:__________

Airphoto No:______ Photographs: Roll:____, Photo No(s):______________________

Pixel Mapped: 1 2 3 (30m by 30m pixels)
4 5 6
7 8 9

Vegetation Characteristics and Percent Cover (to nearest 5%)

	Type	Percent Cover	Height(m)	Circumference(cm)	Canopy Density(%)
Forested Area					
Tree layer:					
Shrub layer(p/np):					
p=present					
Ground layer:					
grass,moss,barren,					
exposed,etc.					
Non-Forested Area					
Shrub layer(p/np):					
Ground layer:					
grass,moss,barren,					
exposed,etc.					

Topographic Information

Elevation (from altimeter):__________m Expected Elevation:________m

Slope Gradient (degrees):________

Slope Aspect (azimuth):__________

Landform Observations:____

APPENDIX B

Principal Component Analysis Report File

PCA Principal Component Analysis V5.2 EASI/PACE 16:10 26-APR-94
e:\pmspans\thesis\tm.pix [S 17PIC 1024P 1024L] 18-APR-94

Input Channels:	1	2	3	4	5	6	7
Output Channels:	11	12	13	14			
Eigenchannels:	1	2	3	4			
Sampling Window:	0	0	1024	1024			
Sample size:	1048576						

Channel	Mean	Deviation
1	70.1462	34.2246
2	30.2300	17.7324
3	31.9591	24.1227
4	54.3249	25.9200
5	66.0432	48.0125
6	111.3310	38.7475
7	31.5210	30.0848

Covariance matrix for input channels:

	1	2	3	4	5	6	7
1|	1171.320						
2|	596.174	314.438					
3|	779.892	420.940	581.904				
4|	603.815	304.727	359.973	671.846			
5|	1454.352	787.512	1082.431	871.567	2305.199		
6|	941.952	419.047	456.544	786.148	1001.947	1501.370	
7|	898.384	492.401	696.262	412.328	1399.469	480.138	905.098

Eigenchannel	Eigenvalue	Deviation	%Variance
1	5976.1748	77.3057	80.20%
2	1103.7997	33.2235	14.81%
3	260.7052	16.1464	3.50%
4	95.8463	9.7901	1.29%
5	8.4447	2.9060	0.11%
6	5.3586	2.3149	0.07%
7	0.8439	0.9186	0.01%

Eigenvectors of covariance matrix (arranged by rows):

TM BD. NO.	Principal Component 1	2	3	4	5	6	7
1	0.42630675	0.22166970	0.29303885	0.26053303	0.59897405	0.35866344	0.35772437
2	-0.02096999	0.06292281	0.19695631	-0.32308465	0.31125325	-0.79970837	0.34060749
3	-0.49781594	-0.17772870	-0.22862433	0.68628705	0.38962960	-0.20619749	-0.05481251
4	0.42343444	0.27091223	0.28636083	0.53866041	-0.36772063	-0.40026093	-0.28235573
5	0.56985712	-0.17305587	-0.65174848	-0.09326916	0.30030519	-0.16532136	-0.30712378
6	0.18168060	-0.21370102	-0.35242131	0.23869994	-0.40826359	-0.04166348	0.75612879
7	-0.18155020	0.87538904	-0.43827873	-0.03028379	-0.02143919	0.00581465	0.08505842

Scaling Information:

Eigen Channl	Output Channl	-----Unscaled----- Min	Max	Deviation Range	Midpoint	Scale Factor
1	11	-150.888	377.933	all	127.500	1.000
2	12	-47.858	130.405	all	127.500	1.000
3	13	-118.111	103.687	all	127.500	1.000
4	14	-62.301	320.285	all	127.500	1.000