DEVELOPING SNOWPACK MODELS IN THE KALKHOCHALPEN REGION

Dissertation
Zur Erlangung des Doktorgrades
an der Naturwissenschaftlichen Fakultät
der Universität Salzburg

eingereicht von
KENNETH WAYNE FORSYTHE

Salzburg, Mai 1999

ABSTRACT

Developing Snowpack Models in the Kalkhochalpen Region: An Example from the Berchtesgaden National Park, Germany

The seasonal snowpack in mid-latitude mountain ranges has implications for a wide variety of matters including drinking water, hydroelectric power, irrigation, and recreation. Snowcover distribution in mountainous areas varies widely due to topographic, landcover, and climatic/environmental factors. Geographic Information Systems (GIS), Digital Elevation Model (DEM) data, remotely sensed satellite imagery, and multiple regression statistical techniques are increasingly being utilized to facilitate the estimation of a wide range of snowcover characteristics.

Elevation data allow for the determination of topographic factors while satellite data are useful in the estimation of landcover state/status and snow-covered area. The methodology used in this research was developed in order to interpolate snow distribution based on statistically estimated models. The fundamental idea is that regions with similar topographic, landcover, and climatic conditions will have closely matching snowcover characteristics. The application of these techniques and this knowledge has many advantages including the possibility of estimating snow distribution in problem areas such as forests, steeper slopes, and shadow zones where satellite sensors have difficulties in directly estimating snowpack conditions.

The empirical data consisted of 94 snow survey points where snow depth and snow-water equivalent (SWE) were measured for the January to April period from 1989 to 1994. The data were split into weekly groupings (not all of the sample points were measured during each snow survey). The snow data were combined with 25m resolution DEM data and Landsat Thematic Mapper (TM) satellite imagery and various derivatives of these two data sources in preparation for regression analyses. Data scaling problems were minimized through the use of the 25m DEM data that compliment the 25m resolution of the georeferenced and resampled satellite data. Integration of a solar insolation model allowed for the determination of potential incoming shortwave radiation at the surface with mountain shadows (topographic effects) being taken into account.

Stepwise multiple regression statistical techniques were used to estimate snow model equations based on data files assembled within the *Arc/Info* GIS. For January-February, the best snow depth model had an adjusted R^2 of 0.875 while the snow-water equivalent model had an adjusted R^2 of 0.880. Elevation, slope gradient, and TM band 4 were the independent variables that explained the snowcover variation in both cases. The best March-April results had adjusted R^2 values of 0.832 in both cases.

The best overall regressor in the snow models was elevation. For snow depth, slope gradient and principal component two (derived from the TM data) were very good regressors for the January-February period, while solar insolation and TM band variables were the best regressors for the March-April period. Snow-water equivalent variation was best related to solar radiation and TM band variables for the January-February period and solar radiation and principal component two for the March-April period. For both snow depth and SWE, profile curvature was a good regressor but only during April or in models where the snowcover was not very well developed. The equations that resulted from the analyses were entered into the *Arcview* Map Calculator for further estimation of snow coverage spatial characteristics.

The success and caliber of these models is dependent on the quality of the available data and very much related to the condition of the snowpack. In snow poor winters such as 1990-91 and 1993-94, the results are not as good when compared to a normal snow winter (1992-93) or a snow rich winter (1991-92). The regression results are generally 20 to 25 percent poorer. This can at least in part be attributed to the lack of snow mostly at the lower situated survey points. The percentage of snow measurement points with a value of zero is normally over 25 percent. This can have adverse effects on the results if there were not many points surveyed.

Overall in this research, quite satisfactory results were obtained with the applied methods and techniques. Good relationships were identified between snowcover and variables that were obtained from Digital Elevation Model and satellite data sources. These procedures can contribute to the estimation of snowpack parameters in rugged terrain. It is anticipated that they will be integrated within snowmelt-runoff models, which have problems in many cases with estimating the initial distribution of snow-water equivalent. There are some interesting avenues for the development of aspects of this GIS-based research in the future.

ACKNOWLEDGEMENTS

Studying in Salzburg was a great experience. I want to thank my supervisors Dr. Heinz Slupetzky and Dr. Josef Strobl for making it possible to complete my Ph.D. in Austria. They supplied the appropriate amounts of guidance and freedom when required. Much credit is also due to Elfriede Eder, who provided me with the necessary support and understanding to see this dissertation through to its conclusion. "Danke schön Schatzi!"

I was fortunate enough to be awarded scholarships and other funding during my studies. I acknowledge the following organizations for their support:

Austrian Science and Research Ministry (Republik Österreich, Bundesministerium für Wissenschaft und Forschung des Österreichischen Akademischen Austauschdienstes)

University of Salzburg, Foreign Exchange Office (Universität Salzburg, Büro für Außenbeziehungen)

University of Salzburg - Grant Foundation (Stiftungs und Förderungsgesellschaft der Paris-Lodron-Universität Salzburg)

The Tauern Hydroelectric Company (Tauernkraftwerke AG)

Austrian Student Union (Österreichische Hochschülerschaft).

Many friends and colleagues in the Department of Geography and Geoinformation (Institut für Geographie und angewandte Geoinformatik) helped me during my stay here. I want to especially thank Alex Dalzio ("Hey Man!") and Gerald Griesebner ("Forget it!") who made life in Salzburg much more enjoyable! I owe Anna Karnassioti ("Chocolate please!") and Guo-an Tang ("Hi Tang!"), a lot of gratitude for keeping things fun and sometimes crazy in the office. It could have been boring otherwise! Many thanks (vielen Dank) also to: Thomas Blaschke, Barbara Brunner, Birgit Fenninger, Walter Gruber, Helmut Heuberger, Felix Lackner ("alte Hütte!"), Anton Langebner (Watch out for that Slivovits!), Eric Lorup, Manfred Mittlböck ("You did something wrong!"), Shark, and Bernie Zagel Junior (No John W. here!).

I appreciate all of the effort and support from Helmut Franz, Rolf Eberhardt, Ralf Bögel and Hubert Vogt (Nationalparkverwaltung Berchtesgaden) in providing me with data and other resources for my research.

This thesis is dedicated to Lee and Biff!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Introduction

There is increasing concern with respect to fresh water quantity and quality in the world. This recognition has much to do with a perceived and sometimes very real shortage of water in some areas. Almost every day, it is possible to read about, watch, or hear some sort of news report regarding regional or global concerns about water. The topics range from the break up of ice shelves in the Antarctic to droughts through to 100-year storms (Associated Press, 1999; Reuters, 1999; Irwin, 1998; NSIDC, 1998; Rack et al., 1998; Salzburger Nachrichten, 1997; Coppola, 1996; Salzburger Nachrichten, 1996).

There is growing concern about whether there are sufficient fresh water resources to support an over populated world. The exact role that anticipated climate warming will have on precipitation patterns is however an unknown factor. Models ranging from the Snowmelt Runoff Model (SRM) (Martinec et al., 1998) to General Circulation Models (GCM) (McGinnis, 1997) try to estimate or predict what will occur.

Snowpack reserves are recognized in hydrology and water resource planning for their role in the overall water balance (Rau, 1993). Seasonal snowcover represents a major source of fresh water for many regions in the world (Brooks et al., 1991). Mountain snowpacks are an excellent storage reservoir for energy production and provide ideal temporary water reserves when one considers the ever-increasing pollution of drinking water resources.

1.2 Geographic Information Science

Geographic Information Science is a well established research area within the geosciences as well as other disciplines. It includes the fields of remote sensing, Geographic Information Systems (GIS), digital terrain analysis, and other areas. The use of Digital Terrain Models (DTM) in surveying, photogrammetry and remote sensing, and geosciences increases constantly (Ebner, 1992).

1.2.1 Remote Sensing

Remote Sensing at least from a non-military satellite perspective began with the launch of the first Landsat satellite in 1972. Landsat 1 began an era of space-based resource data collection that has changed the way science, industry, governments, and the general public view the Earth (Lauer et al., 1997). Most early applications were government or university oriented with a trend over the years towards more commercial applications. The fourth and fifth satellites in the Landsat program have been the main “workhorses” for many data users. Both satellites have exceeded their anticipated operational life. A continuation of the Landsat series of satellites (Landsat 7) was launched on April 15, 1999. This has been long awaited by scientists after the failed launch of Landsat 6 in 1993.

Landsat 7 carries three primary instruments, the Multispectral Scanner (MSS), the Thematic Mapper (TM) and the Enhanced Thematic Mapper (ETM). A MSS has been aboard every Landsat. The TM was introduced on Landsat 4, and the ETM is new to Landsat 7 (ENN, 1999). The ETM views the Earth in three main sections of the spectrum, four visible and near infrared channels, two short wavelength infrared and a thermal long wavelength infrared. Resolution of the ETM is 15 meters in black and white mode, 60 meters in the thermal channel, and 30 meters in the rest of the channels (ENN, 1999). The possible applications of this new data are many and there is also the possibility to improve on algorithms that have been developed using the lower resolution data from Landsat 5. An example of this is the Normalized Difference Snow Index (NDSI) which used TM data to map snow cover in Glacier National Park, Montana (Hall and Foster, 1994).

1.2.2 Geographic Information Systems

GIS technology development started in the early 1960s. The technology of today is certainly much more advanced than the early systems but the principles remain the same. Data analysis, manipulation, and modelling are just some of the functionality that is available. Modelling can mean any number of things and be applied to many different datasets. Alexander et al. (1996) modelled wolf habitat using a GIS prediction model that incorporated Digital Elevation Model (DEM) data. Kempka et al. (1996) modelled waterfowl carrying capacity using GIS and satellite imagery. Deforestation was modelled by Frohn et al. (1996) using remote sensing and GIS techniques. GIS have also been used in applications of environmental models to help protect the drinking water supply for New York City (Gorokhovich and Janus, 1996).

Multivariate statistics are used extensively in geographic analysis. An important statistical tool that often is used in analyzing watershed measurements is regression analysis (Brooks et al., 1991). There are many different examples in the literature that utilize GIS and regression techniques together ranging from burned area mapping (Koutsias and Kateris, 1998) to snow modelling (Elder et al., 1998; Forsythe, 1995) to Aquatic Macrophyte modelling (Narumalani, 1997).

GIS data users have to be aware of all details concerning their data so that error and uncertainty can be minimized. The difference between single isolated errors and systematic error must be recognized. Many data iterations within a GIS can lead to massive errors even if only one data component contains error. Error and uncertainty have always been a feature of cartographic information so it is not surprising that these aspects are also present in digital versions of analogue maps (Openshaw, 1989).

1.3 Snow Research

Field studies of snow accumulation and ablation have been carried out for decades (Linsley et al., 1982). Marsh (1998) states that earlier snow studies recognized the great variability of snow cover, but limited theoretical understanding and/or computational power resulted in most studies considering the snow cover as being spatially homogeneous. This approach must certainly be questioned, especially with regard to mountain areas where the snowcover is certainly not homogeneous.

Snow accounts for more than 50% of the annual precipitation in some mountainous areas. How this resource is distributed is of concern to many different groups ranging from downhill skiers to flood control planners. The timing and volume of runoff are of major interest and studies concerning snow and possible climate warming suggest snowpacks could be dramatically affected (Kuhn and Batlogg, 1998; McGinnis, 1997; Seidel et al., 1997; Baumgartner and Rango, 1995; Goodison and Walker, 1993; Baumgartner et al., 1987). There will be less snowfall during winter in the middle latitudes; it will be limited to higher elevations than at present; and runoff from the accumulated snowcover will occur earlier than it does now. The effects for northern areas are also being studied. Zhao and Gray (1998) state that in most northern regions the melting of seasonal snowcover is important as it supplies reservoirs, lakes, and rivers and recharges soil moisture and groundwater storage.

Solar radiation, the earth's chief energy source, determines weather and climate (Linsley et al., 1982). Snow accumulation and ablation are related to climatic factors and the physical properties of the landscape. Local topographic conditions can affect the temperature and wind regime. Topographic factors such as aspect and slope gradient can be brought into modelling procedures through the analysis of DEM data. Solar radiation inputs have also been integrated using DEM data and analysis routines that account for sun position and sunshine duration.

Estimation of the spatial distribution of the snowpack in mountainous areas is challenging due to various factors that can affect snow accumulation and ablation patterns. Snow modelling in mountainous areas (especially in the forested parts) is still, and will remain for the near future at least, very complicated. A few of the reasons for this are:

- topography changes or landscape breaks occur at finer resolutions than most of the present satellite datasets,
- there is a general lack of snow data that are collected in rugged terrain due to access problems,
- there are problems related to the way precipitation is measured and the interval at which the data are collected,
- forests do not allow the direct sensing of the ground below, and are subject to more sublimation due to the interception of incoming snow by branches,
- normal temperature gradients do not generally apply in these areas, and
- solar insolation values can vary substantially within very short distances.

Beginning in the early 1970s, there was a move towards integrating remotely sensed satellite data into snow analyses. There are now many different types of satellite data that are used in snow models. This includes data from the Advanced Very High Resolution Radiometer (AVHRR) through to the latest RADARSAT satellite images. Most of the snow models concentrate on predicting the timing and volume of runoff (Rott et al., 1998; Rango, 1992). Snowcover mapping is also carried out on regional to global scales. There are however still problems with trying to map and model snowpack properties in rugged or mountainous terrain (Hall et al., 1999), and snow in dense forests can usually not be detected by means of Synthetic Aperture Radar (SAR) satellite data (Nagler and Rott, 1998).

The greatest uncertainty in snow-mapping accuracy is found within the Earth's forested regions which is due, in part at least to the type and density of the canopy (Hall et al., 1998). Pomeroy et al. (1998) in their boreal forest field study of snow sublimation and interception found that 28% to 65% of the cumulative seasonal snowfall can be intercepted and stored in coniferous canopies in mid-winter, and that 30% to 45% of annual snowfall sublimates due to its exposure as intercepted snow.

There has been a lot of snow research work undertaken in temperate mid-latitude mountain ranges. The areas of focus are the alpine regions of Switzerland, Austria, Italy, Germany, and France as well as the Sierra Nevada, Cascade, and Rocky Mountains in the USA and Canada. There are also ongoing research programs in the Himalayas and other mountain ranges throughout the world. Accurate forecasts of snowmelt runoff are needed for many purposes such as flood warning, reservoir management, and the coordination of power generation (Blöschl and Kirnbauer, 1991).

Current research emphasizes two main themes: the integration of remotely sensed data into snow models (particularly snowmelt-runoff models) and the modelling of snow cover and SWE distribution. The use of radars for snow-cover studies has great potential (Koh, 1998). Kirnbauer et al. (1994) state that more work needs to be directed towards measuring and representing the spatial variability of snow in catchments as well as on spatially distributed snow model evaluation. Regression analysis is often used in snow studies (Leydecker and Sickman, 1998; Elder et al., 1997). It can be used to predict snow accumulation, ablation, and the timing of meltwater runoff. This research estimates the influence of the topographic and climatic factors on snowpack properties through the analysis of DEM and satellite datasets.

CHAPTER 2: OBJECTIVES AND STUDY AREA

2.1 Objectives

The overall objective of this research is to further develop statistical and GIS modelling procedures for snowcover that can better estimate the distribution of snow depth and snow-water equivalent (SWE) in mountainous terrain. This overall objective requires that a number of sub-objectives be completed:

1) location and acquisition of all the necessary snow data, satellite imagery, and DEM data,
2) data error identification and correction,
3) processing and integration of these data in a geo-database,
4) investigation into the best DEM spatial resolution for these modelling procedures,
5) statistical analysis using multiple regression techniques, and
6) GIS analysis and visualization of the results.

The goal is to determine whether topographic and climatic/environmental parameters generated from DEM data and remotely sensed satellite imagery together with measured snow depth and SWE can provide useful information for regression modelling. Estimation models for snowpack distribution are developed during the accumulation and ablation snow seasons. Techniques that are presently used have generally good success in mapping snowcover but are hampered in mountainous terrain and forested areas.

Statistical analysis is carried out using the stepwise multiple regression technique. The resulting regression equations are used (within a GIS environment) to interpolate between snow measurement points based on similar site conditions. Mountain snowpacks reflect the influences of rugged topography on precipitation, wind redistribution of snow, and boundary layer energy fluxes during the accumulation and ablation seasons. No widely suitable method yet exists to directly measure the spatial distribution of SWE in rugged mountain regions (Elder and Cline, 1998). These modelling procedures provide a way of accounting for the variable conditions in mountain basins based on data collected in diverse regions of the study area.

2.2 Study Area

The study area for this research is the Berchtesgaden National Park (BNP). It is centrally located in Europe (Figure 1) within the Federal Republic of Germany.

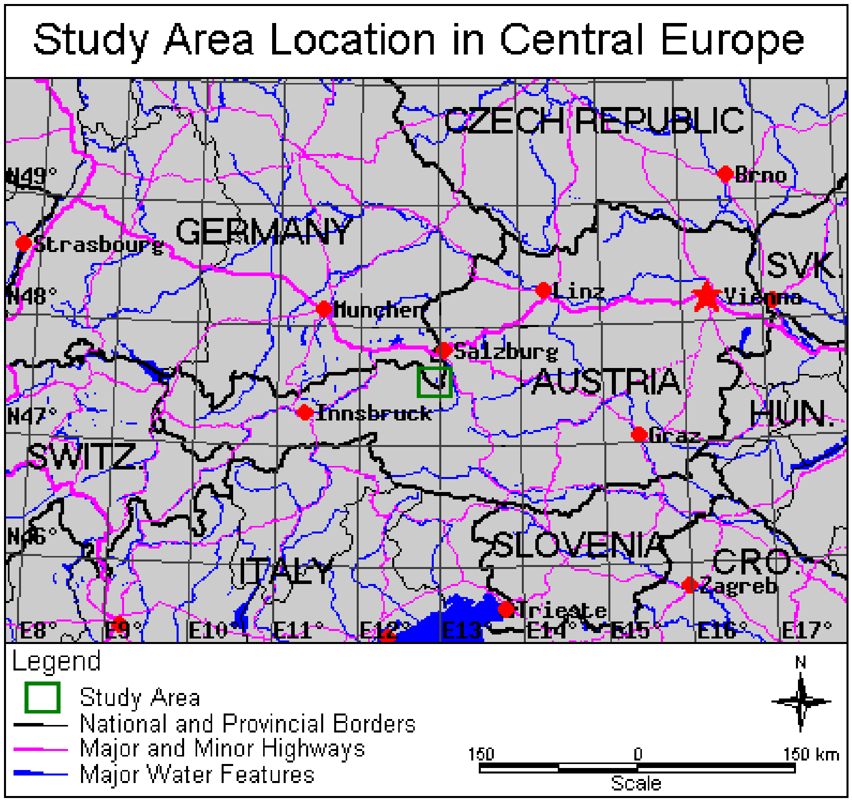

Figure 1: Study Area Location in Central Europe
(Source: modified after original image from: http://www.eurimage.it/)

The BNP is located within the eastern ranges of the Alps and is more specifically found in the Berchtesgaden Alps, which are part of the Northern Limestone Alps. The National Park lies in the southeast corner of the Free State of Bavaria (Figure 2). It borders on the Austrian Province of Salzburg where there is a proposal to create an adjacent National Park (Figure 3) (Blaschke, 1996).

The BNP was established by a regulation of the Bavarian government in 1978 (BNP, 1992). It has an area of approximately 210 square kilometres and ranges in elevation from 603 m above sea level (asl) at the Königssee Lake to 2713 m (asl) at the top of the Watzmann.

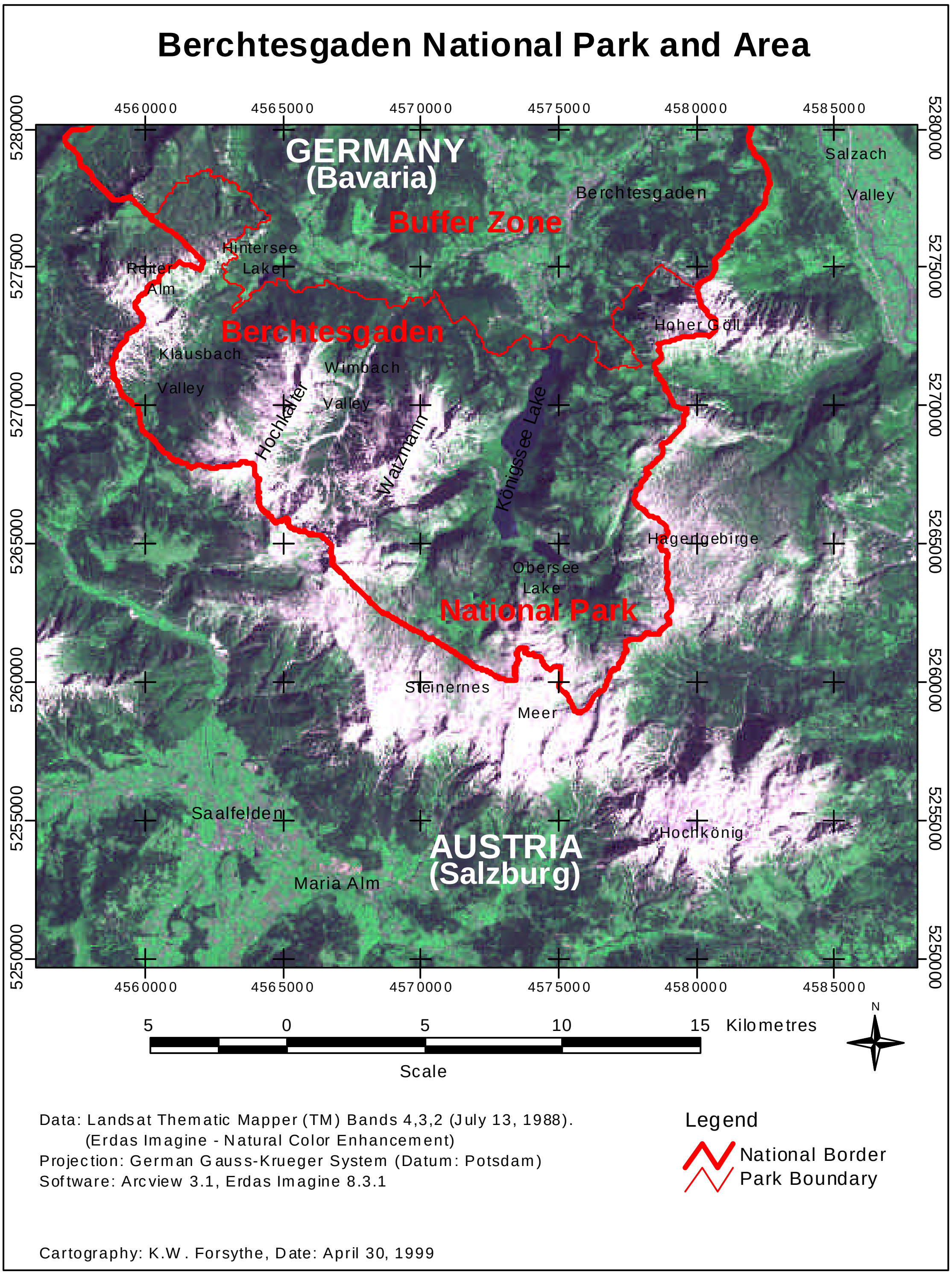

Figure 2: Berchtesgaden National Park and Area

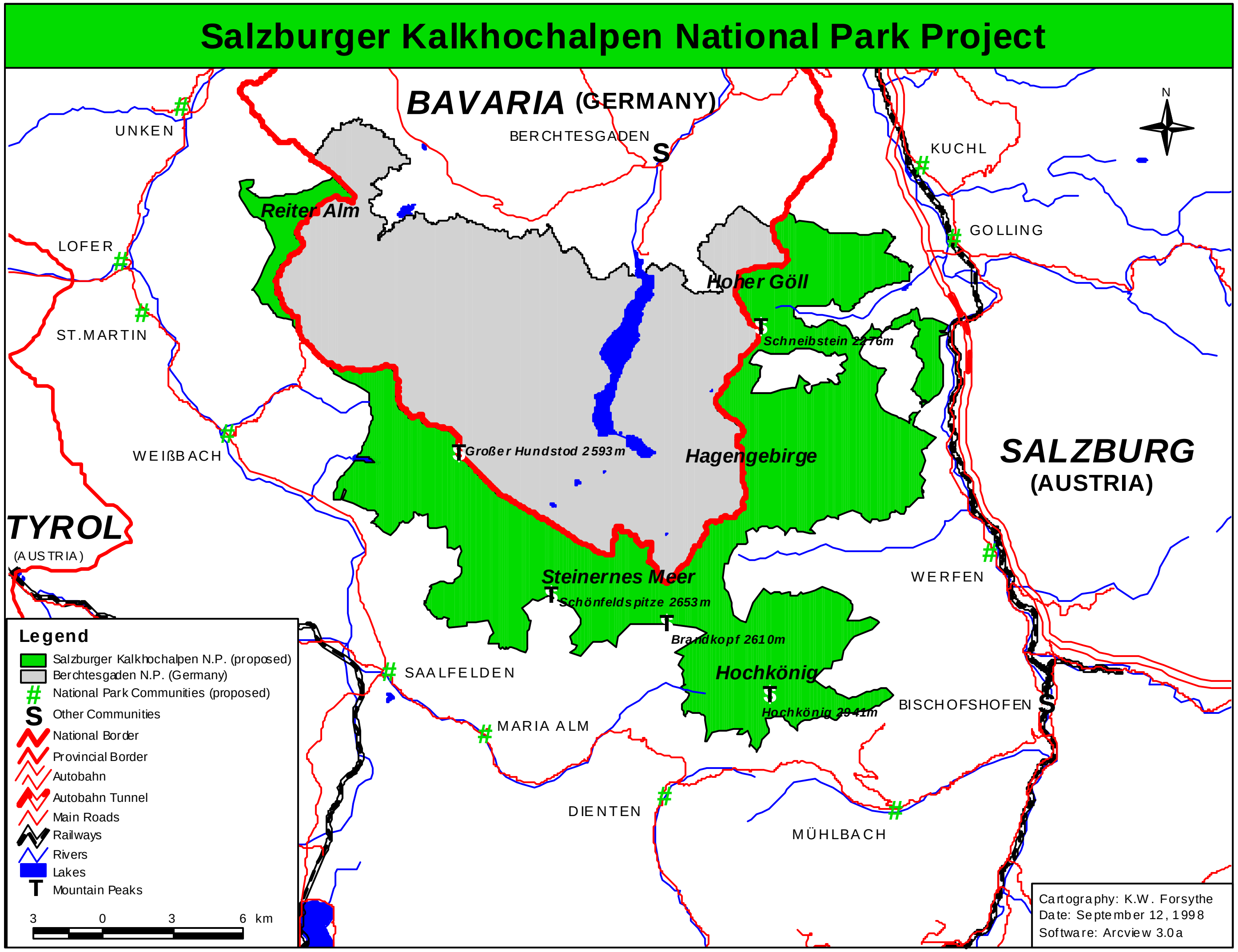

Figure 3: Salzburger Kalkhochalpen National Park Project

The primary reason for the choice of this particular study area was the availability of the necessary data required for this research. The Berchtesgaden National Park Administration (BNPA) along with the Department of Geography and Geoinformation (DGG) at the University of Salzburg provided the data. Included in the dataset are 5793 snow measurements collected at 94 points from 1988 to 1994, a Landsat Thematic Mapper (TM) satellite image, and the necessary Digital Elevation Model data.

The geology of the area is made up mainly of limestone sediments. They were deposited 200 million years ago when the area was occupied by a sea and subsequently lifted and folded. There are three main valleys within the Park that can be thought of as separate watersheds. The Klausbach Valley is the westernmost area in the BNP and it is drained by the Klausbach Stream which flows in a northerly direction into the Ramsau River (Ramsauer Ache). The Wimbach Valley is in the middle of the three main valleys. It is drained in a northernly direction by the Wimbach Stream which flows into the Ramsau River about five kilometres east of the Hintersee Lake. The valley containing the Königssee Lake is drained in a northerly direction by the Königssee Stream. It joins the Ramsau River in the town of Berchtesgaden thus forming the Berchtesgaden River (Berchtesgadener Ache). Drainage does not occur within the Park through above ground means only. The limestone bedrock and soil means that a portion of the precipitation in the Park flows into groundwater where it can be stored or flow underground out of the area.

There are Atlantic and continental influences on the climate. Precipitation totals in the valleys are approximately 1500mm per year, ranging up to 2500 mm on the mountain peaks. Average yearly temperatures are 6 to 8°C in the valleys and 2 to 4°C in the mountains. The average yearly temperature in the town of Berchtesgaden is 7.2 °C (SABD, 1995). June, July and August are the rainiest months with 39% of the annual precipitation occurring during that time (SABD, 1995). A typical element in the weather in the Northern Alps is the foehn wind (Hermann, 1978) and the BNP area is affected by varying numbers of these weather events each year.

The number of days with snow on the ground in Berchtesgaden varies between 71 and 131. Snow normally appears on the ground in the first week of November. Temperature inversions are quite common in the winter, which can lead to pollution problems at lower elevations between 600m above sea level (asl) and 800m (asl). Maximum snowpack is achieved in areas under

1000m (asl) in February; March is the month of maximum in areas higher up. The normal maximum snowpack in the town of Berchtesgaden is 36cm, with 50cm being normal in lower valley areas, and 3 to 5 metres in the higher areas of the Park. (SABD, 1995 and NPVB, 1998). Elevational position, aspect and slope have large effects of the radiation balance in the Park (NPVB, 1998). The climate of the National Park can therefore be divided through vertical, horizontal, and time dependencies. (NPVB, 1998).

The plant communities are influenced by elevation gradients. They occur in approximately the following proportions:

✳ 42% remnants of deciduous forests; mixed mountain forests, dominated by spruce, pines and beeches (in former times these were exploited for the salt mines; nowadays greatly altered by oversized populations of ungulate game and by forest pastures),
✳ 14% alder and dwarf-pine bushes,
✳ 7% alpine meadows,
✳ 33% vegetation growing on rock debris and in crevices, and
✳ 4% other surfaces such as pastures, lakes and a glacier (BNP, 1992).

A variety of alpine animals are found in the park:

✳ Chamois (Gemse), Ibex (Steinbock) - reintroduced in 1930, Marmot, Snow Hare, Alpine Salamander,
✳ Golden Eagle, Ptarmigan, Black Grouse, Caipercaillie, Alpine Chough, Black Woodpecker, Three-toed Woodpecker (BNP, 1992).

The National Park is open year round. There are many recreation possibilities including walking, mountaineering, climbing and ski touring. There are:

✳ 190 kilometres clearly marked and well maintained paths and climbing routes,
✳ 8 mountain huts and mountain restaurants with catering during the summer months, and
✳ 1 shelter hut (BNP, 1992).

2.2.1 Berchtesgaden National Park Research

The purpose and goal of the National Park is that “nature be left relatively undisturbed” (BNP, 1992). The Park promotes ecosystem integrity, and provides opportunities for scientific research and education. Many different research projects have been undertaken in the BNP. An ecological and GIS related summary is provided by Schaller (1994). Other studies have ranged from Chamois and Golden Eagles (Eberhardt et al., 1997) to snow studies (Escher-Vetter et al., 1998; Rau, 1993). A Habitat Suitability Index (HSI) was developed by Eberhardt et al. (1997) within a GIS that included parameters derived from DEM data. The snow studies were primarily concerned with the snowcover and SWE distribution which are also the focus of this dissertation.

CHAPTER 3: LITERATURE AND METHODOLOGY OVERVIEW

3.1 Introduction

This chapter provides a review of the current and past trends in Digital Elevation Model analysis, Satellite Remote Sensing, Geographic Information Systems and snowcover analysis.

3.2 Digital Elevation Models

The terms Digital Terrain Model (DTM) and Digital Elevation Model (DEM) are used interchangeably in the literature. Florinsky (1998) defines a DTM as a digital representation of variables relating to a topographic surface, namely: Digital Elevation Models (DEM), digital models of gradient, aspect, horizontal and vertical landsurface curvatures as well as other topographic attributes.

There has been a lot of work done with respect to DEM analysis, development, and comparison over the last few years. Tang (1998) looked at analyzing error in DEM data at different scales. Issacson and Ripple (1990) compared 7.5-minute and 1-degree DEM data both visually and statistically in terms of elevation, slope aspect, and slope gradient. Florinsky (1998) and Tang (1998) found that large errors could be found in local topographic variables in flat areas.

Moore et al. (1993) state that a Digital Elevation Model (DEM) is an ordered array of numbers (this is valid only for raster or grid data) that represents the spatial distribution of elevations above some arbitrary datum in a landscape. DEM data can be further processed to yield important derivative products, including digital maps of slope and aspect. There is sometimes confusion when slope measurements are given in degrees and/or percent. A 45° slope represents a 100% slope angle as the percentage of slope is calculated as rise over run times 100. A 90° slope has a slope percent that approaches infinity.

All DEM data have inherent inaccuracies not only in their ability to represent a surface but also in their constituent data (Moore et al., 1993). The accuracy of slope and aspect data decreases with lower DEM resolutions (Chang and

Tsai, 1991). In DEM experiments, Jenson (1993) found that increases in cell (pixel) size produced lower slope values.

Strobl (1988) identified the areas of geomorphology, climatology, hydrology, remote sensing, landscape ecology, and GIS as a few of the areas where the use of DEM data could provide useful information. Hutchinson (1996) suggests that the chief limitations of regular grid elevation models appear to lie in not being adaptive to topography with spatially varying complexity and in supporting sometimes overly simplistic hydrological analyses.

The spatial distribution of topographic attributes can often be used as an indirect measure of the spatial variability of hydrological, geomorphological, and biological processes (Moore et al., 1993). Kirnbauer and Blöschl (1993) mapped snowcover patterns (in a high mountain study area in the Austrian Province of Tyrol) based on aerial photographs and analyzed them as a function of such terrain parameters as elevation, slope, aspect, and curvature. Fels and Matson (1996) use DEM data to help in a hydrogeomorphic classification scheme that looks at ground water vulnerability to contamination from above. Rott et al. (1998) used a 25m resolution DEM, together with TM and Synthetic Aperture Radar (SAR) image data to model snowmelt runoff in an Austrian alpine area.

3.3 Remote Sensing Systems and Applications

Using satellite sensors to scan the earth's surface began with the launch of many satellites in the 1970s. Civilian land remote sensing systems are currently being operated by the United States, France, India, Japan, Canada, Russia, and the European Space Agency (ESA) (Lauer et al., 1997). The next civilian satellite that will bring about a great increase in spatial resolution is the Ikonos system which is capable of providing 0.82 metre resolution panchromatic images, as well as 3.2 metre resolution multispectral images in the visible and near infrared parts of the spectrum (SIE, 1999). The first attempt at launching this satellite into orbit failed (Antczakv, 1999), but it is hoped that a replacement will be launched before the end of 1999. The great increase in spatial resolution offered by this sensor could bring about new advances in research especially in rugged terrain.

High resolution satellite images are required in mountainous areas. There are however two major problems associated with these data; the first is the low repetition rate and the second is the fact that cloud cover often impedes the identification of snowcover (Blöschl and Kirnbauer, 1992a). Radar data (active microwave) offer a partial solution to this problem with a better repetition rate but there are other problems associated with this sensor such as wet snow conditions. The estimation of SWE through microwave satellites is only possible when the snowpack is dry (Rott, 1993). Wagner (1995) discusses the details of radar backscattering coefficients in both dry and wet snow conditions.

Passive microwave data have been used in a number of recent studies (Smyth and Goita, 1999; Derksen et al., 1998; Tait, 1998; Basist, 1997; Goodison and Walker, 1994; Chang and Tsang, 1992; Walker and Goodison, 1991). Jin (1997a) used passive microwave Special Sensor Microwave Imager (SSM/I) satellite data to derive snow depth using scattering indices. SSM/I scattering indices were also used in Great Britain to derive snow depth. The indices require that a calculated regression relationship between snow depth measured on the ground and the SSM/I image pixels (Atkinson and Kelly, 1997).

The availability of telemetry and satellite systems has expanded the methods of measuring snowpacks (Brooks et al., 1991). Turpin et al. (1998) state that Earth Observation (EO) data can help to verify snow-covered area in the snowmelt component of hydrologic models.

3.3.1 Remote Sensing of Snow

Snow distribution maps for mountainous areas may contain considerable error because of the paucity of measurements at high elevations (Linsley et al., 1982). It is hoped that as satellite technology improves, there will be opportunities for relating many types of snowpack spectral characteristics with snowpack condition, melt, and other related processes (Brooks et al., 1991). Snowcover is one of the most easily recognized features in a visible-spectrum satellite image of the Earth's surface (Baumgartner and Rango, 1995).

Dozier (1998) outlines some of the problems of snow remote sensing in alpine areas. These include:

✳ there is usually considerable variability in snow depth and other properties at a fine spatial scale,

✳ the analysis of the remotely sensed signal must account for geometric/perspective effects that the sloping terrain and range of elevations cause, and

✳ in some areas, persistent cloud cover hampers regular acquisition of data.

For snow mapping in mountain areas, it is important to account for the varying solar insolation conditions on the ground (Rott, 1993). Snow mapping in the absence of cloud cover, has excellent results using a combination of visible and near-infrared wavelengths. Cloudy conditions dictate that active or passive microwave portions of the spectrum be used. The active sensor (radar) has the finer spatial resolution that is necessary in mountainous areas (Dozier, 1998). The most promising radar technique for snow research is the frequency modulated continuous wave (FMCW) radar (Koh, 1998). Rott (1993) states that for microwave snow studies, there are five important factors:

1) liquid water content,
2) snow depth and density,
3) grain size and form,
4) horizontal layers in the snowpack, and
5) roughness of the snow surface.

Composite use of multi-source satellite (Advanced Very High Resolution Radiometer (AVHRR) and Geostationary Operational Environmental Satellite (GOES), point (manual and telemetered observations) and line (airborne gamma surveys) data has been accomplished with the National Operational Hydrologic Remote Sensing Center (NOHRSC) Operational Product Processing System (OPPS) which uses these databases to derive gridded estimates of SWE and snow depth (Hartman, 1996a). Seglenieks et al. (1997) used Radarsat data to map snowcover during spring melt in Southern Ontario as the 2 to 3 day return period of the satellite was well suited for the monitoring of potential flooding.

Rott (1993) outlines the characteristics of various snow mapping satellite sensors in Table 1.

Table 1: Some Satellite Sensors for Snow Mapping

Satellite	Instrument	Spectrum Area	Channels	Horizontal Resolution	Return Period
Landsat	TM	Optical	0.45-2.35 um (6 channels) 10.4-12.5um	30/100 m	16 days
Landsat	MSS	Optical	0.5-1.1 um (4 channels)	80 m	16 days
SPOT	HRV	Optical	0.5-0.9 (3 channels)	20/10 m	3 days
NOAA	AVHRR	Optical	0.58-12.5 um (5 channels)	1 km	12 hours
Meteosat	Radiometer	Optical	0.5-0.9, 5.7-7.1, 10.5-12.5	2.5/5 km	30 minutes
DMSP	SSM/I	Microwave (passive)	19-85 GHz (7 channels)	12.5/25 km	12 hours
ERS-1	SAR	Microwave (active)	5.3 GHz	30 m	16 days
Radarsat	SAR	Microwave (active)	5.3 GHz	30/100 m	3 days

Source: after Rott (1993).

3.3.2 Satellite Image Processing

Topographic and atmospheric effects can affect satellite image data. In order to correct for these effects, a number of procedures have been developed. These include image destriping and dehazing as well as band ratioing, Principal Components Analysis (PCA), and vegetation indices.

Extensive interband correlation is a problem frequently encountered in the analysis of multispectral image data. Principal component transformations are designed to reduce or remove such redundancy (Lillesand and Kiefer, 1987). For channels of multispectral data, the first principal component includes the largest percentage of the total scene variance with succeeding components containing further decreased percentages of variance. Two different approaches have been used to correct for the varying illumination and reflection geometry caused by topography. The first employs band ratios and statistical transformations like principal component or regression techniques, while the second employs topographic correction techniques that account for solar incidence angles (Richter, 1996).

3.3.2.1 Anisotropic Reflectance (Topographic Effects)

Topographic effects in mountainous basins affect satellite data. One of the few places in which remotely sensed data have not proven effective in discrimination of land-cover types is in areas of high relief due to variations in reflectance caused by different slope angles and orientations (Colby, 1991).

The main problems are related to shadow and perspective. They are illustrated in Figures 4 and 5.

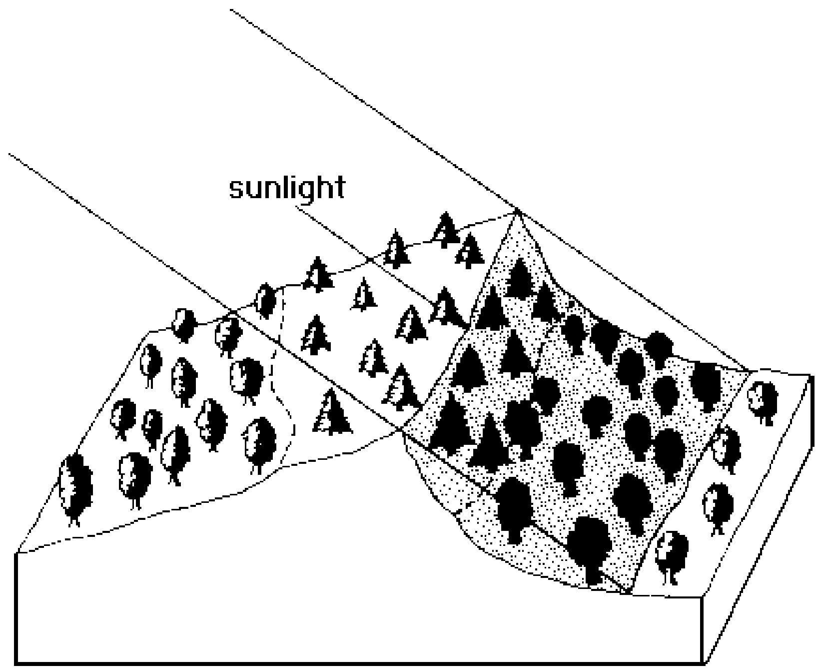

Figure 4: Shadow Effects in Satellite Imagery

Source: Lillesand and Kiefer, 1987.

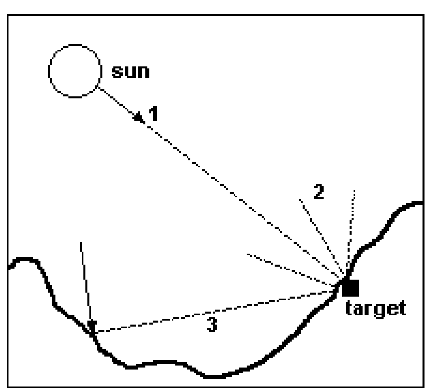

Figure 5: Downward Irradiance Received in a Mountainous Region:

(1) direct irradiance, (2) diffuse irradiance from the sky, and

(3) terrain reflected irradiance.

Source: modified after Kumar et al., 1997.

Anisotropic reflectance is formally defined as the variation in radiances from inclined surfaces as compared to the spectral response from a horizontal surface as a function of the orientation of the surfaces relative to the light source (incidence angle) and sensor position (exitance angle) (Colby and Keating, 1998). Band ratios can help to suppress differential solar illumination effects due to topography and aspect (Lyon et al., 1998). Ratioed images are often used for discriminating subtle spectral variations in a scene (Lillesand and Kiefer, 1987). This is the simplest technique for reducing the effects of anisotropic reflectance (Colby and Keating, 1998), but for the six nonthermal TM bands there are 6(6-1) or 30 possible combinations for band ratios (Lillesand and Kiefer, 1987). This makes trial and error often necessary in selecting ratio combinations.

There is debate as to what methods should be used to correct for anisotropic reflectance. Minnaert constants (which are related to surface roughness) are used in non-Lambertian reflectance procedures. They are not always adequate as explained in Ekstrand (1996). He found that an empirical model that he developed performed better than a model incorporating the constants. Giles (1998) also suggests that within the remote sensing community, there will be no consensus on which technique to use until the methods are better developed. Richter (1997) used a Lambertian assumption to correct for atmospheric and topographic effects with the help of a DEM, whereas the use of a Lambertian model proved inappropriate for Colby and Keating (1998), but application of the non-Lambertian model enhanced their classification accuracies.

Hill (1996) used techniques based on a non-Lambertian model to correct for topographic effects for a vegetation mapping project in rugged terrain, but comparisons were not made with non corrected imagery in terms of accuracy assessment. Correction for anisotropic reflectance is not always performed. Cohen et al. (1998) did not correct for these effects as the forest clearcuts they were classifying had such a different spectral signature than any of the surrounding vegetation over the entire image. This would indicate that the choice to perform a topographic normalization or not depends on the needs of the researcher(s) and the goal(s) of the research. It is hoped that in the near future, standardized procedures can be developed to clarify the methods that need to be used.

3.3.2.2 Vegetation Indices

The use of satellite images for vegetation study is based on different reflectances of near infrared and visible bands of vegetation (Yin and Williams, 1997). A Normalized Difference Vegetation Index (NDVI) was least affected by topographic factors in a change detection study by Lyon et al. (1998) because it is based on a ratio of bands. Numerous forms of linear data transformations have been developed for vegetation monitoring, with differing sensors and vegetation conditions dictating different transformations (Lillesand and Kiefer, 1987).

3.4 Geographic Information Systems (GIS) Applications

Geographic Information Systems (GIS) have made huge strides in being used as systems on which environmental modelling applications can be developed (Karimi et al., 1996). GIS-based models have been developed for many physical applications ranging from soil erosion (Wilson, 1996) to hydrology (Bernhard and Weibel, 1998; Gorokhovich and Janus, 1996; Müller-Wohlfeil et al., 1996)) to topographic modelling (Kumar et al., 1997). Wilson (1996) suggests that the development of new GIS-based methods for estimating land surface/subsurface model inputs will promote the development of new and improved models.

Remote sensors and GIS technologies organize data into two, general protocols (Ward and Elliot, 1995). Remote sensors collect their data in a grid cell or raster format, and GIS technologies process data in raster or vector form, or both, as needed (Ward and Elliot, 1995). The Snow Estimation and Updating System (SEUS) uses the geographic information system GRASS to store, analyze and display the spatial data necessary to perform the estimation of snowmelt characteristics and to develop long-term mean snow water equivalent data (Hills et al., 1996).

3.4.1 Remote Sensing Data as GIS Inputs

A truly great capability of GIS and remote sensing is that a variety of data may be integrated and analyzed in the assessment of hydrological features and processes (Ward and Elliot, 1995). However, Yazdani et al. (1996) state that one major problem in using a GIS is the time and cost of loading and updating the system with meaningful information. Most systems seem to find a balance that brings costs and capabilities to the desired end product.

Numerous examples of satellite data integration within GIS are available in the literature. Many studies deal with the application of these two areas to snow and ice studies (Drobot and Barber, 1998; Elder et al., 1998; Frohn et al., 1996; Foody, 1988). Digital satellite and aerial data allow for efficient and timely capture of snowpack extent and variation on regional to global scales (Rott, 1993). Anderson (1996) describes an operational snowcover mapping system integrating GIS and remote sensing technologies that is tailored to meet end users needs.

3.5 Snow Hydrology

Snow hydrology is a multi-faceted subject and includes many different areas of study. At an October 1998 conference in Brownsville, Vermont, the topics included:

✳ snowcover properties and processes,
✳ chemical processes in the seasonal snowcover,
✳ biotic interactions with the seasonal snowcover,
✳ distributed snowmelt models, and
✳ scaling problems in snow hydrology (Hardy et al., 1998).

The snowcover of an area is primarily the product of short-term events, and after each snowfall the visible lower limit of snow runs almost parallel to the contour lines (Kölbel-Deicke and Heuberger, 1987). In the longer term, snow accumulation on a microscale can be quite variable as it is influenced by wind, local topography, forest vegetation, and other physical obstructions (Brooks et al., 1991).

Climate monitoring in mountain basins is very limited, and the full range of elevations and exposures that affect climate conditions, snow deposition, and melt is seldom sampled (Susong et al., 1998). Felix et al. (1988) wrote about precipitation patterns in the Austrian province of Tyrol and state that the total amount of year-round precipitation increased by 2 centimetres for every 100 metre increase in elevation. They also relate that the same increase can be expected from the flatland/mountain boundary, for every two kilometres (horizontally) inward. Inventories of snow-pack depth and density are made at periodic intervals throughout the snow season in order to estimate total water supply in the watershed snowpack (Ward and Elliot, 1995).

3.5.1 The Importance of Snow

The emphasis on snow studies in many parts of the world demonstrates the importance of snow in worldwide matters. Snow research takes place in many different regions of the world. They range from Antarctic and Arctic (Pomeroy and Gray, 1998; Rack et al., 1998) studies to the various mountain ranges of the world (Johnson et al., 1998; Mätzler et al., 1997; Singh et al., 1995; Bergman, 1989). Snow distribution is also modelled in flat and moderately rugged terrain and in areas ranging from tundra (Li and Pomeroy, 1998) to boreal forest (Davis et al., 1998; Pomeroy and Gray, 1998; Metcalfe and Buttle, 1997) to open prairie (Derkson et al., 1999; Wagner, 1995).

3.5.2 Some Processes Influencing Snowcover Distribution

Since it usually remains on the ground for some period of time, snow does not need to be measured as it falls (Brooks et al., 1991). This statement must be tempered of course with respect to the research problem and the specific requirements of the study. Snow depth and snow water equivalent can be measured manually on snow courses using cylindrical tubes with a cutting edge.

Many processes can influence the distribution and depth of the snowpack. Wind can redistribute snow but local up and downdrafts make determining its exact role difficult at smaller scales. The temperature lapse rate generally decreases with increasing elevation but there are microclimates throughout the landscape that depend on aspect, exposure, general wind direction, etc. Anderson (1973) found that the thermal gradient up mountainsides can significantly differ from the lapse rate in the free atmosphere. In avalanche prone areas, snow is redistributed from higher to lower elevations.

3.5.3 Snow Modelling

Davis (1998) states that research and operational efforts to implement spatially distributed models of snow have some common interrelated issues. These include 1) the tradeoff between model complexity and computational expense; 2) the estimation of error due to forcing variables (i.e., surface meteorology) and due to model performance; 3) the approach to segment landscape and terrain data at suitable scales in relation to surface heterogeneity; and 4) the challenge of validating and/or updating model predictions over large areas.

Various snow studies are undertaken which depend on the interests of the researcher and the project objectives. A few examples (both large and small in scale) are provided here from the literature. Chaoimh (1998) correlated European snow coverage with summer time temperature anomalies. Fassnacht et al. (1998) found that weather radar was able to assess snow accumulation on a regional level to within 15% of gauge data over the snow season and found it particularly useful due to its large spatial coverage. Anderton et al. (1998) studied the strength of relationships between observed SWE and elevation, slope gradient, aspect, and curvature in a small basin in the Pyrennes.

Snow covered area is the most important variable for the Snowmelt Runoff Model (SRM) (Baumgartner et al., 1987) and the data must be evaluated quickly to compute runoff volume in a timely manner. Martinec and Rango (1995) point out that there are two main sources for runoff volume forecast errors with the SRM: 1. Difficulties in the evaluation of snow reserves on the first of April from point measurements, and 2. Unpredictable precipitation in the summer half of the year. In some years, the advantages of the SRM approach could not be fully demonstrated because snow accumulation was far from normal, rainfall in certain months was heavy, and the water balance was influenced by glacier melt due to extremely high summer temperatures (Martinec and Rango, 1995). Knowledge of SWE distribution is therefore a critical factor for snowmelt models. It enables more efficient operation and allows for better estimates of the volume and timing of runoff.

The ideal snow information system should include detailed point data as well as regular remote sensing data coverage (Rott, 1993). SAR sensors provide repeat pass observations irrespective of cloud cover and are therefore of interest for operational snow melt runoff modelling (Nagler et al., 1998).

3.5.3.1 Distributed Snow Models

Distributed snow models are increasingly becoming a major research focus. They try to estimate snow depth, SWE, and snow density. Some of the models incorporate landcover variables determined from satellite imagery and others incorporate snow coverage interpreted from satellite imagery or both.
Hartman et al. (1996b) derived gridded estimates of SWE by combining

satellite-derived snow classification and snowline with field observations of SWE in a process that incorporates elevational detrending. Singh et al. (1997) used satellite determined snow covered area together with rainfall, evapotranspiration, and discharge data to estimate snow and glacier contribution to meltwater volume in the Western Himalayas.

3.5.4 Model Scales

Grayson et al. (1993) state that it is unfortunate that most distributed hydrologic models have been developed for research catchments that are orders of magnitude smaller than management areas. However, many studies look at rather large basins. They are not concerned with a pixel by pixel approach but look at the basin as a storage unit for potential runoff.

Boreal forest studies tend to focus on runoff potential, tree interception, and remotely measured snow coverage. Alpine studies look at runoff potential from high alpine basins to major river watersheds.

Anderton et al. (1998) found that slope curvature and an area averaged elevation value had the strongest relationships with SWE, which suggested a topographic control on snow accumulation and redistribution in their small alpine basin. Hood et al. (1998) found that 15% of the seasonal snow accumulation was lost through sublimation at a Colorado plateau study area.
Balk et al. (1999) have worked on methods for determining the redistribution of snow above the tree line and improved snow depth model results. Guneriussen (1997) examined the relationship between Synthetic Aperture Radar (SAR) and TM satellite data for analyzing snowcover in southern Norway. Moore and McCaughey (1997) found that forest canopy coverage (estimated from ground measurements) had the largest impact on peak snow water equivalent on the forest floor. Davis et al. (1998) used tree height and stand density to model SWE distribution in the boreal forest in order to show the potential for determining total water volume over large areas. Derksen et al. (1998) used passive microwave (SSM/I) derived observations to estimate SWE in a ground validated North American Prairie scene.

3.6 Estimating Model Error

The sophisticated graphics and data handling features of GIS can be used to seduce the user into an unrealistic sense of model accuracy (Grayson et al., 1993). Openshaw (1989) lists a number of sources of spatial data error which include the fact that there are no standard methods for tracking error propagation through spatial databases and that there is little knowledge about what effects the various GIS operations have on error, whether amplification, maintenance, or removal. Computer generated maps, manipulated through GIS are powerful tools for analyzing complex spatial interactions (Walsh et al., 1987), but error inherent in the source data and operationally produced through data capture and manipulation must not be forgotten.

Problems can occur in GIS based regression modelling in that most spatially-distributed data stored in a GIS contain errors from a wide variety of sources and these errors may have a significant impact on the validity of applying regression equations in a GIS environment (Elston et al., 1997). The major sources of error include:

- the resolution at which the data are recorded and stored,
- properties of the data source (e.g. variables estimated by remote sensing),
- the method of interpolation used to obtain a complete coverage of a region when a direct observation has been made at a sample of locations,
- representation of continuous variables as being constant within polygons,
- positional inaccuracies, and
- error propagation when a GIS is used to derive new variables (Elston et al., 1997).

3.7 Snow Studies in the Berchtesgaden National Park (BNP)

Meyer (1995) used Landsat TM data for snowcover mapping in the Berchtesgaden National Park. One of the big problems encountered was that the images contained huge amounts of shadow due to the great topographic relief in the park and also the fact that the Landsat 5 satellite passes over this area at around 9:30am. This is very early in the morning during the deepest winter months of December and January. Meyer (1995) states that snowmelt patterns in the Park cannot be correlated with elevation due to snow redistribution from higher to lower elevations, wind effects, and distinct local differences in solar radiation.

The occurrence of the warm foehn winds in the area also can lead to differential melting of the snowpack. In open areas, the snow melts at a faster rate than in sheltered areas at the same elevation. Rau (1993) identified 5 snowpack-elevation zones in the Alps using (in part) observations from the

BNP. Table 2 illustrates them but does not consider the role of evaporation and condensation on the snowpack, which can lead to snowpack loss and gain respectively.

Table 2: Characteristics of Snowpack Storage in Various Elevation Zones in Central Europe

Elevation Zone	Storage Details	Region(s)
5. > 3600m (asl)	Accumulation Snow temperatures are negative for the entire year, no ablation, loss of mass through mechanical transport (wind, avalanches) to zone 4 or through metamorphosis to ice (glacier), normally a positive mass balance	Central Alps
4. 3600-1500m	Accumulation and ablation clearly separated, normally no division in single snowpack periods, no rain influence on snowpack development, accumulation and ablation balance out and are positive or negative over various snowpack periods depending on weather patterns	Central and High Limestone Alps (Kalkhochalpen)
3. 1500-1000m	Accumulation and ablation not clearly separated, $0^{o}C$ isotherm can be reached during the accumulation period through breaks caused by melt, after the start of the ablation period there are melt losses despite mass growth caused by further precipitation, sometimes rain influences snowpack development (eg: Christmas warm periods- Weihnachtstauwetter), storage development influenced by inversion processes, accumulation and ablation balance out	Limestone Alps (Kalkalpen)
2. 1000-500m	Constantly changing accumulation and ablation stages through the snowpack period, $0^{o}C$ isotherm frequently reached, division of the snowpack period through frequent melt phases, high melt season normally is very short and heavily influenced by rain, accumulation and ablation balance out	Limestone Alps (Kalkalpen), Foothills
1. < 500m	Accumulation and ablation occur at the same time, $0^{o}C$ isotherm is normal, relatively short snowpack period, large rain influence on snowpack development, accumulation and ablation balance out	Foothills, Plains (Flachland)

Source: modified after Rau (1993).

Rau (1993) also states that *Weihnachtstauwetter* or a warm period that occurs normally around Christmas can lead to measurable losses from the snowpack through melting, especially at lower elevations. Figures 6 to 10 illustrate the normal accumulation and ablation cycles for the five elevation zones described in Table 2.

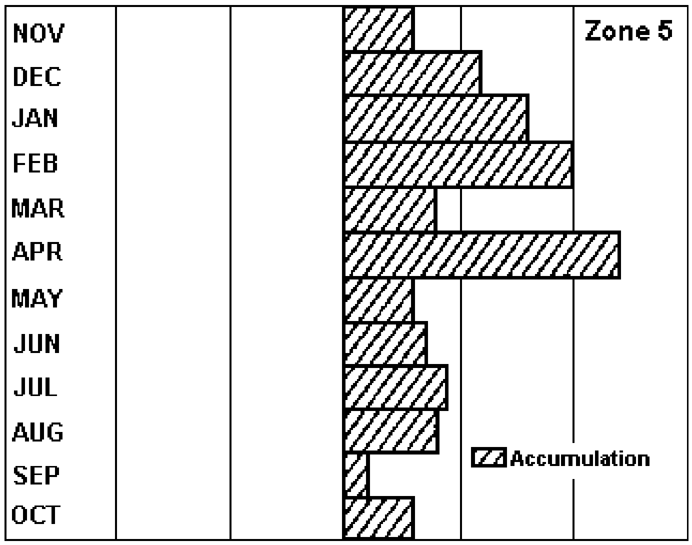

Figure 6: Zone 5 Accumulation Cycle
Source: modified after Rau (1993).

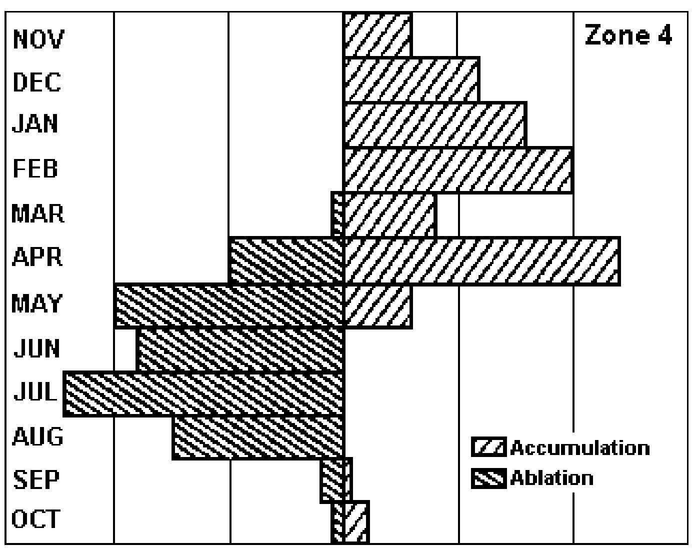

Figure 7: Zone 4 Accumulation and Ablation Cycles
Source: modified after Rau (1993).

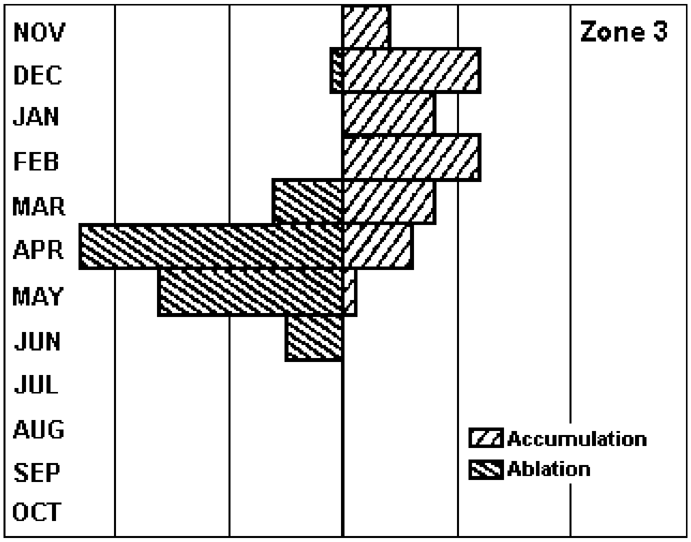

Figure 8: Zone 3 Accumulation and Ablation Cycles
Source: modified after Rau (1993).

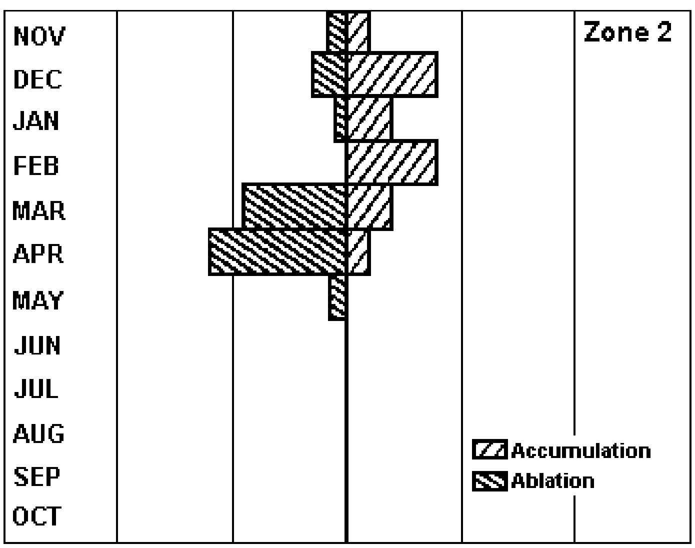

Figure 9: Zone 2 Accumulation and Ablation Cycles
Source: modified after Rau (1993).

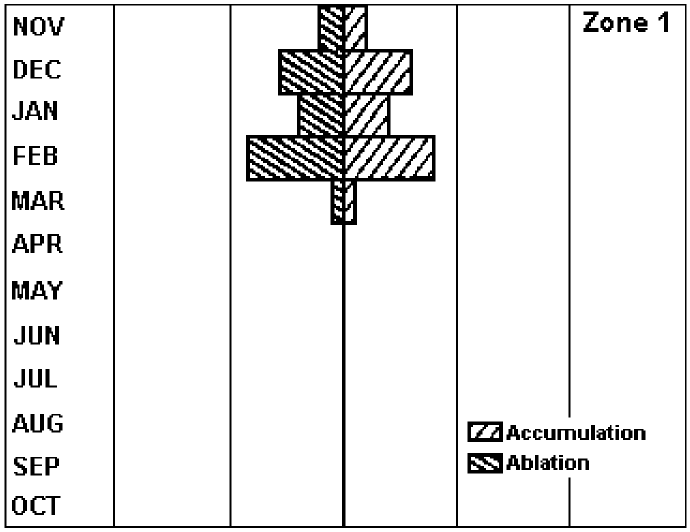

Figure 10: Zone 1 Accumulation and Ablation Cycles
Source: modified after Rau (1993).

3.8 Grid-based Solar Insolation Applications

Solar insolation can be calculated based on variables generated from DEM data. The method used in this research combines aspect, slope gradient, and elevation together with sun angle and sunshine duration to model incoming shortwave radiation. DEM grid data facilitates contouring and the calculation of slopes and other measures of surface characteristics (Mulugeta, 1996). Grid or cellular approaches to subdividing the landscape provide the most common structures for dynamic, process-based hydrologic models (Moore et al., 1993).

A Lambertian reflectance model assumes that the surface reflects incident solar energy uniformly in all directions, and that variations in reflectance are due to the amount of incident radiation (Erdas, 1998). Landsat TM data were used by Bordeleau and Gratton (1998) to estimate the total amount of meltwater from each pixel (30m resolution) in procedures that incorporated the net radiation balance.

3.9 Regression Analysis

The basic purpose of regression analysis techniques is to quantify relationships between two or more variables (Brooks et al., 1991). Clarke (1994) states that often we need to explore the relationships between two or mores variables. The response variable is explained by what are known as the explanatory variables. If a model fits the data exactly, we would have the most parsimonious model possible.

It is common practice for scientists to use regression models to describe the relation between a response (dependent) variable of interest and a set of covariates (independent variables), and to use the fitted regression equation to predict the response variable from new sets of covariate values (Elston et al., 1997). Data used to build predictive regressions models are typically obtained at closely monitored training sites or experimental plots where all variables can be measured. For many cases of spatial phenomena, statistical surfaces must be generated from a finite set of observations through manual or automated interpolation; hence the true characteristics of the resulting surfaces are known only imperfectly (Mulugeta, 1996).

The examples of regression use in the research literature are many. A polynomial regression was used by McGinnis (1997) to incorporate nonlinear relations that may exist between atmospheric circulation data and snowfall data. Multiple regression and GIS have been used by Narumalani et al. (1997) in modelling the adaptability of plant species to changes in water levels. Dadhwal and Sridhar, (1997) developed a non-linear regression between crop yield and vegetation indices. Hopkinson and Young (1997) used a multiple regression model incorporating monthly average temperature and precipitation (with snow course data) to estimate river flow. Multiple regression techniques show promise as an effective avenue to pursue the development of SWE algorithms over first-year sea ice (Drobot and Barber, 1998).

Brooks et al. (1991) state that multiple regression equations are often used in trying to predict the volume of snowmelt runoff. The technique is however not always successfully used. Hills et al. (1996) state that regression techniques work well in estimating snowmelt in average years; however, these techniques tend to be inaccurate in extreme years.

3.9.1 Multiple Regression

It is desirable, in a program for the computation of multiple regression, to be able to add new variables, in the sense that, if they result in an improvement to the goodness of fit they are to be retained in the regression equation, but otherwise left out (Clarke, 1994). A cardinal principle in the building of statistical models, in hydrology as in other sciences, is that we should use the smallest number of parameters necessary to describe adequately the variation in the independent variable (Clarke, 1994). This is what the stepwise regression technique is designed to do.

Weighted linear regression is a slightly different multiple regression form. All observations on the response (dependent) variable are given equal weight in the analysis (Clarke, 1994).

3.9.2 Regression Trees

Regression tree models allow for complex interactions between independent variables that are determined beforehand using standard linear regression models. An example is that snow accumulation may increase up to a certain elevation and then decrease with increasing elevation above that point. Standard linear models can only take advantage of that fact if a mathematical expression for the relationship is formulated and expressed before model implementation. Tree models can use this knowledge to diverge or branch at this elevation point and take the changing snow-elevation relationship into account.

The SWETREE model uses binary decision trees (regression trees) to estimate the spatial distribution of SWE with physically based independent variables (net solar radiation, topography, soil and vegetation cover type) and SWE measured at individual points as inputs (Blöschl and Elder, 1998). It is designed in order to interpolate SWE across a gridded domain (Cline and Elder, 1998).

It is not always the better regression modelling technique as was evidenced by Leydecker and Sickman (1998) in their study of snow depth in the Sierra Nevada Mountains in California. They found that linear regression techniques provided better results than tree regression models. They used subsets of 75% of their snow measurement data (approx. 750 of 1000 points) and found that modelled values were poorly correlated with the 250 actual values that were left out.

Advantages of the regression tree method include that it is well suited for mixed data types and that it can resist data outliers. One of the main disadvantages is that it generally requires a large dataset.

CHAPTER 4: DATA ACQUISITION AND RESEARCH METHODS

4.1 Introduction

This chapter provides an overview of the procedures and methodologies that were necessary in order to complete this research. There is a description of the data sets and the applied image processing and GIS techniques that were involved. The steps required to perform the solar insolation and the regression analyses are fully explained in terms of database development, manipulation, and verification.

4.2 Data Acquisition

Data for this research were acquired from two primary sources, the Berchtesgaden National Park Administration (BNPA) and the Department of Geography and Geoinformation (DGG) at the University of Salzburg.

4.2.1 Satellite Imagery

Earth Resources Technology Satellite (ERTS) number 1 was launched on July 23, 1972. After the launch of ERTS-2 in 1975, both satellites were renamed to Landsat 1 and Landsat 2 respectively. Landsats 3, 4, and 5 were launched in 1978, 1982, and 1984 respectively. It is incredible that good data are still being received from Landsat 5 considering that the platform is already 15 years old and has well exceeded its expected mission duration and design lifetime.

A partial Landsat Thematic Mapper (TM) scene that encompassed the BNP study area was available from the DGG at no cost. The image was acquired on July 13, 1988 at 09:28:39. The orbital/image characteristics were:

- Orbit/Frame 192-27
- Quarter 2, Band 1,2,3
- Sun azimuth: 130.80
- Sun elevation: 56.53

The TM data have a spatial resolution of 30m over 6 bands (1 to 5, 7) ranging from 0.45 um to 235 um. The thermal band (band 6) with a spatial resolution of 120m covering the 10.4 um to 12.5 um range was not part of the data set.

4.2.2 GIS Data

The entire BNP *Arc/Info GIS* (ESRI, 1991) database was obtained from the National Park Administration (courtesy of H. Franz). Franz (1997) describes the data that comprise this extensive database in detail. Multiple data layers (coverages) ranging from boundaries to vegetation types are contained in approximately 38 megabytes of data (status: 1996).

4.2.3 Digital Elevation Model (DEM) Data

The DEM files were obtained in either *Erdas Imagine* (Erdas, 1998) format or the *Arc/Info Grid* format. A 50m resolution grid DEM (/dgmsbg) was available from the DGG as well as a 50m DEM (/mhoegrid) from the Park's GIS database. In addition, a set of digitized contour lines (hoe2.shp) for the National Park and its buffer zone were available. This consisted of approximately 15000 individual lines that each had an elevation value attached to them. The contour interval was generally 20 metres but in areas of non-rapid terrain change was sometimes 10m or even 5m.

An approximately 5m resolution (4.9991m to be exact) DEM became available from the Park in the fall of 1998. It was interpolated using the same digitized line set as above.

4.2.4 Snow Data

The snow data were obtained from the BNPA (courtesy of H. Vogt) in a *dBase IV* format. They consist of 5793 original snow depth and snow-water equivalent measurements (smsgest.dbf) taken from 1988 to 1994 over a 94 point network (Figure 11). The sampling distribution indicates areas of sparse and dense coverage, which is related to the ease of access to the measurement locations.

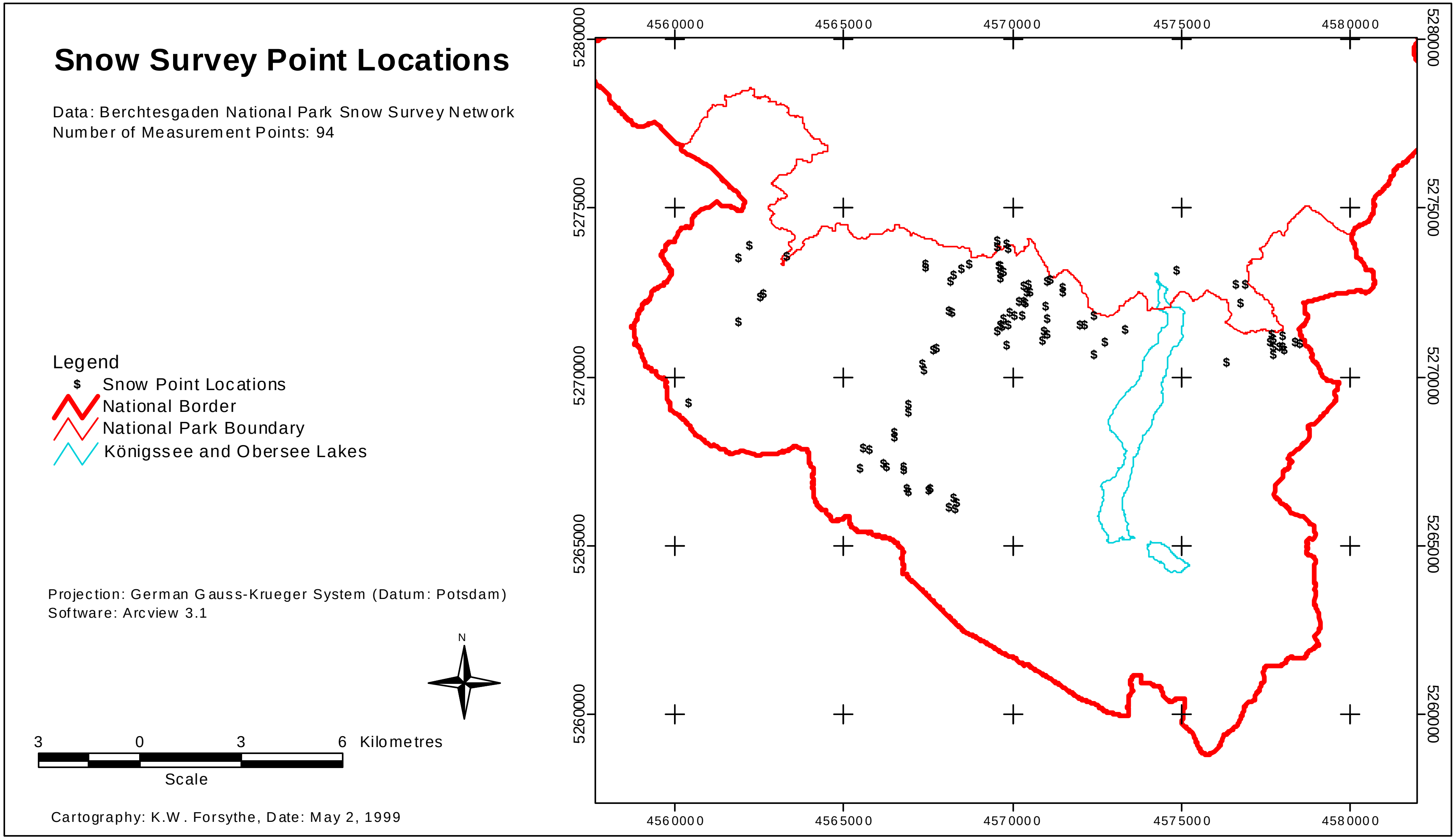

Figure 11: Snow Survey Point Locations

4.2.5 Reference Maps

Paper maps were obtained from the DGG. The German Topographic Maps that were used included the following at a scale of 1:50000:

- L 8542 Königssee
- L 8544 Hoher Göll
- L 8342 Bad Reichenhall
- L 8344 Berchtesgaden

4.3 Satellite Image Processing and Geocorrection

The data were found to have different map projections and were in various file formats once they were obtained. This required that a common reference system be applied to ensure compatibility between layers and file conversion so that all layers could be brought under the same data format “umbrella” to reduce the potential sources of error.

4.3.1 Pre-Processing

The original TM satellite image (tm1-7.img) was previously georeferenced to the Austrian Gauss-Krueger System (AGKS) map projection and resampled to a 25 metre spatial resolution. This is a fairly standard procedure in image processing as the 25m pixels provide for better registration with map coordinate systems and with various DEM data that are commercially available. It was decided that the image data would be switched to the German Gauss-Krueger System (GGKS) projection to ensure compatibility with all of the data available in the BNP database.

It was however first necessary to correct a problem with the TM data. TM band 7 was georeferenced “directionally” in terms of being registered with the projection grid. Unfortunately and for unknown reasons, it was approximately 75 metres out of line to the northeast. In order to ensure that all data would be compatible it was necessary to use functionality within the *Imagine* software to correct this problem.

The first step was to separate band 7 from the other bands and then correct the registration problem using the *Image Info - Change Map Model* function within *Imagine*. Simply subtracting the necessary amount of metres in N-S and E-W directions made the necessary adjustments. The new band 7 was then brought back into line with the 5 original bands. It was then however necessary to trim the new image to the data where all bands intersected. (This is the image data already presented in Figure 2).

4.3.2 Austrian to German Projection Transformation

The change of projection also involved using the *Imagine* software. A simple analytical projection change from AGKS to GGKS was first attempted using *the Coordinate Calculator* and *ImageInfo (Add/Change Projection and Change Map Model functions)*. Huge errors were very evident when the resulting image was compared to boundary data sets from the BNP GIS database. The N-S error was nine pixels or 225 metres while the E-W error was twenty-one pixels or 525 metres. These large errors could not be tolerated and in order to keep error minimized, alternative methods were employed.

The original image was opened and the *Geometric Correction* function was selected. A polynomial transformation was selected which requires at least 10 Ground Control Points (GCP). The original projection parameters were entered and 25 GCP were digitized on the image. The GCP information was then entered into the *Coordinate Calculator* where new coordinates in the GGKS projection were generated.

The projection change to the GGKS projection was then performed with control point errors of:
x:0.0326 y:0.0221 total:0.0393 (pixels)
This translates to an average error of less than 1 metre on the ground. There was however a problem when these data were compared visually to data from the GIS database. There were once again ground errors in both the N-S and E-W directions. The errors were x: -40 and y: +10 (metres). These are not huge errors but something within the translation process did not function correctly. As a result, the *Image Info- Change Map Model* function had to be utilized to register the newly transformed image with the GIS data.

A second attempt using a commercial coordinate transformation package (Blue Marble Graphics) was tried to see if the small transformation errors were a one-time event or a general occurrence. A similar problem occurred with control point errors of:

x:0.2349 y:0.3230 total:0.3994 (pixels)
The total error here translates into approximately 10 metres on the ground but the measured registration errors were: x: +80 and y: -6 (metres).

The projection for the DEM data (dgmsbg.img) was changed with the following errors:
x: 0.1507 y: 0.2766 total:0.3150 (pixels)
x: -50 y: +13 (metres).

What caused the errors in each projection transformation is unknown. Perhaps however it has something to do with the way that the software determines the coordinates for the original GCP locations. All of the errors that occurred in the various methods suggest that there may also be a geodetic datum problem.

All projection transformation functions were performed using a nearest neighbour resampling algorithm. This helps to retain as much of the original image information as possible from the previously resampled image. The final task involved cutting a subset out of the resampled image to avoid having blank data areas caused by the projection shift. The resulting image was used for the analyses detailed in the next sections.

4.3.3 Dehazing and Destriping

The elimination of unwanted atmospheric effects and sensor irregularities is a step that is sometimes undertaken in satellite data analysis. It is not however always necessary to correct for these effects as they are not always present. The TM image used in this research was put through the radiometric correction procedures available within the *Imagine* software with less than satisfactory results. Instead of improving image quality and clarity, both the dehazing and destriping procedure produced some effects that they were designed to eliminate. The dehazing procedure resulted in a “grainy pixel” appearance, which is perhaps not so surprising as it is an edge detection filter. The destriping procedure resulted in visible stripes in the image. Together, the two procedures produced a result that was both grainy and striped. This perhaps suggests that these procedures do not have to be performed on this image data. Figure 12 illustrates the normal image data versus the dehazing and destriping result.

The image data were obtained from Landsat 5. The problem of striping or banding has been largely eliminated from this sensor (Erdas, 1998). Histograms also show that the spectral reflectance values are quite similar for these 2 images (Figure 13). The effect of the correction procedure actually results in a reduction of the overall reflectance within the image.

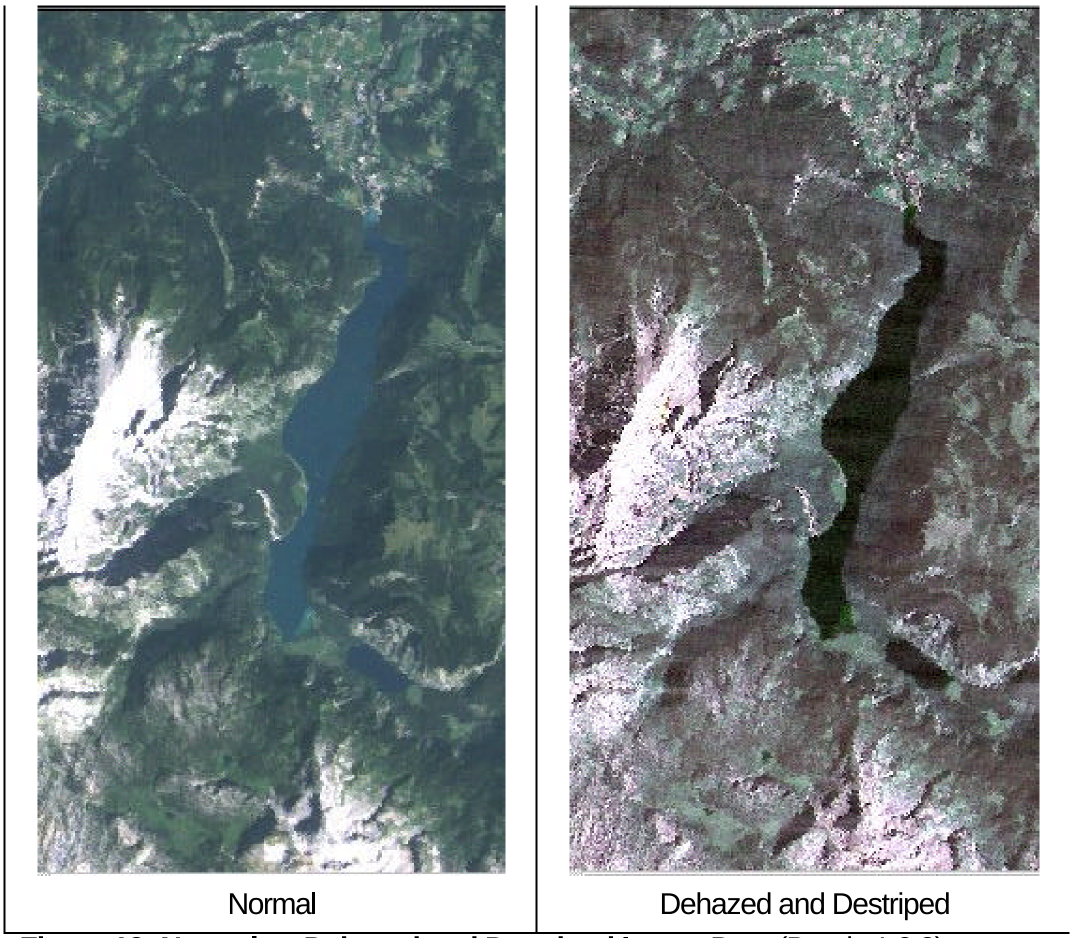

Figure 12: Normal vs Dehazed and Destriped Image Data (Bands 1,2,3)

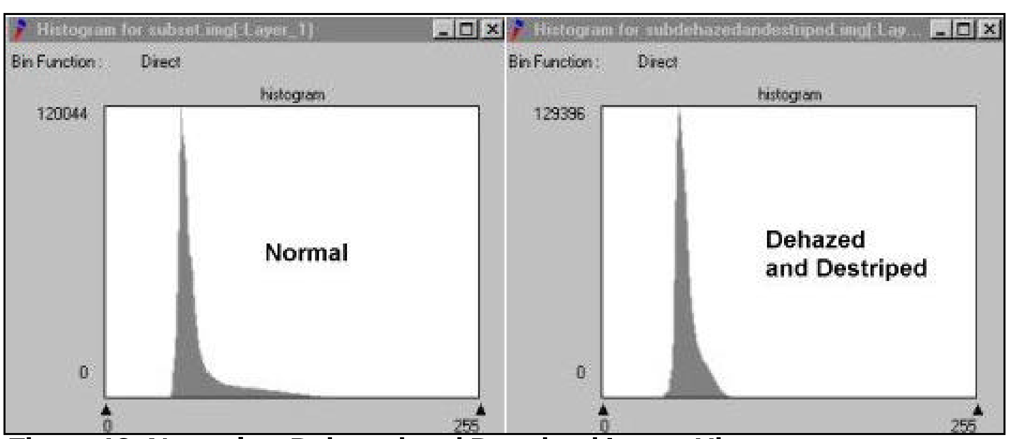

Figure 13: Normal vs Dehazed and Destriped Image Histograms

Accounting for anisotropic reflectance (Colby and Keating, 1998) or topographic effects in the imagery was not attempted in this research. It was thought that shadow affected areas in the imagery were more likely to have higher snow levels than those that are not affected and this could possibly be a key component in the modelling process.

4.3.4 Vegetation Indices Calculation

Indices have been used in remote sensing/image processing applications for many years. They are used extensively in mineral exploration and vegetation analyses to bring out small differences between various rock types and vegetation classes (Erdas, 1998). Vegetation indices are used to try and assess the differences in the amount of biomass on the ground that is present in digital data. This can help to assess crop damage, vegetation vigour, and many other things. Klein and Hall (1997) used Normalized Difference Vegetation Index (NDVI) values from a summer satellite image to help map snowcover using their Normalized Difference Snow Index (NDSI) derived from a winter satellite image.

The vegetation index task list in the *Imagine* software is extensive. A NDVI which is a measure of biomass (or vegetation vigour) was calculated with TM bands 3 and 4 (4-3/4+3) (Figure 14).

The other vegetation indices (and their TM band equivalents) that were calculated were the:

- infrared/red (IR/R): (band4/band3)
- square root (IR/R): SQRT(band4/band3)
- vegetation index (IR-R): (band4-band3)
- transformed NDVI ((SQRT(IR-R/IR+R)+0.5))

Kölbel-Deicke and Heuberger (1987) state that the relationship between duration of snow cover and period of vegetation growth has great influence on the patterns of vegetation distribution.

4.3.5 Principal Component Analysis (PCA)

A Principal Component Analysis (PCA) of satellite data is a way of deriving

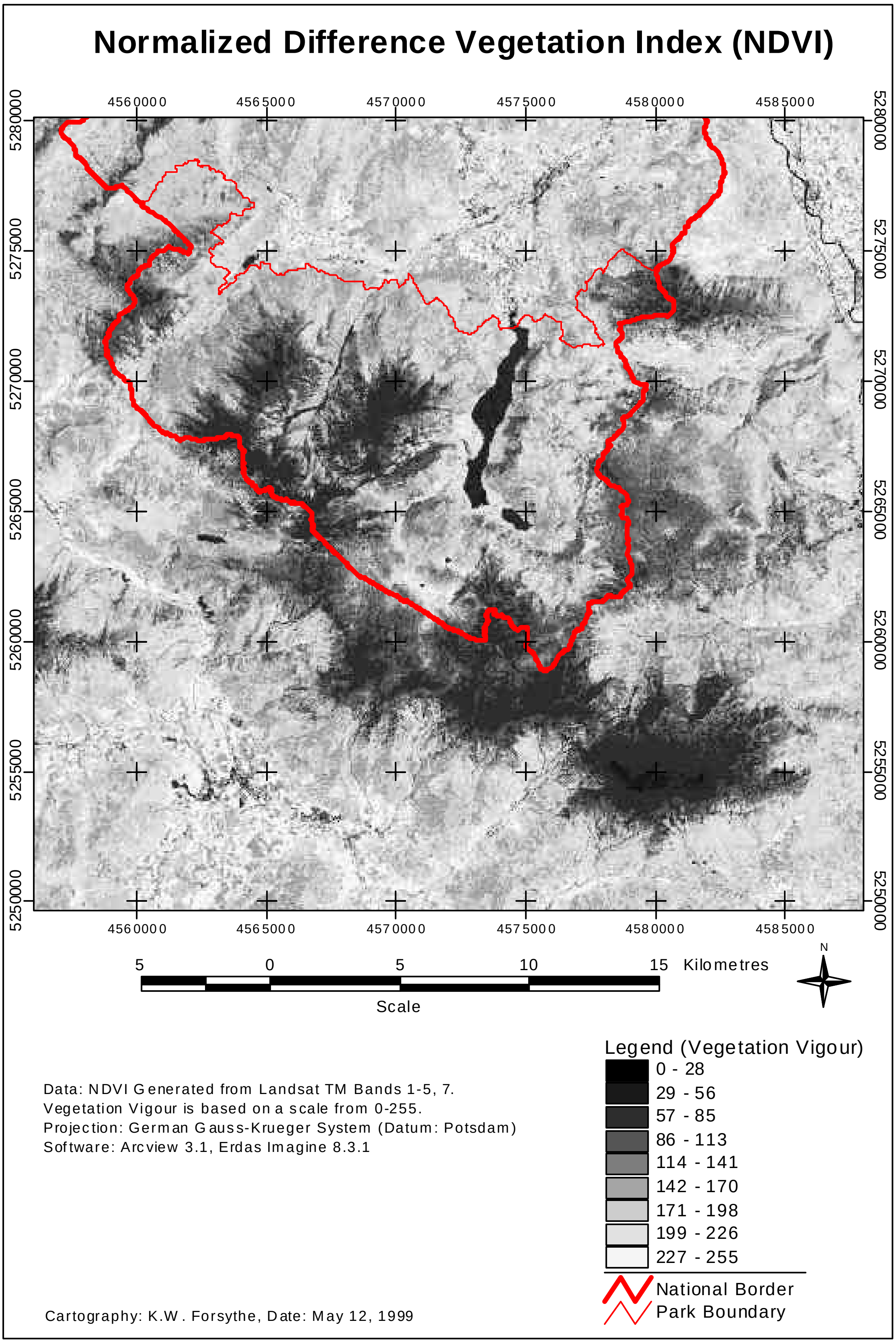

Figure 14: Normalized Difference Vegetation Index

additional information from the image. It separates the original data along independent orthogonal axes. Principal component enhancement techniques are particularly appropriate where little prior information concerning a scene is available (Lillesand and Kiefer, 1987). PCA helped Meyer et al. (1996) improve tree species classification results in a study area in Switzerland. PCA was performed using the TM image and four components were derived which had explanatory significance greater than any one of the contributing factors. Tables 3 and 4 outline the results and Figure 15 shows the image for Principal Component Two.

Table 3: Results of the PCA

////////////////////	Principal Components					
TM Band No.	**1**	**2**	**3**	**4**	**5**	**6**
1	0.354304	-0.364104	-0.506961	-0.116523	0.685426	0.038751
2	0.217309	-0.155025	-0.308356	-0.062860	0.386812	-0.824673
3	0.289061	-0.267210	-0.369140	-0.115979	0.615887	0.562149
4	0.297777	0.842334	-0.404716	0.187962	0.023540	0.046082
5	0.711707	0.106990	0.548739	-0.424362	0.023597	-0.016473
7	0.385346	-0.225879	0.216180	0.868105	0.011851	0.002559

Table 4: PCA Eigenvalues and %Variance

Eigenchannel	Eigenvalue	%Variance
1	3227.348	81.05%
2	555.534	13.95%
3	142.733	3.58%
4	47.049	1.18%
5	8.333	0.21%
6	0.816	0.02%

4.4 Digital Elevation Model Generation

Quality problems with the original 50m DEM data from the DGG and the BNPA resulted in the need for a better elevation model. It was therefore decided to create a series of elevation models from the digitized contour line dataset. The 15531 digitized contour lines in hoe2.shp had to first be checked for data integrity. There were numerous digitizing errors in this data set. Overshoots, undershoots, and mislabelled lines were the three biggest problems.

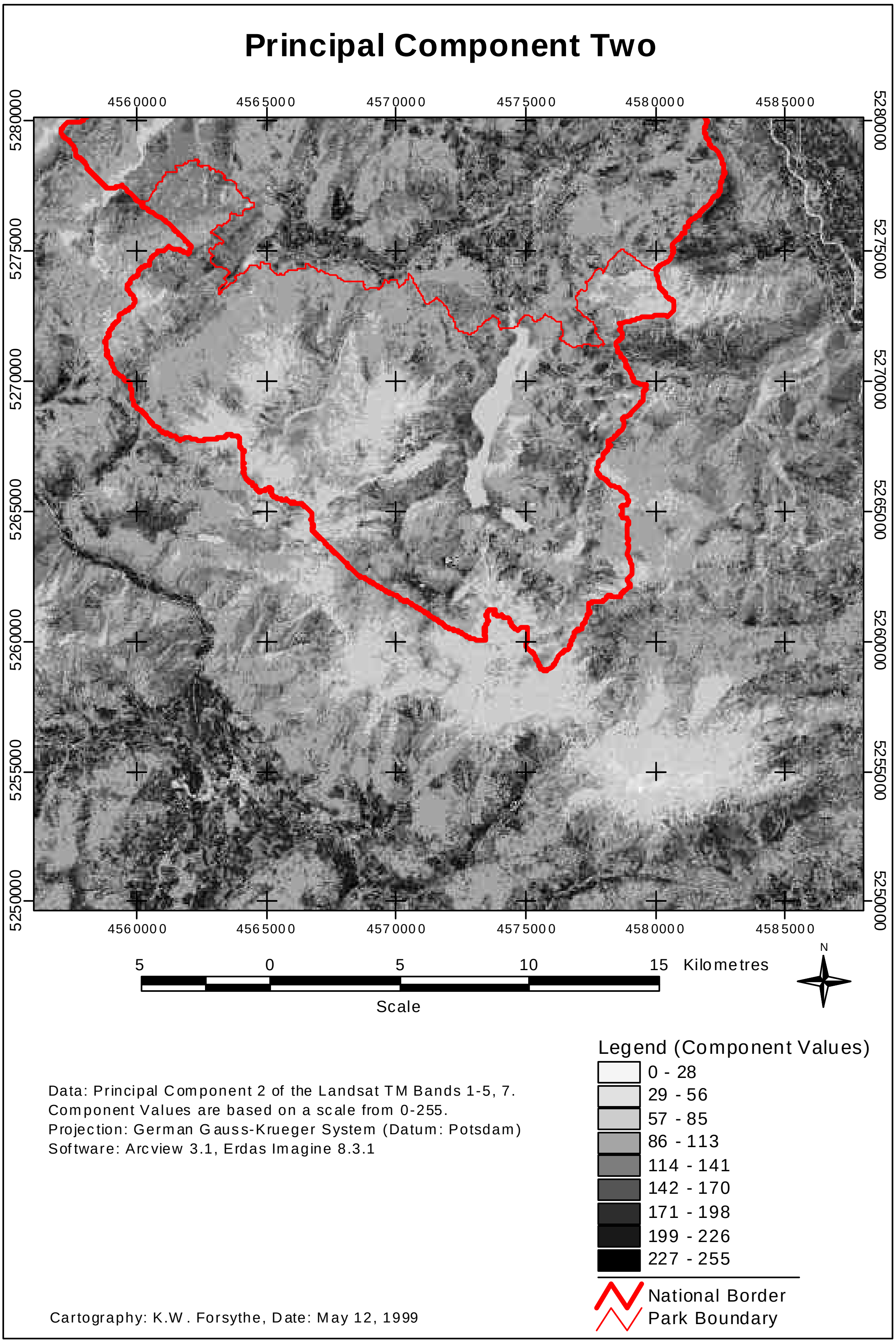

Figure 15: Principal Component Two

Arcview GIS was used to repair the problems. The process was however very time consuming but resulted in a higher quality dataset. The resulting data file consisted of 15194 digitized lines (hoe2new2.dbf). Many badly digitized lines were deleted and a few new ones were added; most notably, contours for the lakes within the park and the peak of the Watzmann.

Originally, the new DEM were to be intepreted with *Arcview GIS* or *Arc/Info GIS*. These programs could not however perform the required analysis. Therefore, the *Idrisi GIS* (Eastman, 1990) software was used.

The *Arcview* shape files were imported into Idrisi and raster data files were created to accept the vector data. The boundary coordinates entered for these files were:

XMIN = 4556000
XMAX = 4583500
YMIN = 5257500
YMAX = 5288500

These coordinates represent a rectangle that contains the study area. Four different DEM were interpolated. Their specifications were:

- 2750 columns x 3100 rows (10m pixels)
- 1375 columns x 1550 rows (20m pixels)
- 1100 columns x 1240 rows (25m pixels)
- 550 columns x 620 rows (50m pixels)

The vectors were converted to raster data with the *Lineras* function from *Idrisi*. The elevation values were then attached to the rasterized lines with the *database workshop*. The *Intercon* module performed the interpolation. Processing times varied from 20 minutes for the 50m DEM to over 6 hours for the 10m DEM. The analyses were run on a Pentium 233 Personal Computer (PC) with 128 megabytes of RAM.

The completed DEMs were then exported from *Idrisi* format to the *Erdas GIS* file format. *Imagine* was then able to import the old file format and create/export a grid for use in *Arc/Info* and *Arcview*. Figure 16 illustrates the 25m DEM.

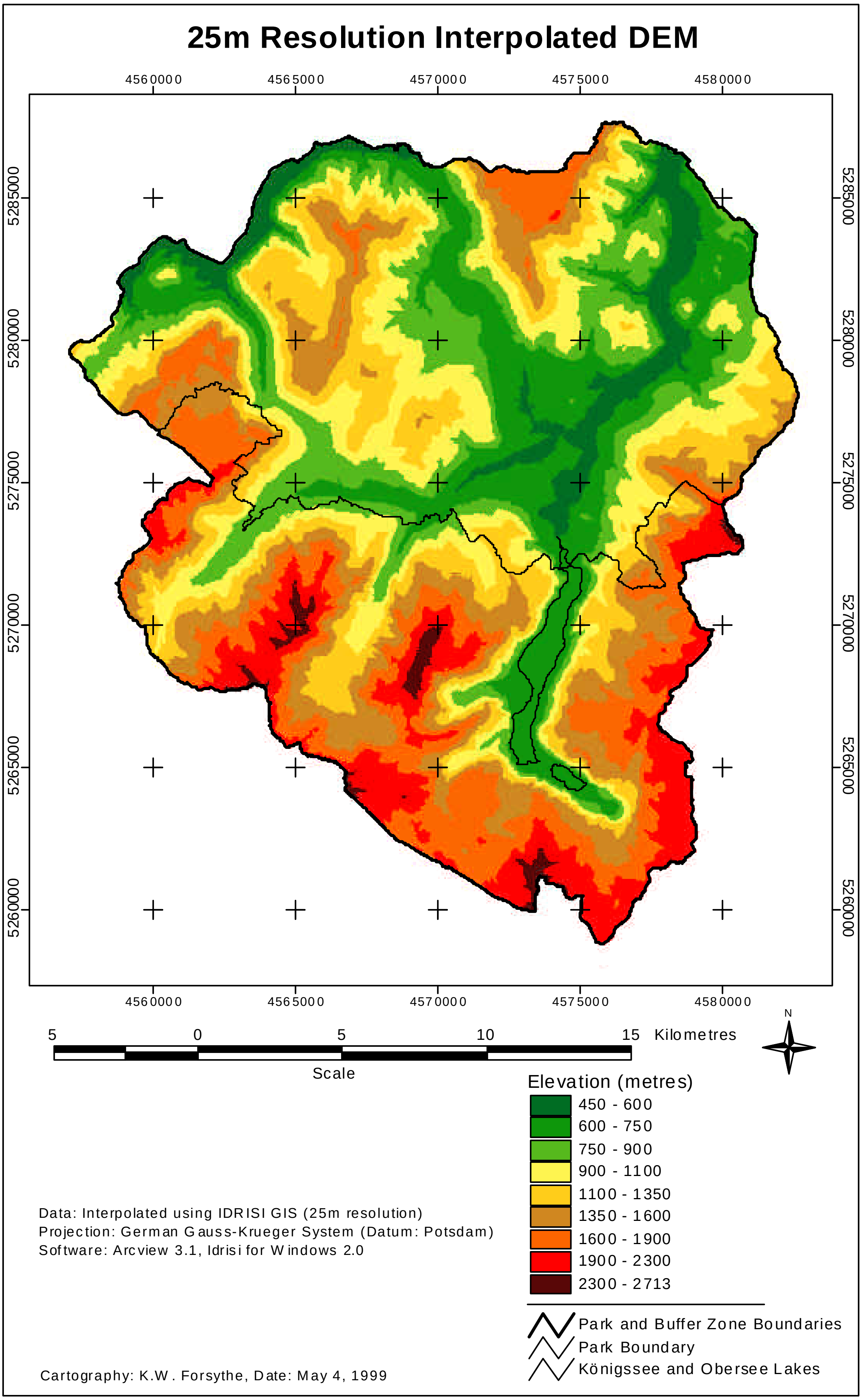

Figure 16: 25m Resolution Interpolated DEM

4.5 DEM Analysis

Satellite derived DEM data were not available for this study. This was however not a huge problem and the results of a study by Giles and Franklin (1996) reinforce the idea that extreme caution must be exercised before a satellite-derived DEM is relied upon to provide estimates of derivative topographic variables.

If a DEM contains errors, further processing can lead to more error. First order derivatives such as aspect and slope as well as curvatures can be affected. Lopez (1997) used a Principal Component Analysis that is different from normal image processing PCA to analyze DEM errors. Carrara et al. (1997) compared various methods of calculating DEM from contour lines. All had problems in relatively flat areas, so local filtering techniques are suggested as a way of reducing artefacts. The problem of defining aspects is greatest on the most gentle slopes (Carter, 1992).

Hodgson (1995) found that slope and aspect derivations from grid DEM data represent cell sizes 1.6 to 2 times larger than the size of the central cell. It is suggested that when possible, slope and aspect should be determined first before resampling elevation datasets of a finer resolution to a larger cell size.

4.5.1 Procedures

A total of seven DEM were available for further analysis. The four interpolated DEM, the two original 50m DEM, and the 5m DEM that was obtained later.

The 50m DEM from the BNPA GIS database first had to have a projection change from five-figure Gauss-Krueger coordinates to the seven-figure version. The projection shift was easily accomplished within Arc/Info using the following command:

Grid: npbdhm = shift (mhoegrid, 4557072.998, 5258808.998, 10.003).

The x and y coordinates had 4500000 and 5200000 added to them (respectively) while the cell size was taken from information obtained using the *Arc/Info describe* command. (The DEM has a resolution of 10.003 m according to the information). This related the data to the projection coordinates of the other database layers and updated the resulting grid file (/npbdhm) to the new National Park projection standard (Franz, pers. comm., 1998).

Topographic analysis of the DEM layers was now possible. *Curvature* analyses were carried out within *Arc/Info GRID*. The commands (with the names of the original data files) were:

curve5m = curvature (hoe, prof5m, plan5m, slope5m, aspt5m)
curve10m = curvature (npb10m8, prof10m, plan10m, slope10m, aspt10m)
curve20m = curvature (npb20m8, prof50m, plan20m, slope20m, aspt20m)
curve25m = curvature (npb25m8, prof25m, plan25m, slope25m, aspt25m)
curve50m = curvature (npb50m8, prof50m, plan50m, slope50m, aspt50m)
curve50n = curvature (npb_dhm50nn, prof50n, plan50n, slope50n, aspt50n)
curvenpb = curvature (npbdhm, profnpb, plannpb, slopenpb, asptnpb)

This resulted in five different coverages for each DEM. The generated covers were (respectively):

- elevation,
- profile curvature,
- plan curvature,
- slope, and
- aspect.

It is interesting to note that the slope and aspect calculations using *Arc/Info GRID curvature* produce slightly different results than those with the stand-alone *slope* and *aspect* functions. Figures 17 and 18 illustrate the aspect classes for the 25m interpolated DEM and the 50m National Park DEM. The latter clearly illustrates the reasons that contours are not the best solution for DEM generation. The "terracing effect" in areas with less relief and the abundance of flat areas are the result of interpolation errors. This DEM was not ultimately used in the later analyses due to the numerous errors that were evident through aspect and hillshade analyses performed on the data.

4.6 GIS Data Integration and Processing

The study area was defined within *Arcview* as being the area within the borders of the National Park and the Buffer Zone for which there was satellite data available (see Figure 2). *Arcview* and *Arc/Info* were used together in order to create the databases for the analyses. In addition, data files were taken from the BNP GIS database. The most important files were the boundaries of the park and buffer zone, the lake polygons, and the vegetation map. All of these files had to undergo a projection shift similar to the one

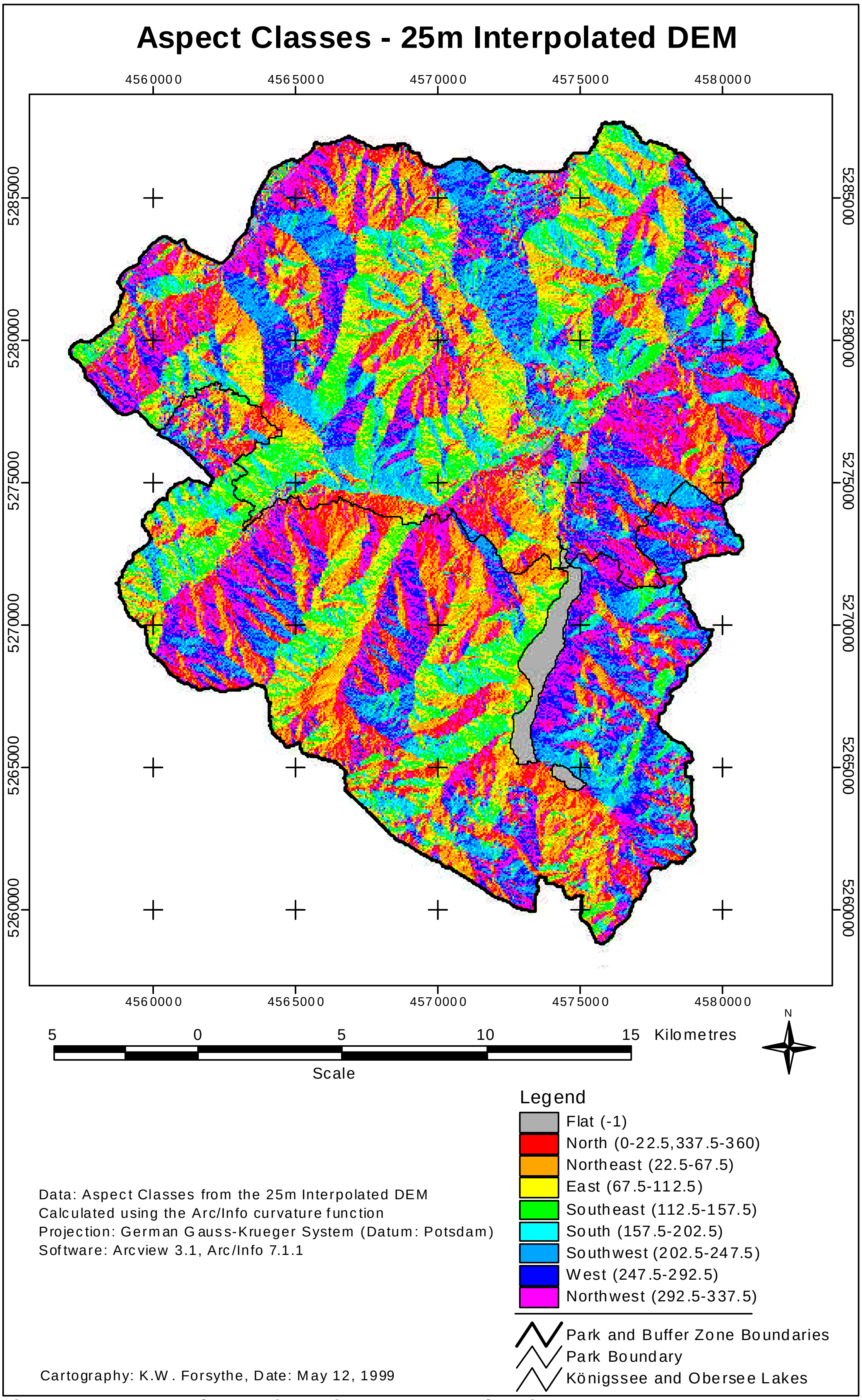

Figure 17: Aspect Classes from the 25m Interpolated DEM

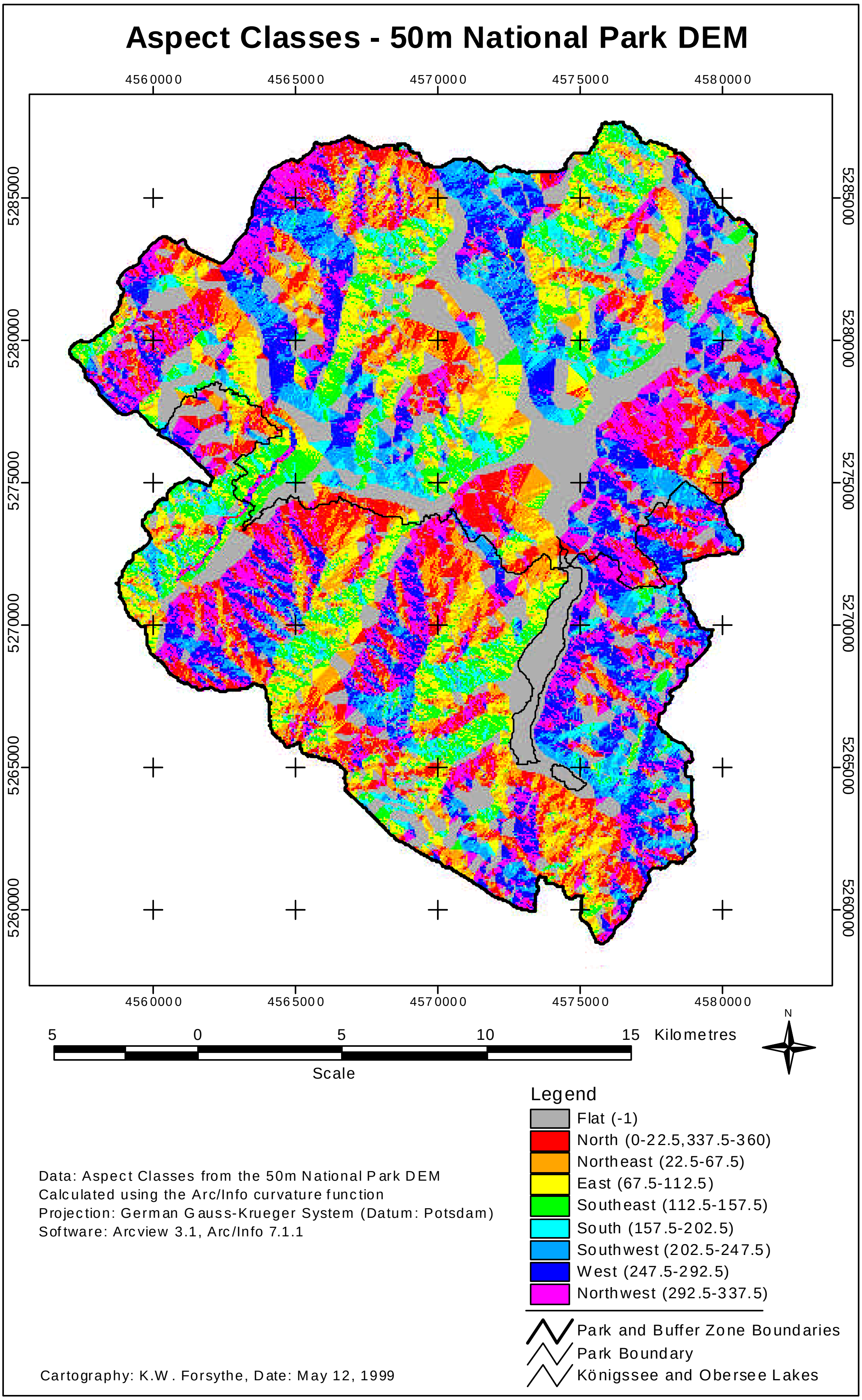

Figure 18: Aspect Classes from the 50m National Park DEM

described above. It was also necessary to cut away unwanted polygons from some of the coverages. This was performed with *Arcedit* within *Arc/Info*.

4.7 Data Manipulation and Integration Challenges

The 50m DEM that was interpolated from the already georeferenced contour lines was combined with a subset of the original DGG 50m DEM to make sure the projection transformation had been performed correctly. It is more difficult to assess projection change effectiveness with a DEM as opposed to TM data because of the difficulty in identifying features in DEM data. When polygon coverages (such as the Königssee Lake and the Park boundaries) from the BNP GIS database are overlaid on DEM data, assessing their position is very troublesome.

The combined data file was analysed with respect to aspect and hillshading to see if there were major inconsistencies in the join areas. The results showed that applying the same geocorrection procedure with the follow up adjustments to x and y as performed with the TM data were successful.

4.8 GIS Variable Extraction: DEM and Snow Data Integration

The main goal of this research is to develop estimation models for snowpack characteristics. It is therefore necessary to integrate the historical snow data with the topographic and landcover variables provided through DEM analysis and image processing techniques.

The original snow data file (smsgest.dbf) from Berchtesgaden was imported into *Arcview* using the *Tables-Add* command. The coordinate values in the x direction had 4500000 added to them and the y values had 5200000 added to them. This was necessary in order to reference the data to the GGKS projection. The editor was then used to delete the records that were incomplete as well as the columns in the file that were unnecessary for the analyses.

The resulting file had a total of 5747 snow measurements. Using *View-Add Event Theme*, the file was brought into the view analysis window. It was then converted into a shape file (snowpoints.shp). The resulting snowpoints.dbf file was then added using the *Tables-Add* command. In order to attach the various coverage file values to the snow point values the coverage had to be converted to *Arc/Info* format. This was accomplished in *Arc/Info* using the *shapearc* command. The point coverage “snow” resulted.

4.8.1 DEM and Vegetation Indices Comparison Dataset

The first data set that was produced was for analyzing whether there was a difference in snow model performance or estimation ability in terms of explained variation due to DEM resolution and/or vegetation indices. To this end, the snow data values had additional data columns added to them using the *Arc/Info* command *latticespot*. This command calculates the value for each data coverage at each snow measurement location and appends that value to the point coverage. An example command for appending the value for plan curvature from the 25m DEM to the snow file within *Arc/Info* is shown below:

Arc: latticespot plan25m snow plan25m
Computing point spot values...
Z values stored in item plan25m...

The various DEM attributes were added using the above command and are illustrated in Table 5.

Table 5: Topographic Variables Added to the Snow Data File

ORIGINAL DEM FILE	ELEVATION	ASPECT	CURVATURE	PLAN	PROFILE	SLOPE
NPB50M8 NPB25M8	NPB50M NPB25M	ASPT50M ASPT25M	CURVE50M CURVE25M	PLAN50M PLAN25M	PROF50M PROF25M	SLOPE50M SLOPE25M
NPB20M8	NPB20M	ASPT20M	CURVE20M	PLAN20M	PROF20M	SLOPE20M
NPB10M8 HOE	NPB10M NPB5M	ASPT10M ASPT5M	CURVE10M CURVE5M	PLAN10M PLA N5M	PROF10M PROF5M	SLOPE10M SLOPE5M
NPB_DHM50NN (DGMSBG.IMG) NPBDHM (MHOEGRID)	NPB50N NPBNPB	ASPT50N ASPTNPB	CURVE50N CURVENPB	PLAN50N PLANNPB	PROF50N PROFNPB	SLOPE50N SLOPENPB

The vegetation indices were also added in a similar fashion to produce the data file for the analysis. Only the winter seasons 1988/89 and 1991/92 were used as they provided the best regression results for Forsythe (1997).

4.9 Integrating the Solar Insolation Model

The surface layer energy budget is a driving force for evaporation and transpiration processes occurring at the land surface and is highly dependent on topography (Moore et al., 1993). Kumar et al. (1997) modelled the topographic variation of solar radiation using GIS (*Arc/Info* and *Genasys*).

The *Arc/Info Macro Language* (AML) files strahlunggeo.aml, xadd.aml, and split.aml were obtained from the BNPA. Modification of the original files was necessary in order to integrate all of these files together which resulted in the files solarins**m.aml where ** indicates the DEM resolution. New data file names for aspect and slope gradient were also edited within these new AML files in order to correspond with the file names used in this study.

The solar insolation model accounts for the potential incoming shortwave radiation at the surface and the role of shadow. It integrates solar angle and sunshine duration by accessing tables that are located within the *Info* portion of *Arc/Info*. The potential incoming shortwave radiation was calculated for the 5th, 12th, 19th and 26th days of each month from January to April. Figures 19 to 22 illustrate the results for the 12th day of each month.

4.10 Preparing the Snow Model Datasets

The final step was to prepare the data files for the regression analyses. All topographic and landcover attributes along with the solar insolation results were appended to the snow attributes. This data file was then taken into *Arcview* where it was first divided into the snow/winter seasons from 1988/89 to 1993/94. These files were then divided according to the dates when snow surveys took place.

Generally the snow sampling network was measured in 3-day intervals. Unfortunately, the monitoring intervals were not constant throughout the snow season. It should also be noted that the same measurement points were not surveyed from one survey to the next or from year to year. Some points were measured fairly regularly but others were only measured very sporadically. This is one of the problems of working in the mountains, as access to particular areas is sometimes very restricted.

A total of 156 separate data files (78 each for snow depth and SWE) were

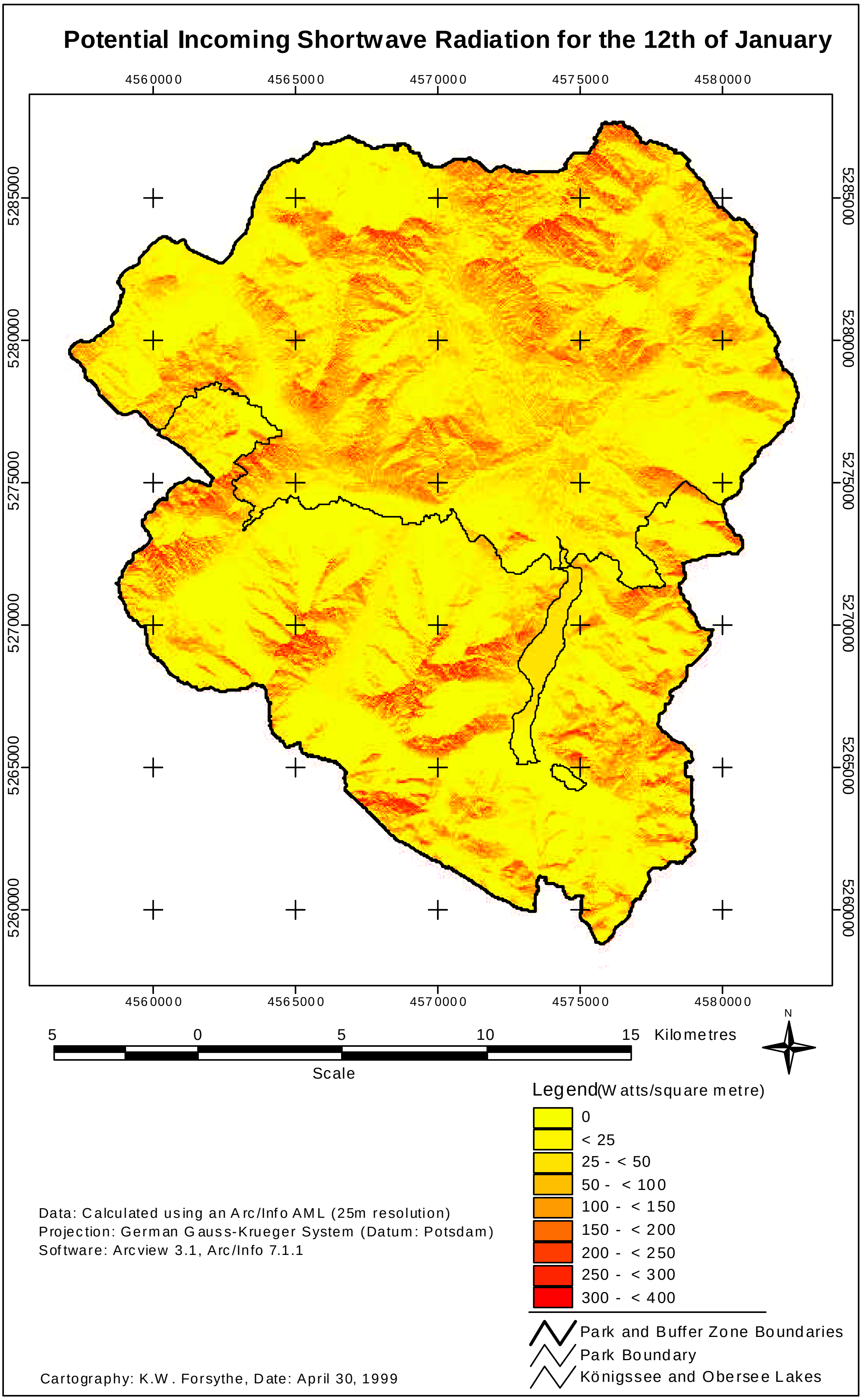

Figure 19: Potential Incoming Shortwave Radiation for the 12th of January

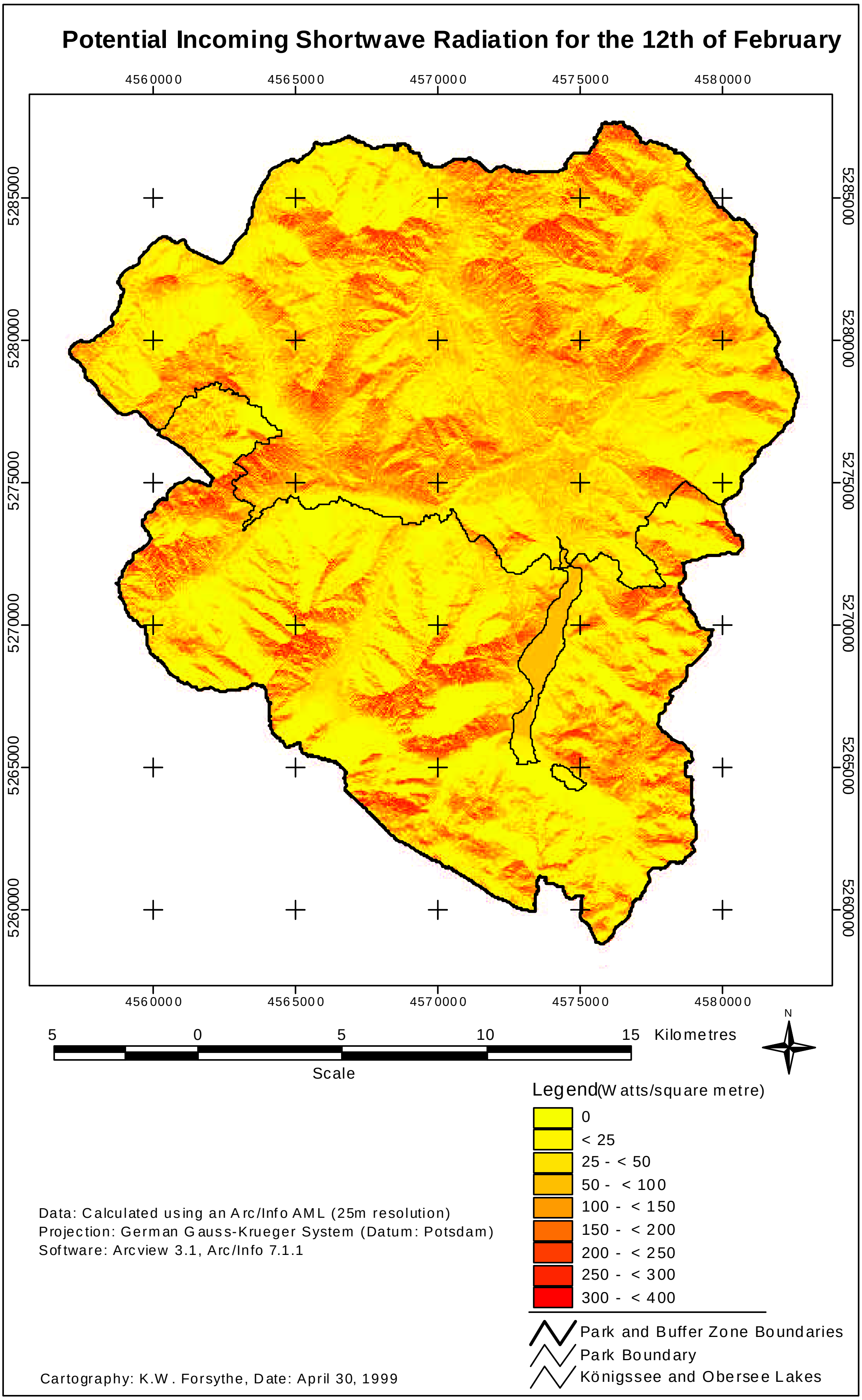

Figure 20: Potential Incoming Shortwave Radiation for the 12th of February

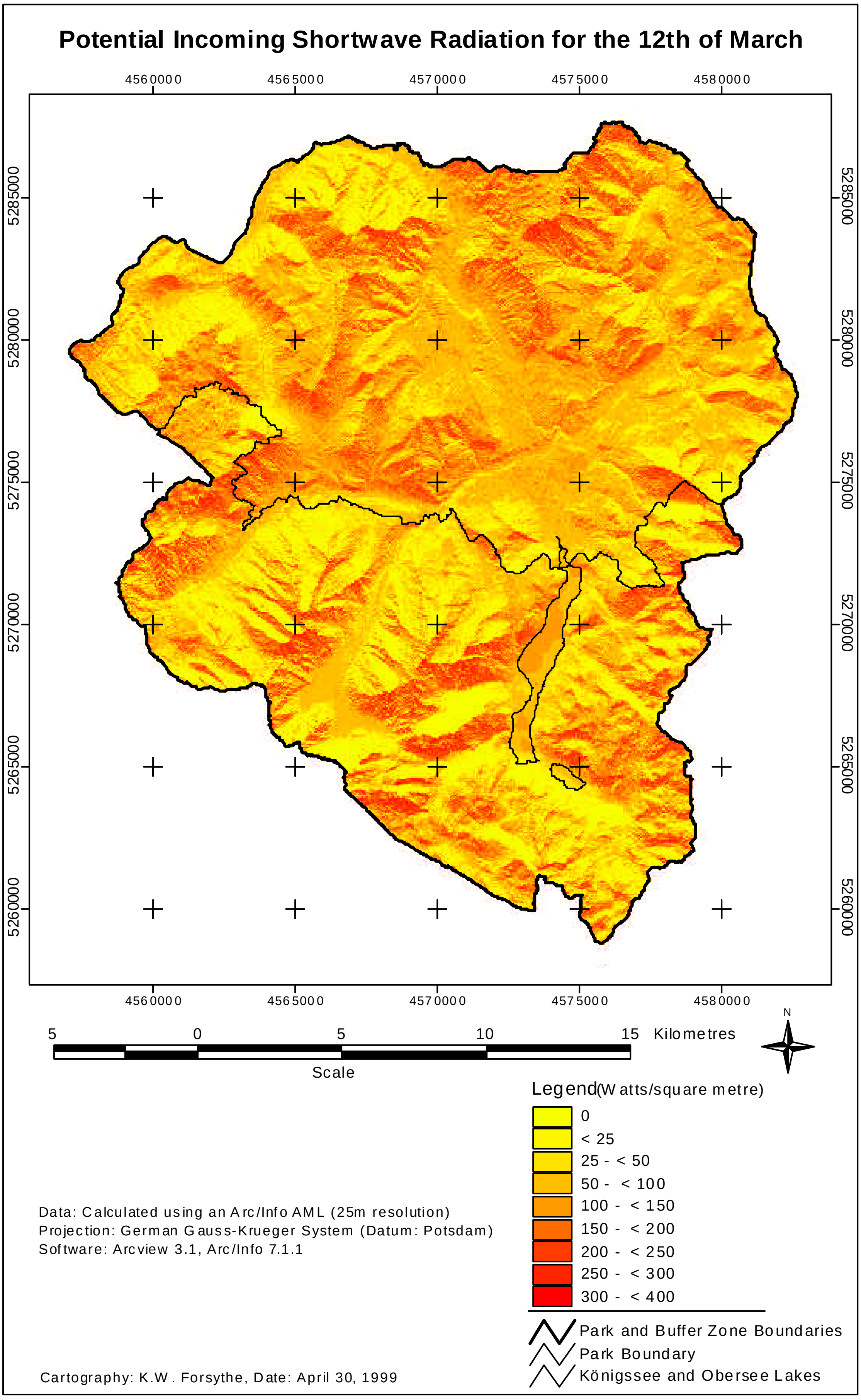

Figure 21: Potential Incoming Shortwave Radiation for the 12th of March

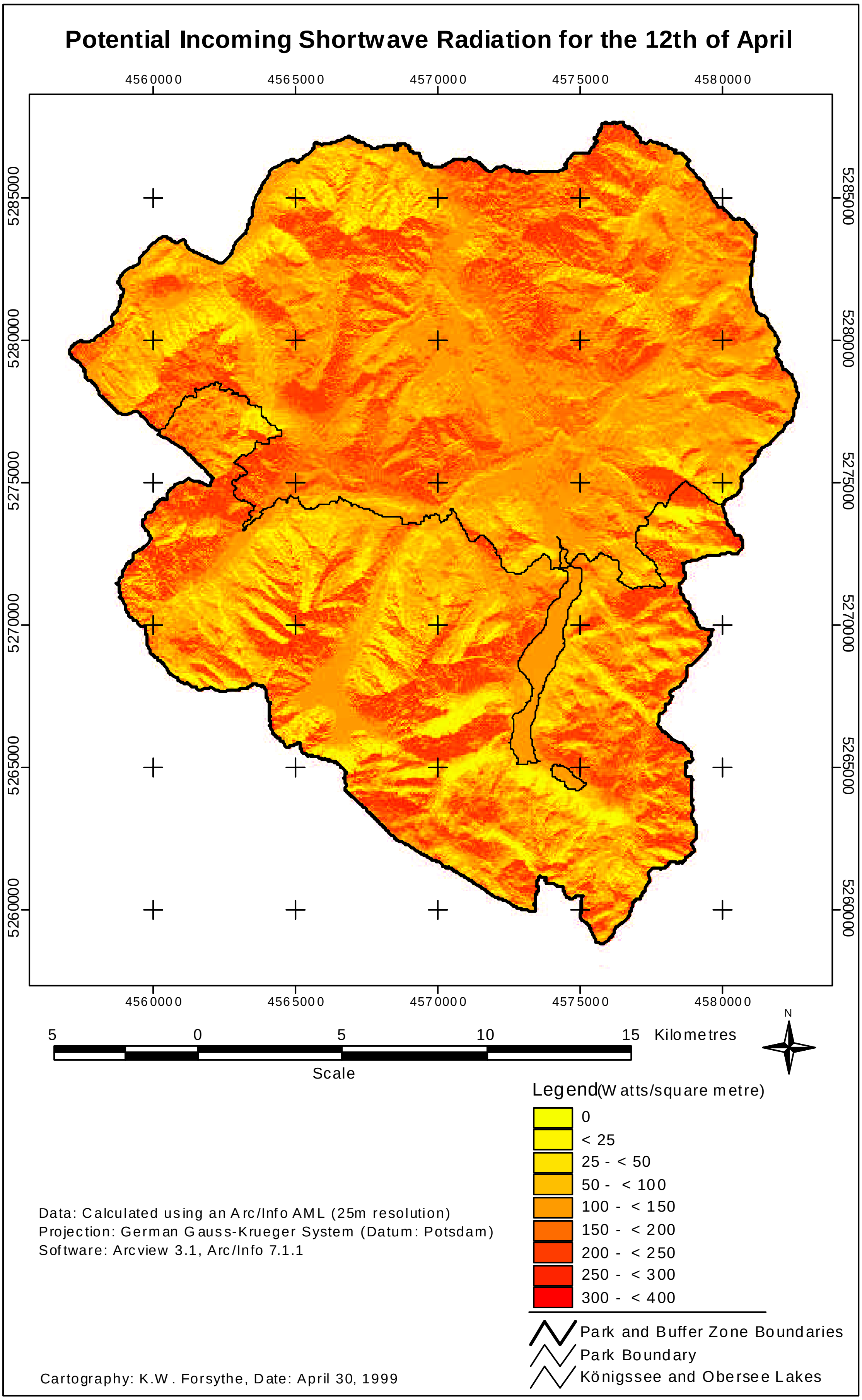

Figure 22: Potential Incoming Shortwave Radiation for the 12th of April

created for the first to fourth weeks of January through April over six winter seasons. There were only 156 files as no surveys were conducted for a few weeks during some winters. The data files contained the snow depth and SWE measurements along with all of the values for the topographic, landcover, and solar insolation variables. The file format is *.dbf which can be easily imported into the statistical software for the regression analyses.

CHAPTER 5: ANALYSIS, DEM AND VEGETATION INDEX RESULTS

5.1 Introduction

In alpine regions, there are many types of climate data that are available but time consuming procedures are necessary to extract the required information (Baumgartner and Rango, 1995). The datasets were prepared for the analyses with an emphasis on minimizing GIS error (propagation). The snow data sets were very carefully examined and wayward data were deleted. The digitized contour line file for the DEM generation was also thoroughly inspected to assure that the elevation contours had the correct elevation values attached to them. The TM data were carefully registered with existing data coverages out of the BNP GIS database to ensure full compatibility. In this way, data propagation errors should be kept to a minimum. There is at present no reliable way to track error propagation but with extra prudence it is hoped that it is minimized in this study. This chapter explains how the analysis procedures were performed.

5.2 The Best DEM Resolution for the Snow Models

Many researchers have examined the role that DEM resolution has in the modelling of hydrological processes. Garbrecht and Martz (1994) examined the impact of DEM resolution on extracted drainage properties using DEM of increasing grid size. Anderton et al. (1998) found that when they area averaged their 1m DEM data, the relationships between observed SWE and terrain characteristics was stronger.

The selection of a suitable grid cell size has to take into account the size of the digital files created, loss of spatial data, and the required degree of accuracy of the results (Goonetilleke and Jenkins, 1996). Gao (1997) found that terrain representation accuracy decreased moderately at intermediate resolution, but sharply at coarse resolutions for three different terrain types.

As outlined in section 4.8.1, the first task of the analysis phase was to determine the best DEM resolution for performing the full sets of regression analyses to follow. A total of 31 regressions for the winters of 1988/89 and 1991/92 were run for both snow depth and SWE. Each regression was however performed three different times with the various DEM data (50m, 25m and 5m) being substituted in and out. The total number of times that the various resolution DEM data (together with the identical sets of the other independent variables) provided the best regression results are presented in Figure 23.

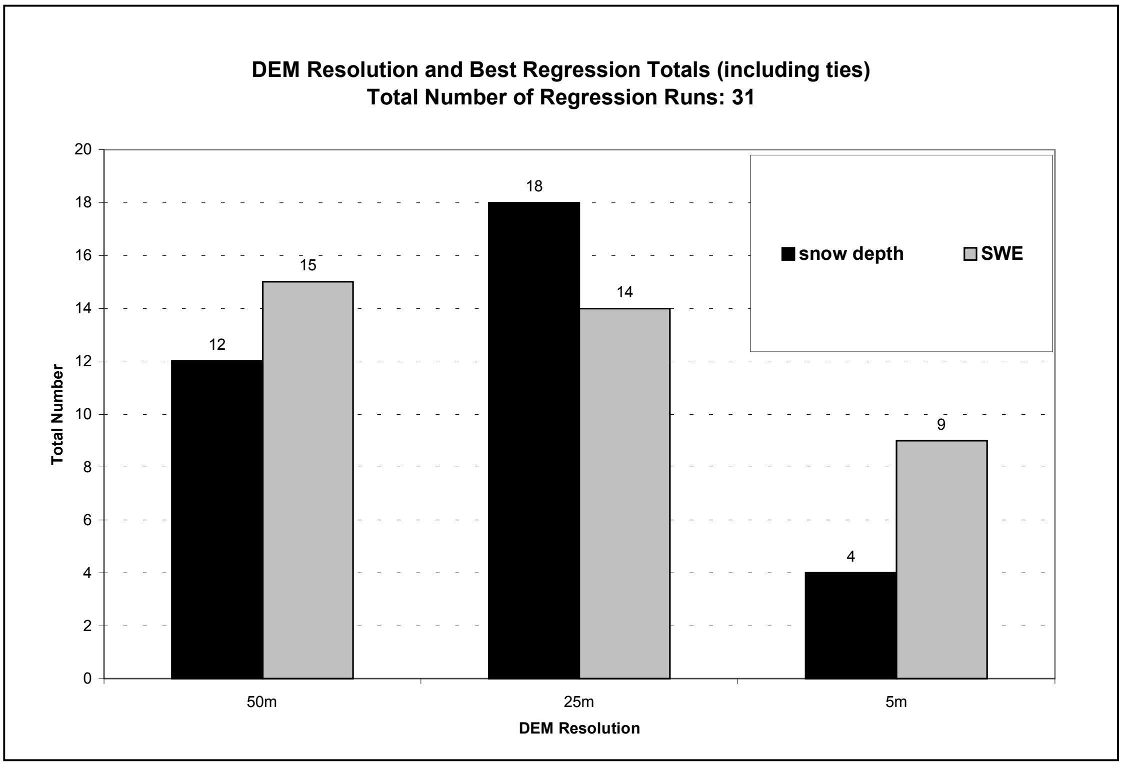

Figure 23: DEM Resolution and Best Regression Totals

The results of the analyses showed that the best overall model performance came when the 25m interpolated DEM and its derivatives were included. Good results were also obtained with the 50m interpolated DEM and the poorest results came from the 5m DEM. The 25m DEM was chosen for the further regression analyses due to the fact that 25m resolution DEM data are becoming readily obtainable for many areas and this would allow for direct comparison of the modelling techniques used here. The 25m resolution is also identical to the resampled satellite data, which helps to avoid data scaling problems. Processing time and computational expense also ruled against the 5m data when they were considered together with the poorer results. An explanation of the better performance of the 25m data is that perhaps the 5m data have higher variance than is found in the snow datasets and thus broad snow patterns are missed, and the 50m data are too universal which can lead to generalization and interpolation errors.

5.3 Vegetation Indices Selection

Many vegetation indices were calculated using the *Imagine* software. They were used as inputs for the regression analyses to account for variation in landcover parameters that can be obtained from the TM data. Yin and Williams (1997) used NDVI to parameterize vegetation for use in a hydrologic model. Colee et al. (1998) used soil type and vegetation cover from a satellite image as inputs into a snowmelt model. Rott et al. (1998) are developing models that integrate both landcover characteristics derived from snow-free images and snow cover extent derived from winter images. The data sources are the NOAA AVHRR, Synthetic Aperture Radars (SAR) of ERS and Radarsat, and high-resolution optical sensors including Landsat TM and SPOT High Resolution Visible (HRV).

The results of the vegetation index inclusion in the DEM regression runs did not provide much new information. NDVI was the vegetation variable that was the most significant in the regressions. When other indices were more significant than NDVI, their subsequent exclusion resulted in NDVI becoming statistically significant without a drop in overall explained variation. Various vegetation indices used by Lyon et al. (1998) had similar spatial and statistical characteristics and provided similar change detection results.

Biomass across large geographic areas has primarily been estimated using the NDVI (Todd and Hoffer, 1998). NDVI is an indication of biomass. Perhaps snow that stays longer in areas higher up which results in less biomass and in this way it is possible to use NDVI as a regression variable.

5.4 Calculating the Solar Insolation with the Various DEM data

Initially, the solar insolation AML files were run using DEM data of 50m, 25m, 10m, and 5m resolutions. The processing times to calculate the total incoming solar radiation per day were as follows:

50m = 33 minutes
25m = 1 hour and 45 minutes
10m = 5 hours and 30 minutes
5m = unable to process for an entire day due to disk space limitations.

The solar insolation AML works by calculating grids on a half-hour time interval throughout the day. Depending on the size and resolution of the original DEM, the calculations can become very computationally expensive. This was the case with the 5m DEM. In order to calculate the entire daytime insolation using this DEM, a total of 3.5 gigabytes of disk space would be required (each half-hour grid required approximately 113 megabytes) and processing over the DGG network where the necessary free disk space was available would have required 81 hours. This enormous use of computing resources is not entirely practical in a multi-user environment such as the DGG. These figures are based on a trial run that was completed for an 11am to 2pm time period using the 5m DEM data on a Pentium 233 PC with 128 megabytes of RAM.

The AML only calculates insolation values for a user defined base area where 1 = data and 0 = no data. The DEM data are used together with the DEM derivatives slope aspect and slope gradient in the calculations.

Potential direct solar radiation input (that accounted for slope gradient, aspect, and topographic shading) was also used as an independent variable by Anderton et al. (1998). Blöschl et al. (1991a) modelled snowmelt in an Austrian alpine basin using digital terrain data and a solar radiation model that took topographic variations into account. Schaab and Lenz (1997) integrated cloud cover into their solar insolation model. This requires however an estimation of cloud cover for each day that will be analyzed.

5.5 Aspect Dependent Snow Modelling Results

The problem with the aspect dependent modelling in this study was the number of overall points that were surveyed. An attempt was made to divide up the data (67 points) for the 2nd week of February 1992 into aspect zones and perform regression modelling procedures. This resulted in an uneven distribution into the eight cardinal aspect classes (as displayed in Figures 16 and 17) with 4 (southwest, northwest), 5 (south, southeast), 6 (north), 7 (west), 13 (east), and 23 (northeast) points respectively. Due to the limited number of observations in some aspect zones a regression analysis was only performed for the northeast. The resulting explained variation or adjusted R^2 was 0.714 where elevation, slope gradient and TM band 5 were the independent regressors. A further division of the points into slope classes within aspect zones would have been desirable but was not possible due to the limited number of points that were sampled.

5.6 SPSS Analysis

After all of the data files had been separated into their weekly groupings, it was possible to run the regression procedures. The model variables were entered into the *SPSS* program with the options defaulted. Figure 24 illustrates the *SPSS Linear Regression* window.

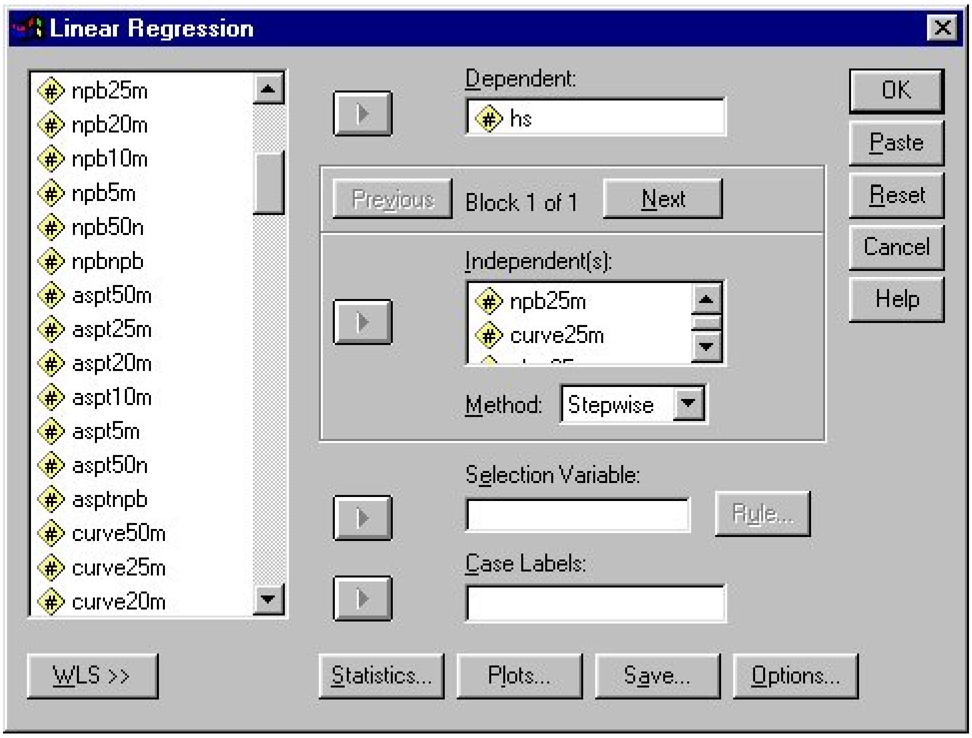

Figure 24: SPSS Linear Regression Window

5.6.1 Good, Normal, and Poor Snow Winters

The number of measurements where there was no snow along with whether it was a good, average, or poor snow winter help to explain the results. Excellent regression results were obtained in the good snow winter of 1991/92. All of the other winters were poor snow winters with the exception of 1992/93 which was poor to normal. The snow winters (good, normal, and poor) are based upon Slupetzky (1996, 1995, 1993a, 1993b, 1992, and 1991), Kirnbauer and Blöschl (1993), and Escher-Vetter et al. (1998). Slupetzky's observations were made at the Rudolfshütte Research Station which is located in the Central Alps (Hohe Tauern Massif) about 50 kilometres southwest of the BNP. Kirnbauer and Blöschl studied snow cover depletion in the Langen Valley, near Kuhtai, Tyrol, Austria (Ötztaler Alps - Alpen) which is approximately 120 kilometres west-southwest of the BNP. Escher-Vetter et al. worked in the northern ranges of the Alps approximately 100 kilometres to the west of Berchtesgaden.

The winter seasons for the model years can be summarized using Slupetzky's work.

1988/89

December 1988 was unbelievably snow rich (371 mm of precipitation compared with an average of 152 mm over a 25 year period (Slupetzky, 1991). High winter was precipitation poor and the snowpack grew slowly from January to March. December had average temperature while the high winter months were milder than normal.

1989/90

The winter was very mild and precipitation poor. It was one of the warmest Februarys of the century at Rudolfshütte. High winter was especially precipitation poor. January had only 1/3 of its normal precipitation, but February had more than double of the normal to almost make up for the deficit. The most snow came from the 10th to 16th of February.

1990/91

January and March were warmer than normal. The winter was overall precipitation poor. From December to March the snow totals were 30-40% below normal. April was also below normal.

1991/92

Winter was a bit milder than normal but also had more precipitation (snow) than normal. December 1991 had 130% of normal precipitation and February to April recorded more precipitation than normal. January was a bit milder than normal and had less precipitation than average.

1992/93

The winter months with the exception of March were much warmer than normal. January and April had slightly above normal snowfall while February and March were below average.

1993/94

Winter was warmer than normal and March was extremely warm (4°C warmer than normal). Precipitation values were slightly below normal overall but January and February were much below average.

Additional statements from the other authors include the following: the winter of 1989/90 had a lower than normal amount of early winter precipitation which led to a much earlier melt than in 1988/89 (Kirnbauer and Blöschl, 1993). The years 1990/91 and 1993/94 were poor snow years (Escher-Vetter et al., 1998). Kirnbauer and Blöschl (1993) report that snow cover depletion was significantly faster in 1990 than in 1989 due to lower solid spring precipitation.

In a study in the Hirschbach Valley (which is located in an area of the Northern Alps with similar climatological conditions to the BNP), Hermann (1973) found that foehn winds and rainfall led to substantial melt under the 1100m to 1200m elevation zone and that in some areas (especially south facing slopes), the snowpack disappeared completely. Felix et al. (1988) explain that there is almost never a persistent snow cover in valley areas around 1000m in elevation during poor snow years. The snow consistently melts and a continuous snowpack can first be found around 1300m.

5.7 Equation Determination

Model selection and the use of appropriate covariates (which are common to all regression problems) will provide for unbiased regression coefficients (Elston et al., 1997). If the training sites provide a suitable sample from the region of interest, the regression equation can be applied to other areas where covariate values are measured similarly.

The regression equations for each model that would be estimated in the GIS were determined from the beta values provided in the SPSS output. Each equation includes a constant plus the significant independent variables and their coefficients that explain the variation in snow depth or SWE.

5.8 Using the Map Calculator

The *Map Calculator* available within *Arcview* was used to estimate snow surfaces based on the regression equations. This is an excellent feature of the software as equations can be directly entered into a dialogue box (Figure 25).

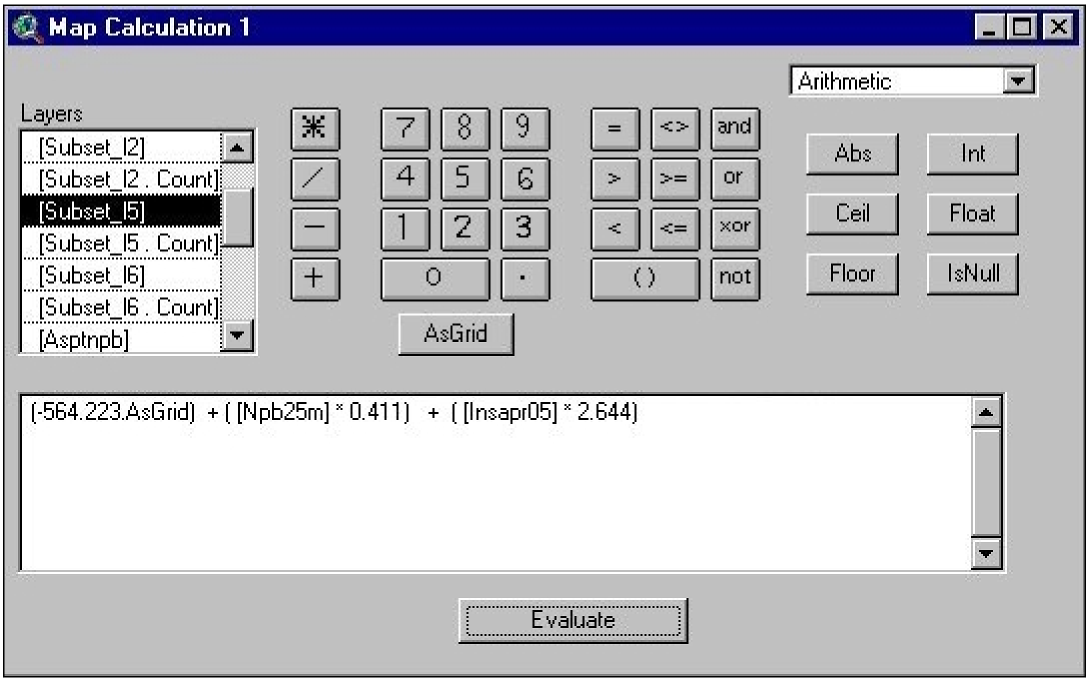

Figure 25: Map Calculator Dialogue Box

CHAPTER 6: REGRESSION MODEL RESULTS

6.1 Introduction

The intention of the models in this research is to estimate a continuous surface (where snow is present) from discrete data points. Distributed snow model research that incorporates landcover, topographic, and solar parameters has become increasingly popular in the last 5 years (Balk et al., 1999; Anderton et al., 1998; Elder et al., 1998; Forsythe, 1995).

Blöschl and Elder (1998) state that scaling problems arise in snow hydrology because measurements never capture all the detail of the natural variability and because model scales are generally different from measurement scales. A coarser grid cell size could result in a loss of primary data and the introduction of gross errors in the modelling results (Goonetilleke and Jenkins, 1996).

Some researchers have studied the relationship between snow accumulation and topographic and forest variables using multivariate statistics. Multiple regression research results from Forsythe (1995) and Golding (1972) indicate top explained variation regression results of approximately 64% and 58% respectively. The figure of 60% explained variation is used in this research as a delimiter between a very successful and a somewhat less successful model.

6.2 Monthly Results

February, the month of maximum snowpack at lower elevations (up to 1500m (asl) in the BNP) had 58.8% (10 out of 17) of the snow depth and SWE regressions with an explained variation of 60% or greater. This was despite the influence of poor snow winters that were included over the six-year study period. Four out of four or 100% of the snow depth regressions had explained variation values ranging from 66.7% to 80.3% during the good snow winter of 1991/92. The numbers for SWE were 62.2% to 74.8%.

January had 57.9% (11 of 19) of the regressions with explained variation values of 60% or greater for both snow depth and SWE. March had only 35% (7 of 20) of the regressions with explained variation of 60% or greater. April had 36.4% (8 of 22) and 31.8% (7 of 22) for snow depth and SWE respectively with over 60% explained variation. The variables that were the best regressors from month to month are summarized in Table 6.

Table 6: Best Monthly Regression Variables from January to April

//////////////////	January	February	March	April
Snow Depth	Elevation, Slope Gradient, Principal Component Two (PCA2), TM Band 4	Elevation, Slope Gradient	Elevation, TM Band 5, TM Band 7, Insolation	Elevation, Insolation, Slope Gradient, Profile Curvature
SWE	Elevation, Insolation, TM Band 5, PCA3, TM Band 4	Elevation, Slope Gradient, TM Band 2, TM Band 5	Elevation, Insolation, TM Band 5	Elevation, Insolation, PCA2, Profile Curvature

6.3 Weekly Results

The weekly regression model results are presented in Figures 26 to 37.

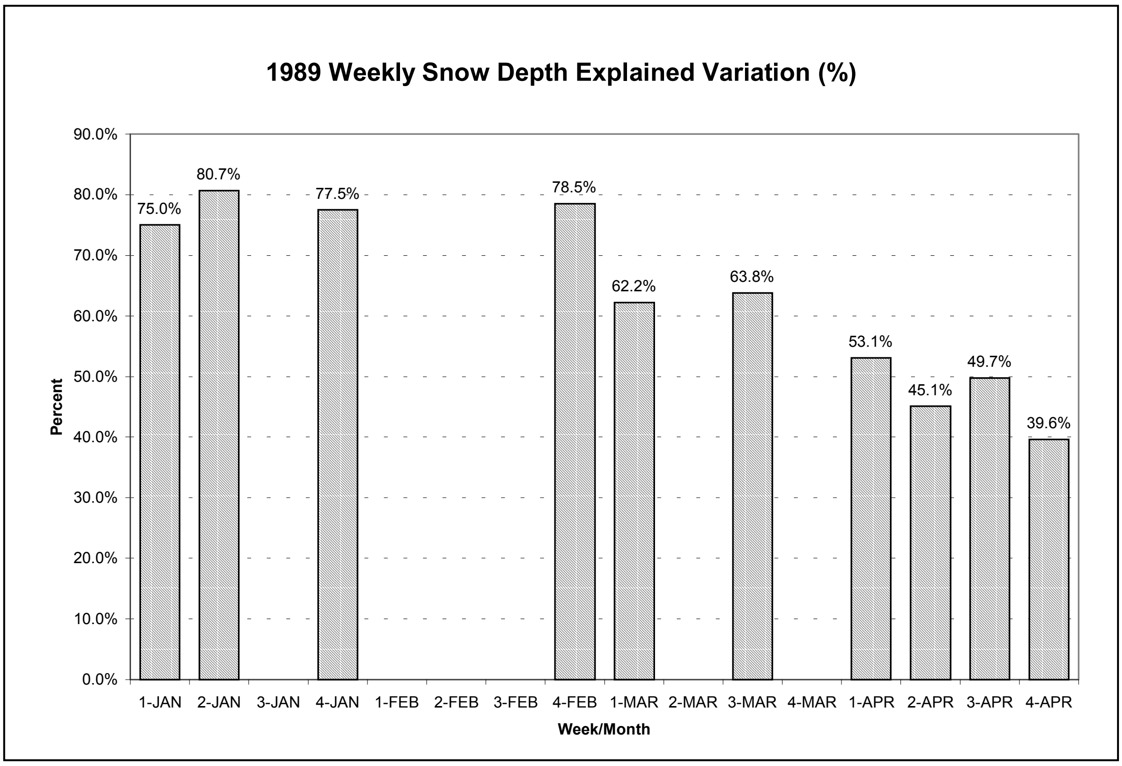

Figure 26: 1989 Snow Depth Model Results

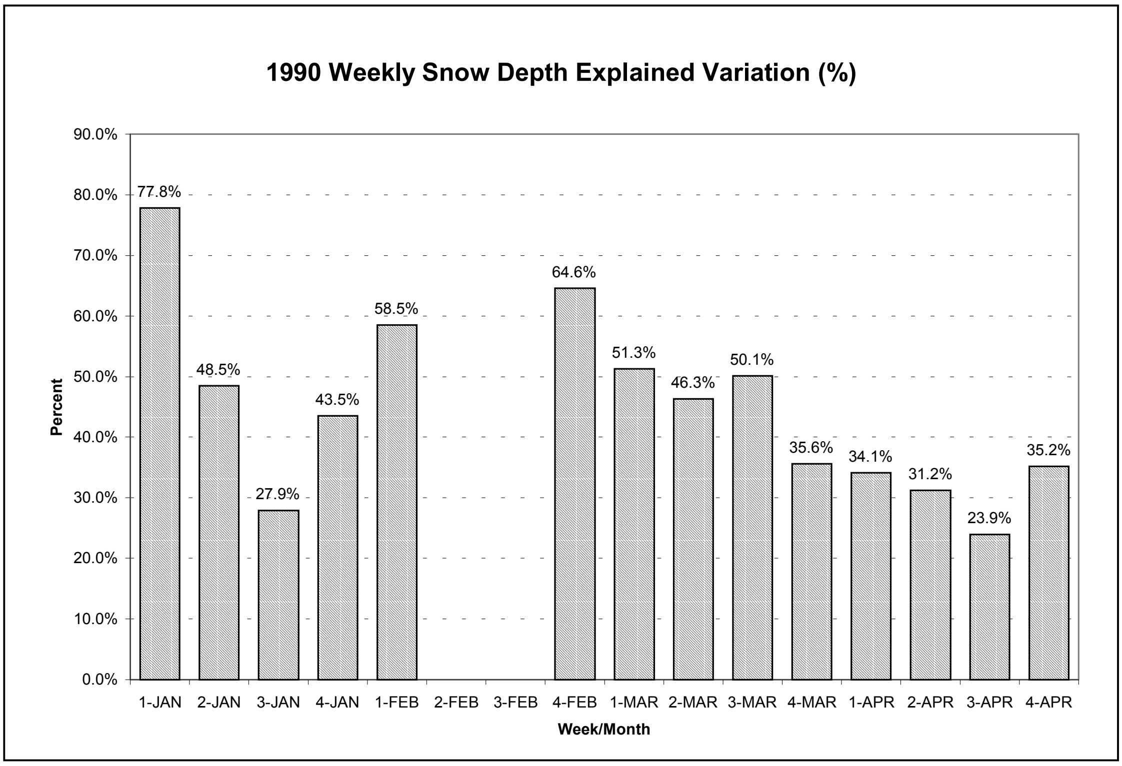

Figure 27: 1990 Snow Depth Model Results

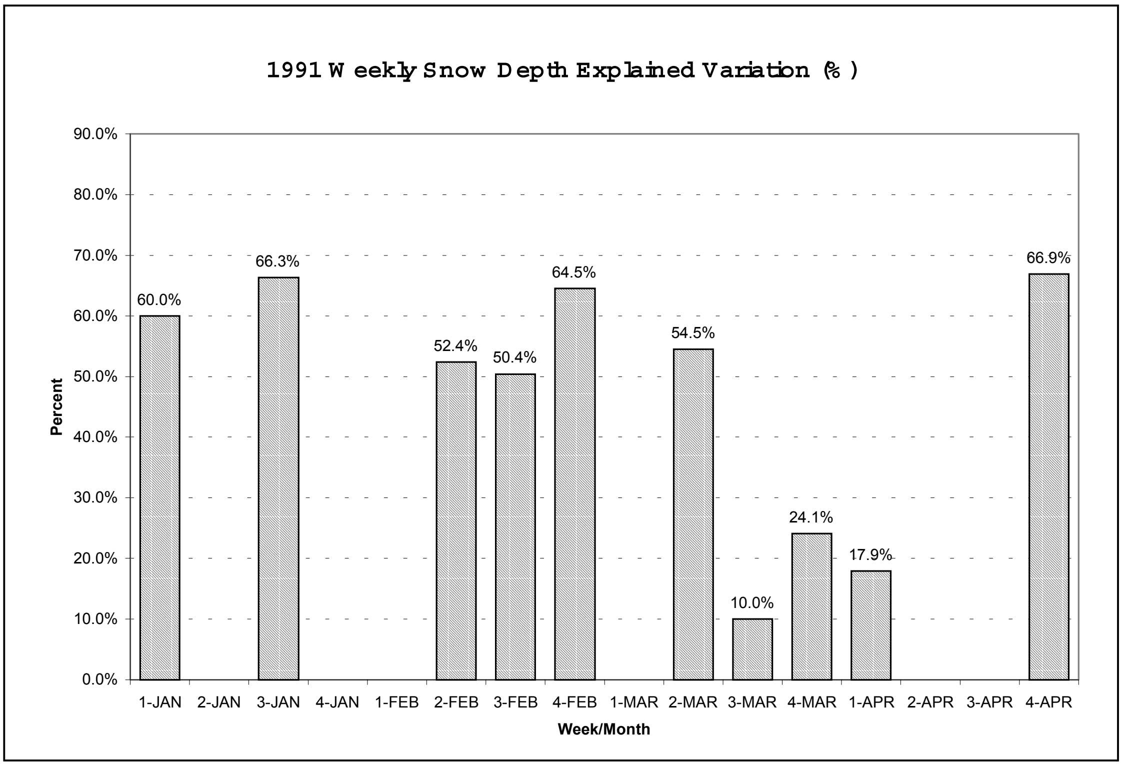

Figure 28: 1991 Snow Depth Model Results

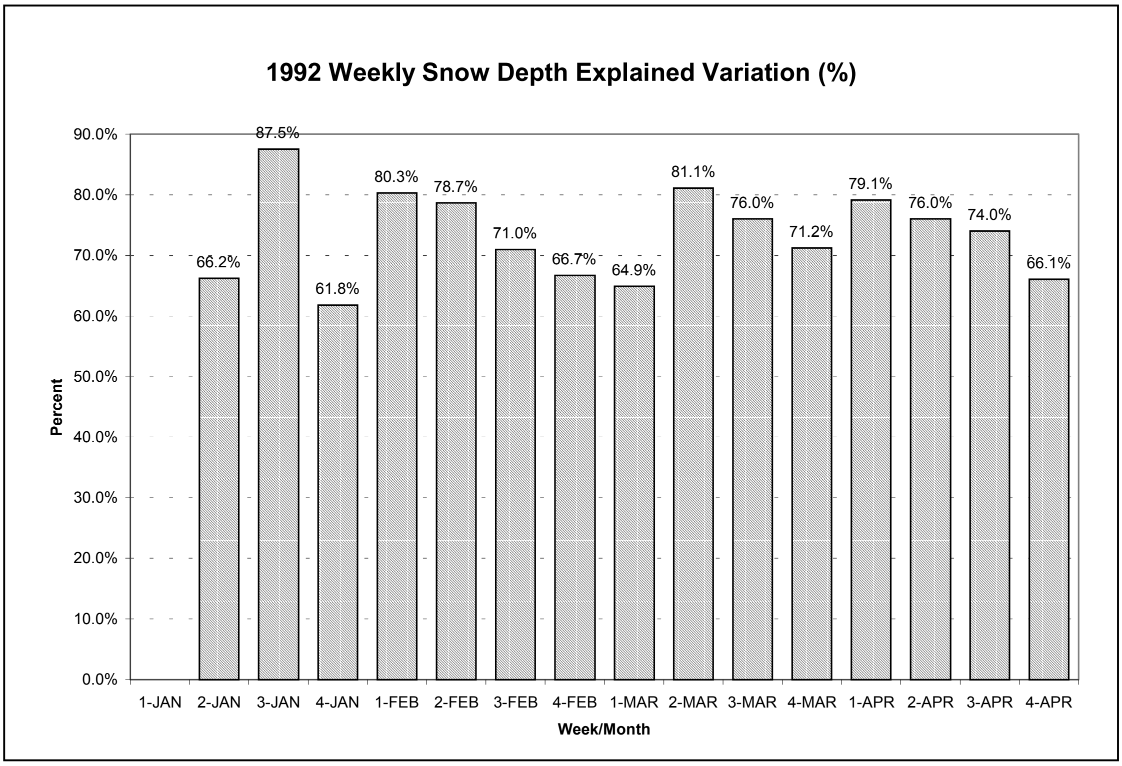

Figure 29: 1992 Snow Depth Model Results

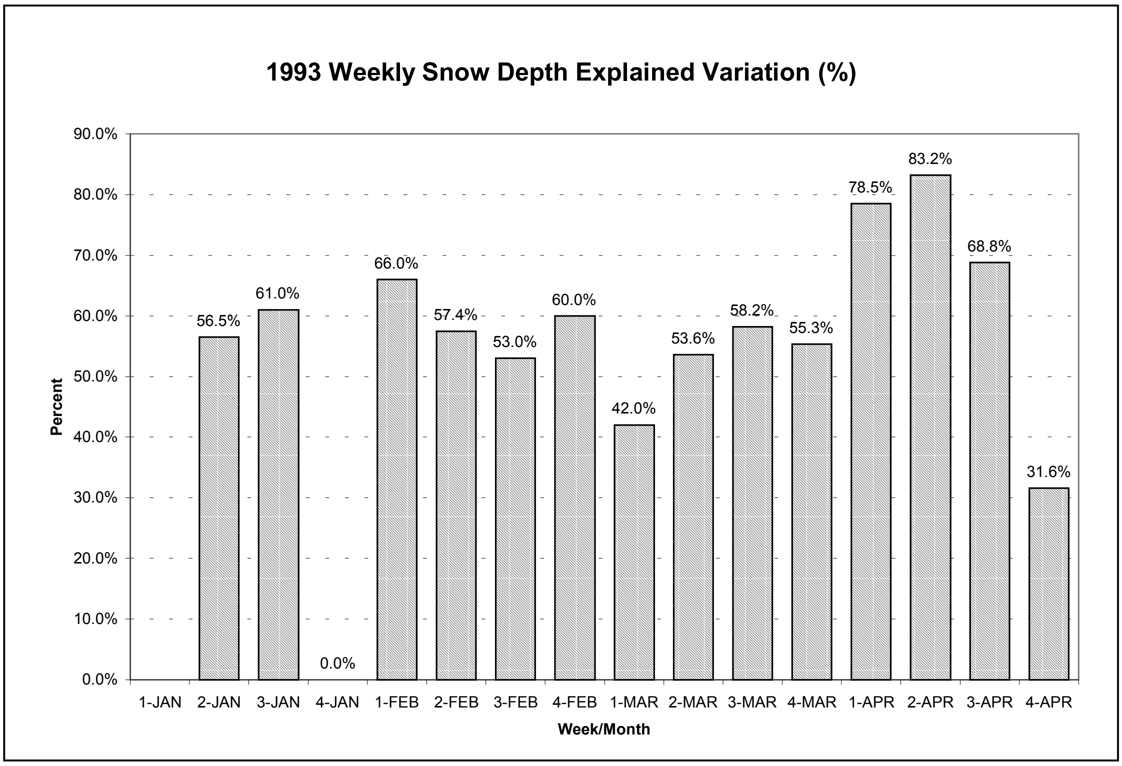

Figure 30: 1993 Snow Depth Model Results

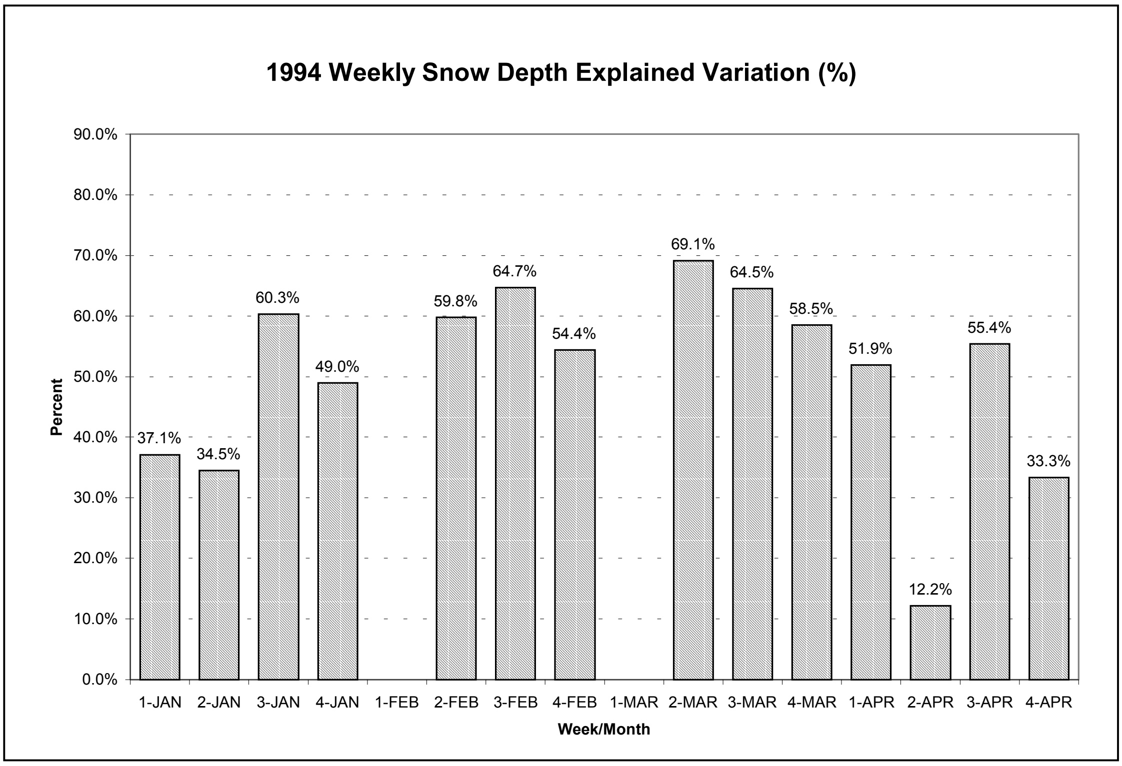

Figure 31: 1994 Snow Depth Model Results

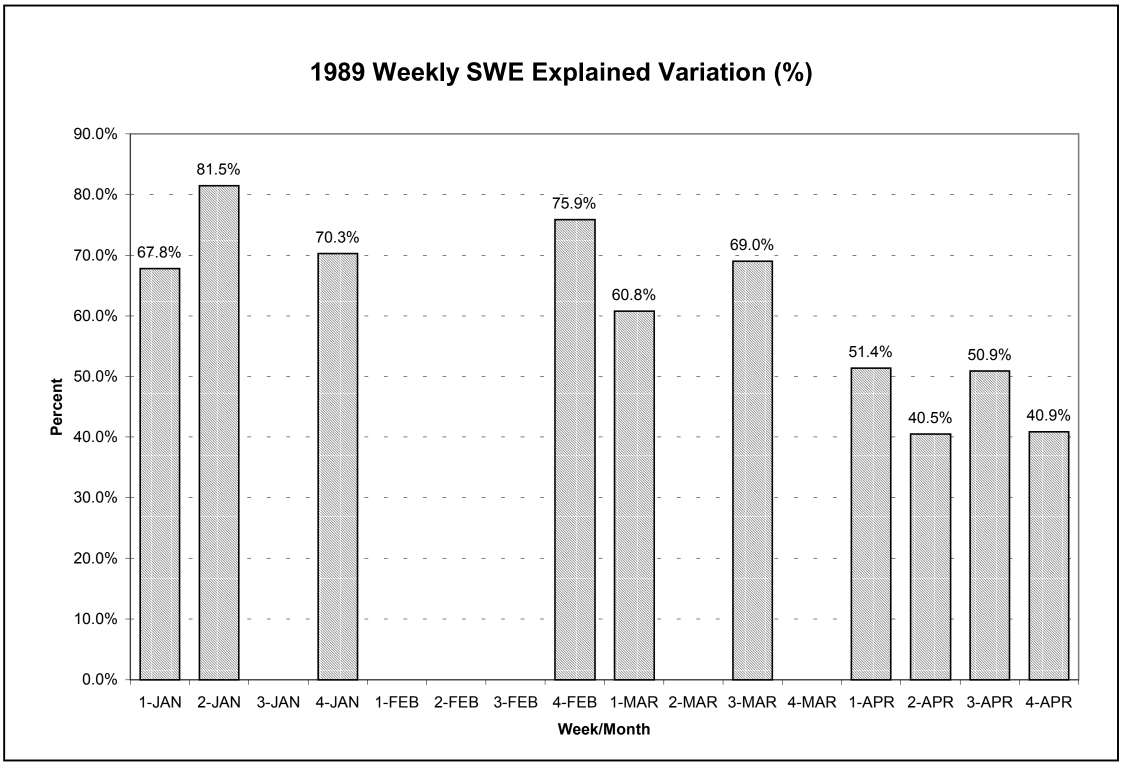

Figure 32: 1989 SWE Model Results

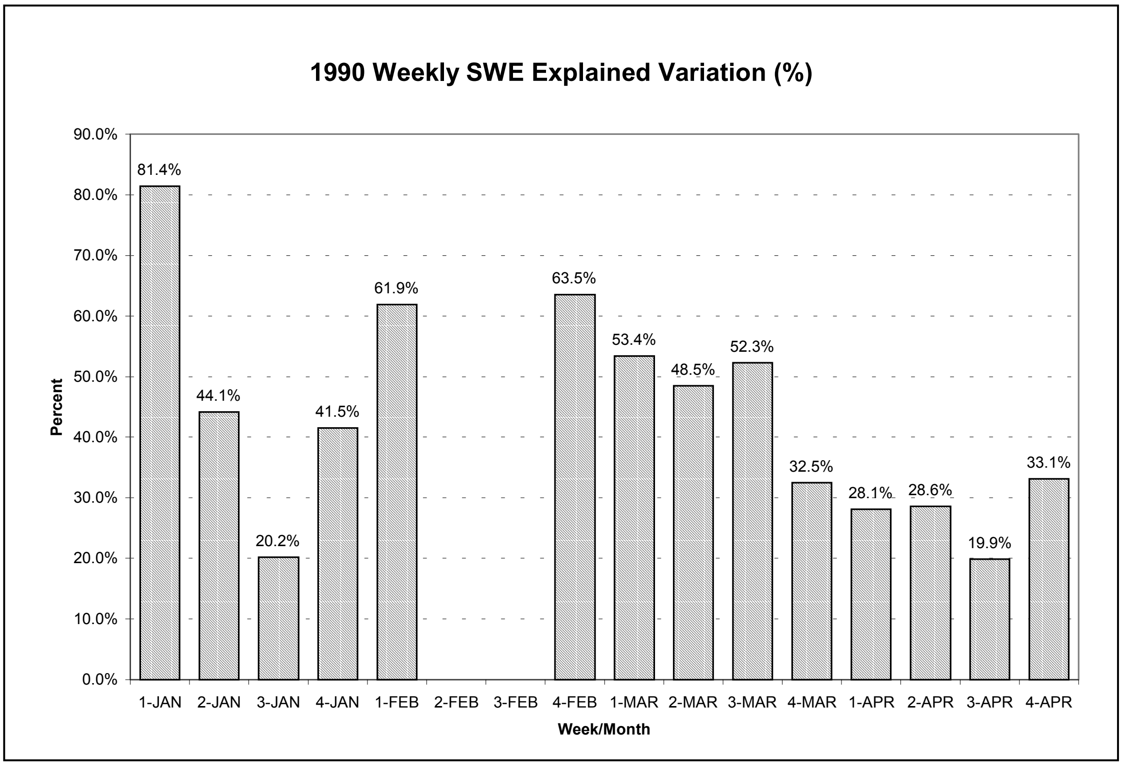

Figure 33: 1990 SWE Model Results

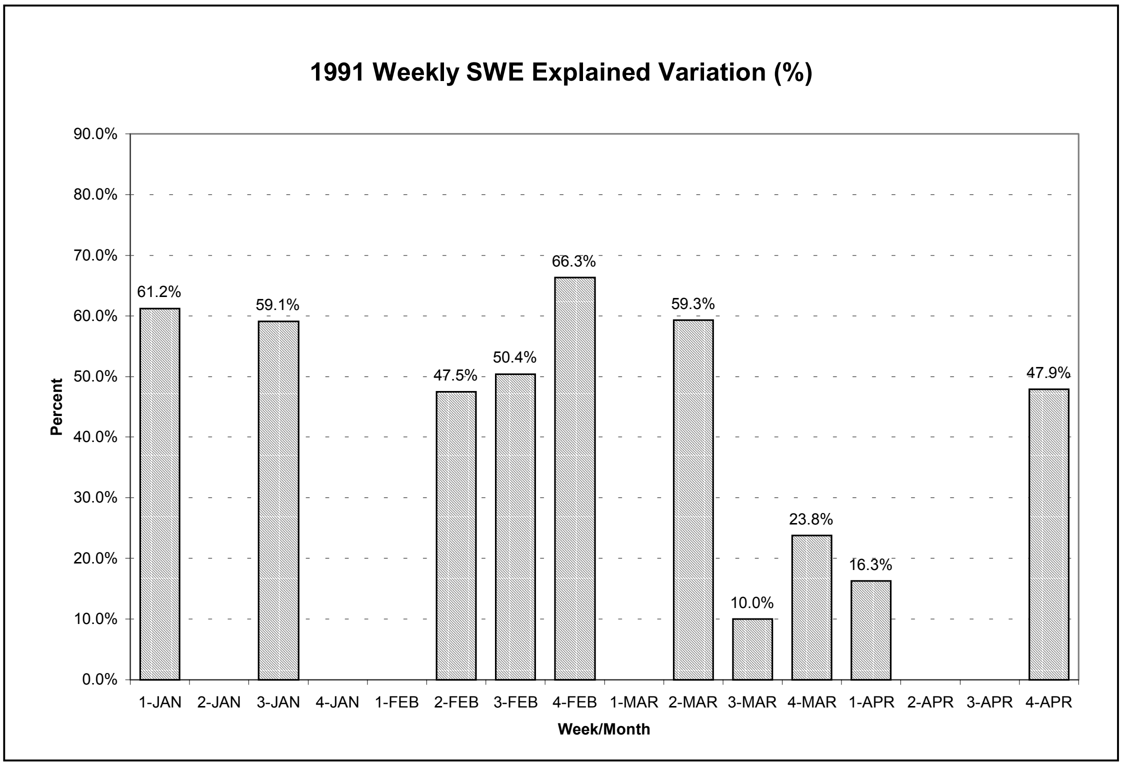

Figure 34: 1991 SWE Model Results

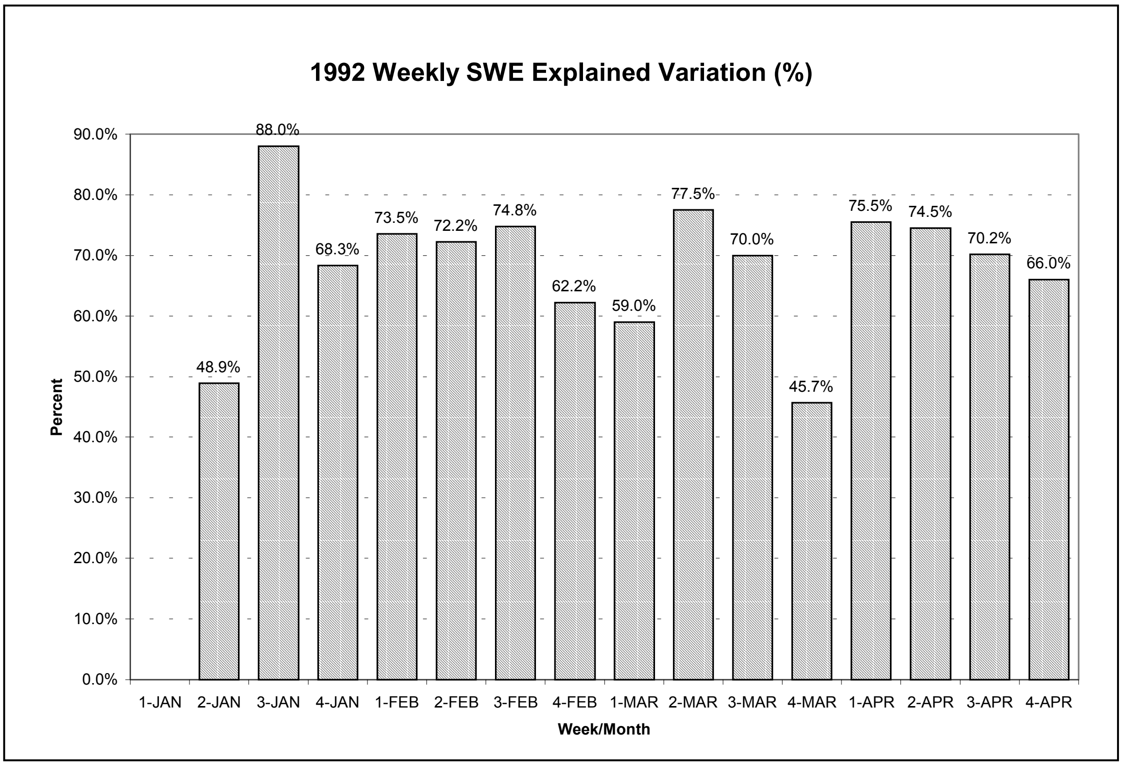

Figure 35: 1992 SWE Model Results

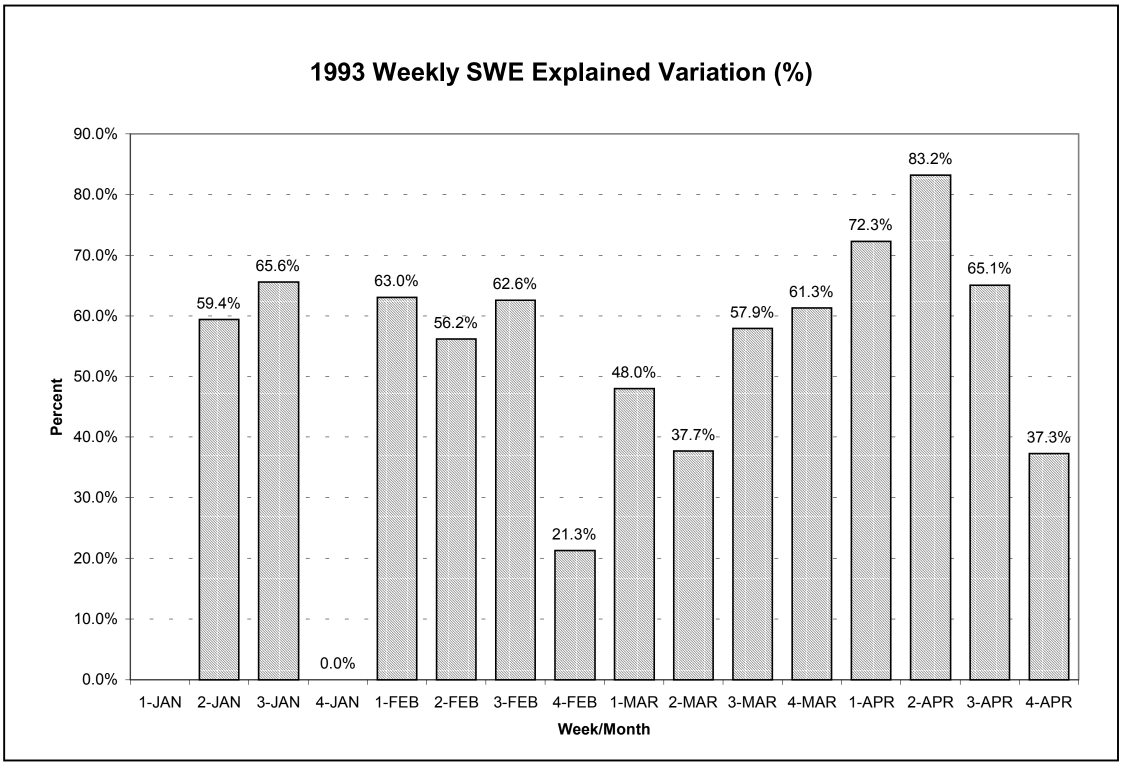

Figure 36: 1993 SWE Model Results

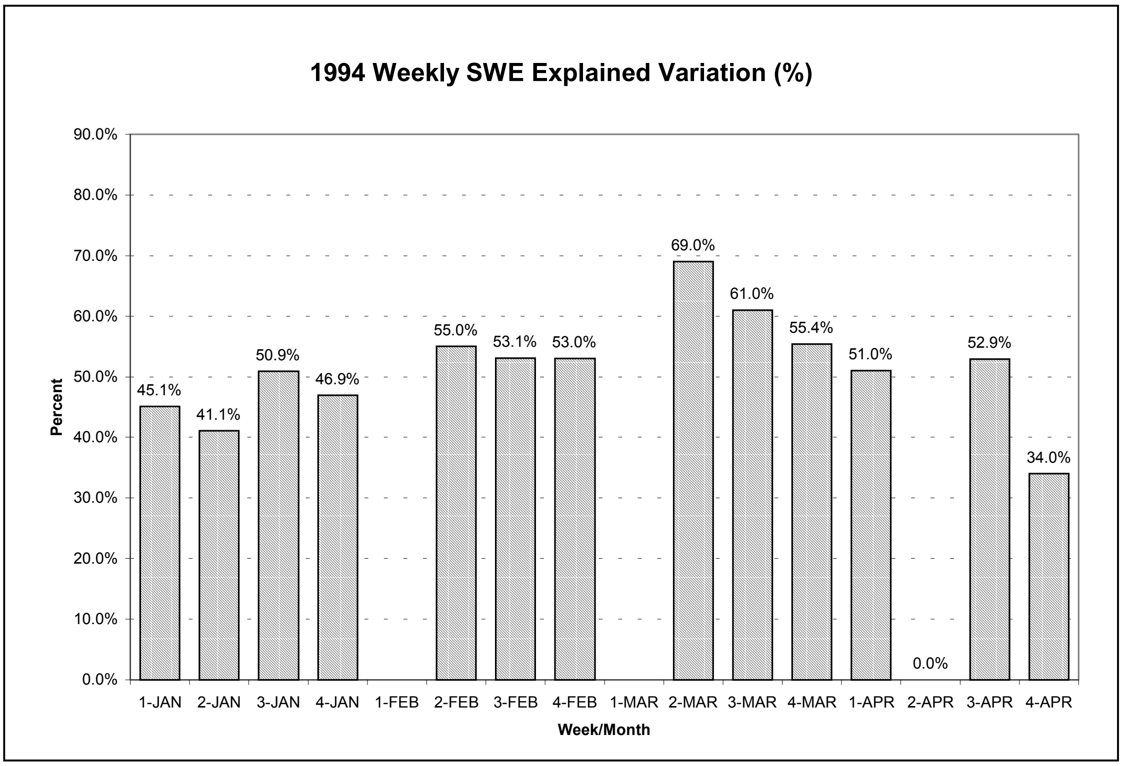

Figure 37: 1994 SWE Model Results

6.4 Map Output

Elston et al. (1997) observe that regression equations between a response variable and candidate explanatory variables are often estimated using a training set of data from closely observed locations but are then applied using covariate data held in a GIS to predict the response variable at locations throughout a region. This is the procedure that was used in this research. Result maps for some of the best regression models (in terms of explained variation) for snow depth are presented in Figures 38 and 39. Other excellent snow depth estimation maps can be seen in Appendix A. The SWE result maps are presented in Figures 40 and 41 and Appendix B. In all of the model result maps, the snow points are overlaid for reference to the original analysis data. Grey regions represent areas that were not estimated due to a lack of data.

Ablation patterns have been shown to be about the same from year to year by a number of authors. It is possible to see some similarities between the snow maps that were produced which is not too surprising due to the fact that the explanatory variables are quite similar in each estimation model. While snow conditions vary from year to year, the factors that influence the distribution appear to be quite similar. A typical snow or snow-depletion pattern may be

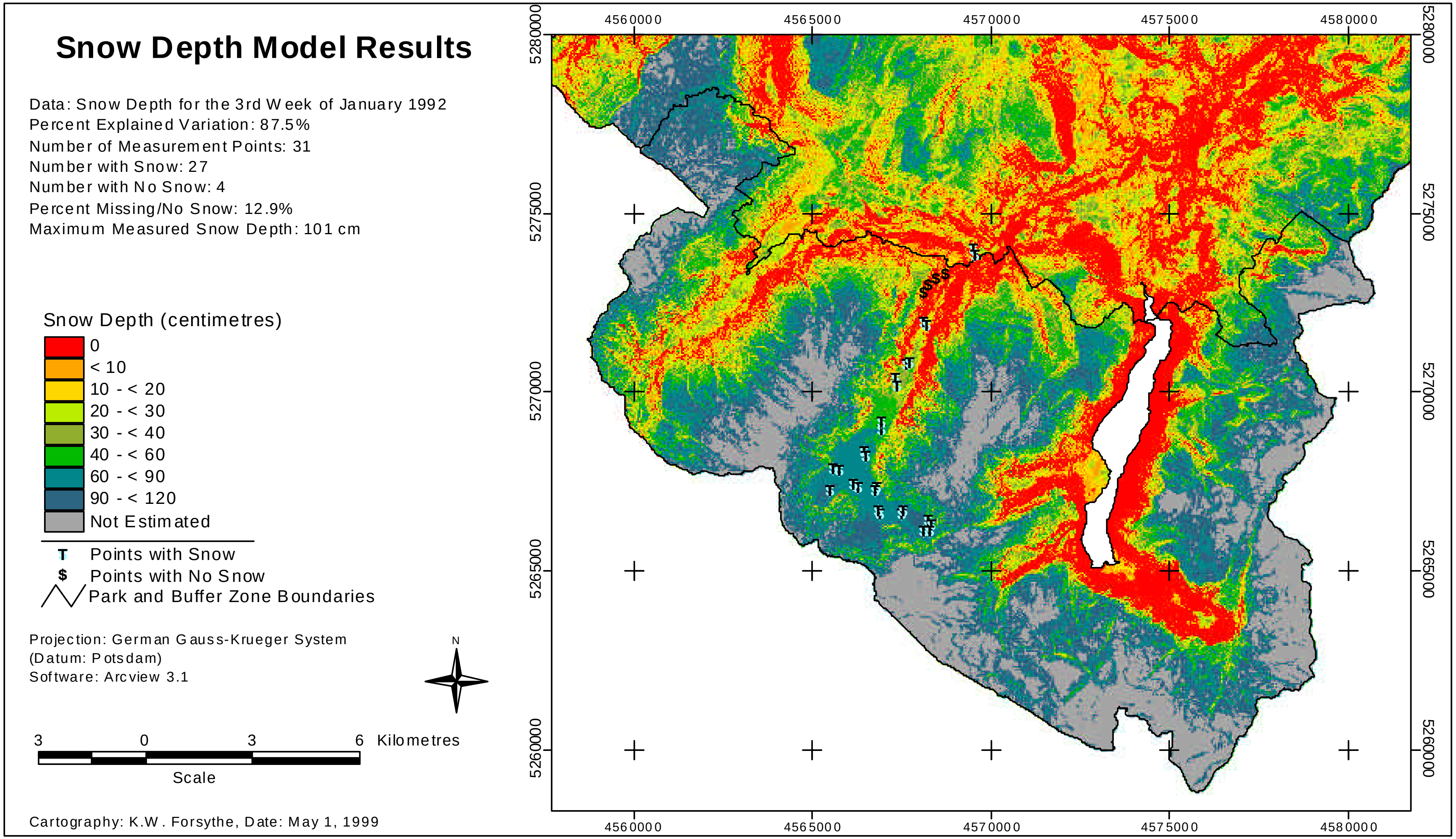

Figure 38: Snow Depth Model Results - 3rd Week of January 1992

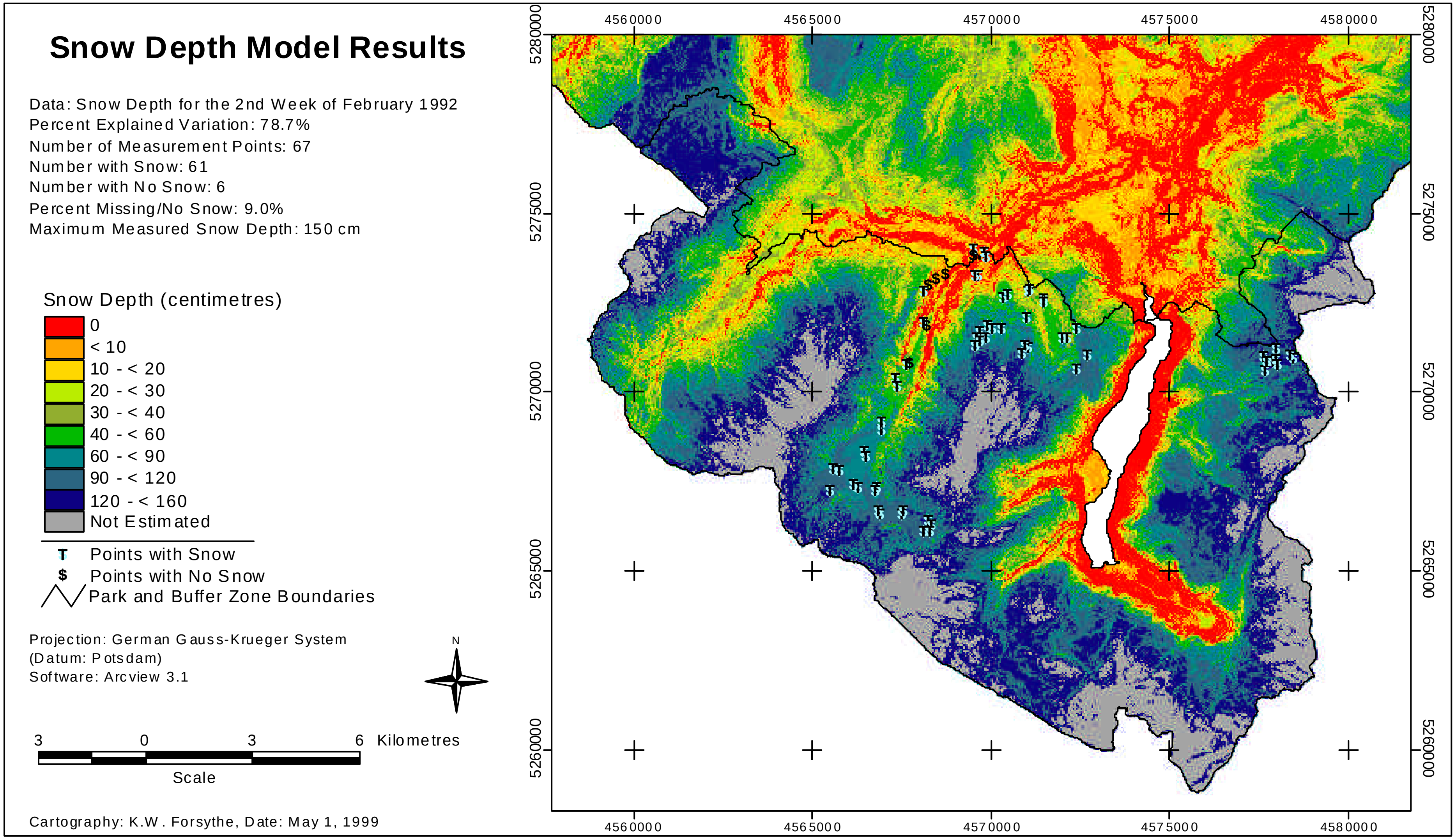

Figure 39: Snow Depth Model Results - 2nd Week of February 1992

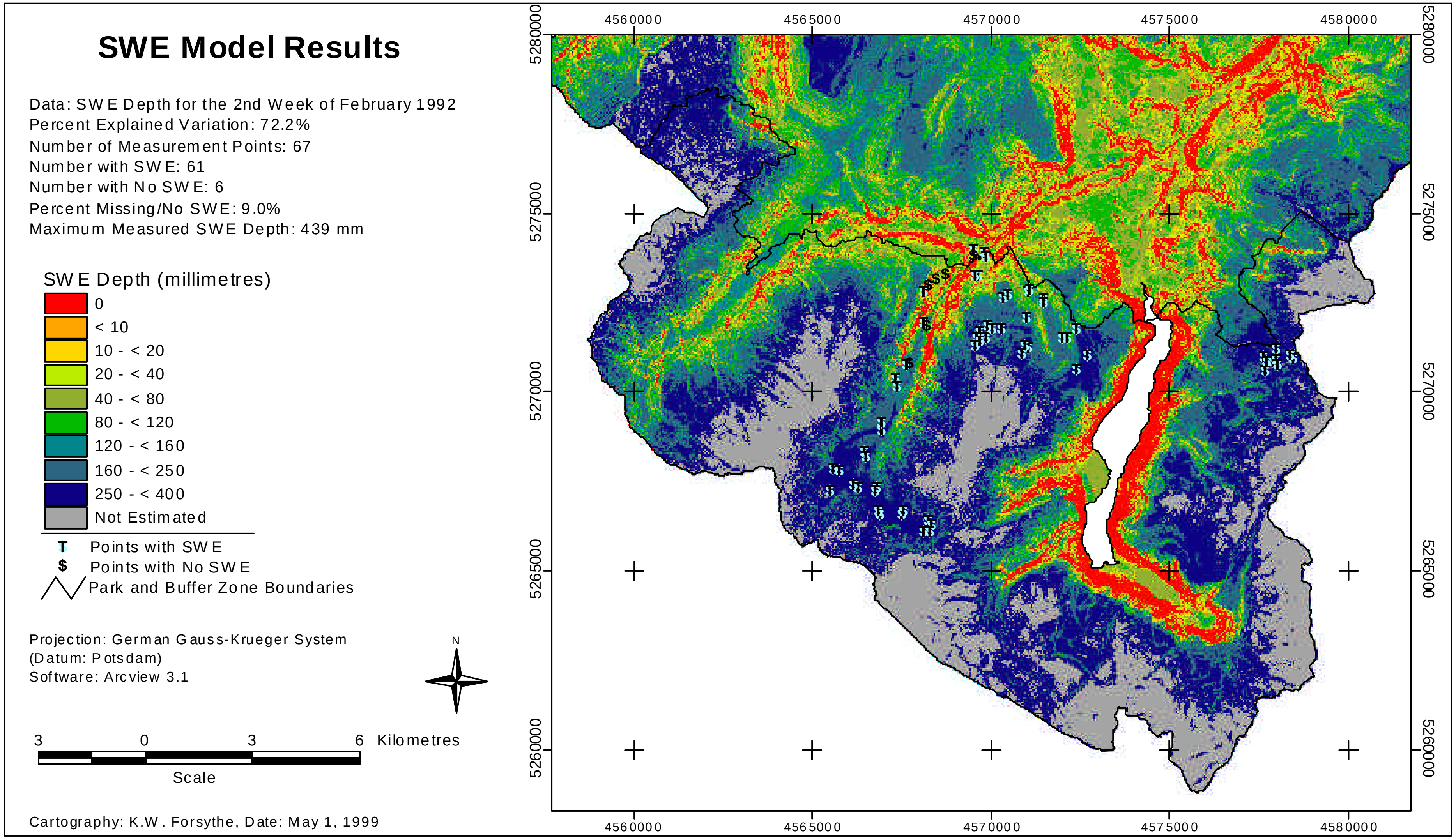

Figure 40: SWE Model Results - 2nd Week of February 1992

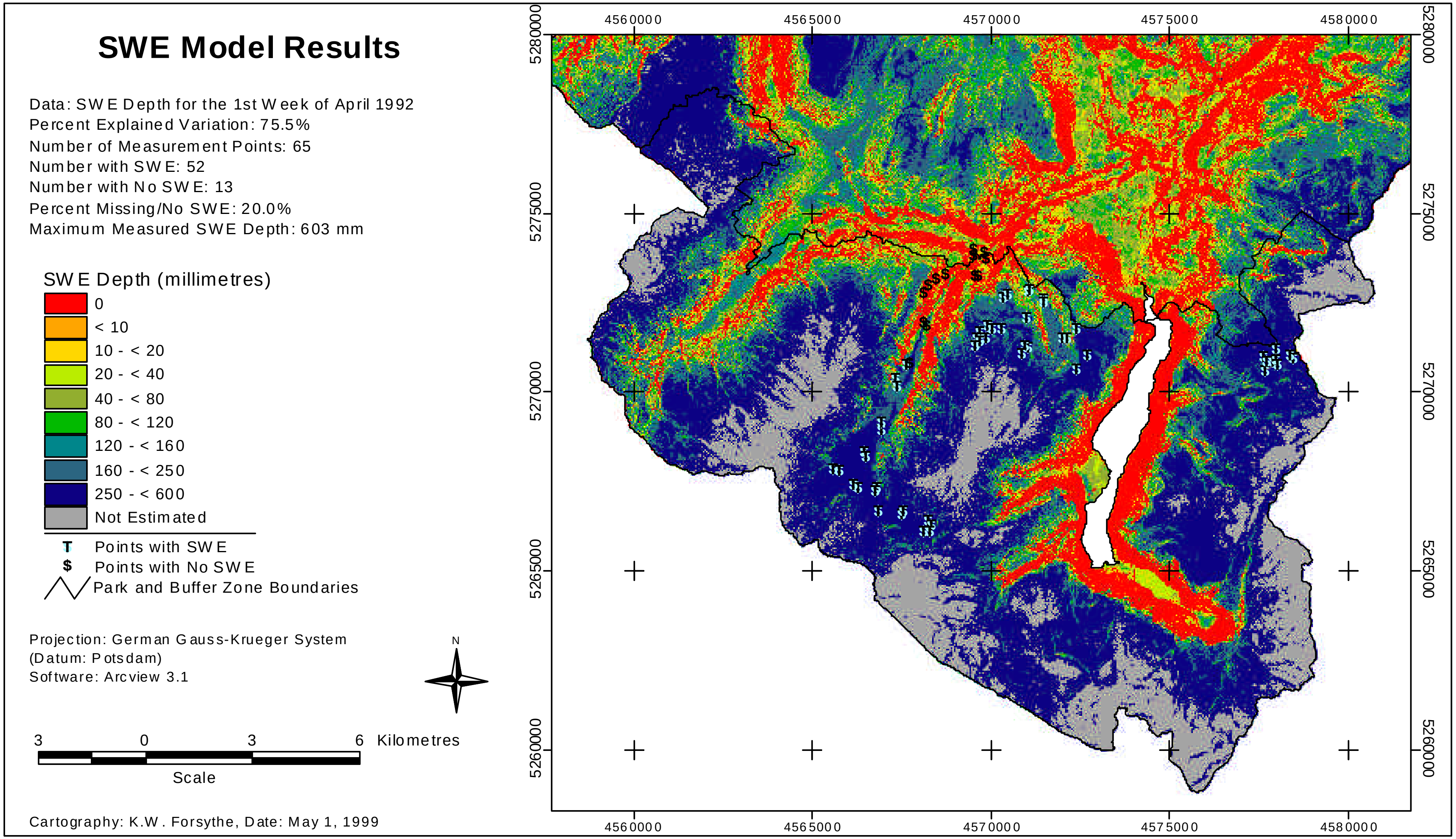

Figure 41: SWE Model Results - 1st Week of April 1992

visible for weeks in one year but for only days, or less, in another (Kölbel-Deicke and Heuberger, 1987).

6.5 Investigation of the Results

The model results can be broken down into the accumulation and ablation seasons. Regression results were the best for the month of February, which is the normal month of maximum snowpack at lower elevations in the BNP. While January does not have a maximum, temperatures are generally cold enough to preserve whatever snow is on the ground and prevent melting of new snow that may fall. There can however be problems in the BNP during poor snow winters as rainfall, foehn winds, and solar radiation can combine to completely melt the snowpack at elevations below 1300m (Rau, 1993).

March and April results were not especially good due to the changes in snowcover that occur during this time period. March is the month of maximum snowpack at higher elevations in the National Park but it is also the time of substantial snowmelt in lower reaches of the area. Figures 40 and 41 help to illustrate this. In February (Figure 40), there is a fairly consistent snowcover throughout the area (even at lower elevations). By April (Figure 41), there are larger snowfree areas at generally lower elevations and areas that are higher in elevation have increased values of SWE.

In many cases of less than satisfactory regression results, there were a large percentage of snow measurement points that were snowfree. As many as 83% of the data points in these regressions had measured snow values of zero. Appendix C provides some example maps showing the location of snow survey points and the total number of points with no snow. It is easy to imagine why regression models based on these data would not be very successful.

Elevation was (as expected) the variable that explained the most variation in snow depth and SWE in the models. It was followed in significance by slope gradient, insolation, principal component two (PCA2), and TM bands four and five. The dominance of the topographic and topographically derived variables was expected, but the fact that variables generated from TM imagery are also significant indicates that landcover influences the distribution of snow as well. PCA components and the TM bands are good regressors throughout the January to April period.

Plan and profile curvatures did not have a large effect on the regression results until the March-April period. This can be attributed to the fact that as snowpacks build up over the accumulated season, the underlying topography has less of an influence. However, in the spring melt season, the concave areas in the landscape will have more snow simply because it collects there naturally and it is less exposed to wind and radiation influences.

The BNP is an area with a highly variable temperature regime. Melt processes can be very significant during the entire winter season. Redistribution of dry snow by wind can also be a factor. The role of avalanches in snow redistribution was not considered here, as the collection of calibration data in these areas is quite dangerous.

Two things that must be remembered are that early in the snow season the amount of snow that falls at different elevations may be the same, but lower down the snow is subject to more chances of melting. Also rain may be falling at lower elevations while higher up the precipitation falls as snow. The Environmental Temperature Lapse Rate (ETLR) of 0.6°C per 100m elevation change plays an important role here as variations in terrain, landcover, and climatic factors can combine so that this rate (while not literally changing) will not hold true, especially on cloud free days.

Another factor to consider is the local nature of some snowfall events. It can be snowing quite heavily in one area but yet one kilometre away, it will not be snowing at all. This can be attributed to local convective effects that occur given suitable meteorological and terrain situations.

6.5.1 Comparison of Mapped Estimates

A comparison of sets of mapped snow estimates would be entirely feasible if the same data points had been used for each snow survey. This was not the case however so visually comparing the results (as explained above) remains an alternative. A quantitative assessment of the differences with respect to changes over time and using different independent variables is hindered by the limits of the empirical snow data used for the models. For each regression, there are different minimum and maximum snow values beyond which it is difficult to extrapolate because there are no available reference data. Arbitrary limits within the empirical datasets of two (or more) model results could be chosen to compare values from successive regressions but the modelled map estimates cannot be analyzed completely.

CHAPTER 7: DISCUSSION AND CONCLUSION

7.1 Introduction

This research integrated variables determined from DEM data, satellite imagery, solar insolation models, and snow data for use in GIS-based distributed snow models. Stepwise multiple regression was the technique used to estimate parameters for the snow depth and SWE distribution models.

It is hoped that the modelling procedures developed here will be a further extension of previous work and lead to new opportunities. Baumgartner and Rango (1995) state that the net effect of future climate change (temperature, precipitation, radiation, clouds) on snowcover variations and on the economy is very complex, and is an important topic for more intensive study. It is also important to note that one third of the water used for irrigation in the world comes from snowpacks (Brooks et al., 1991). Validation of methods to interpolate between snow collection points can therefore be very valuable in assessing the amount of water that is in the snowpack.

The data and computer requirements for this study were enormous. A total of 3.5 gigabytes of data were either obtained or derived from the original data sources. Without the computing power that was available in the DGG, it would not have been possible to complete this research. The work was mostly carried out on a Sun Sparc10 Unix workstation and then later on a Pentium 233 PC with 128 megabytes of RAM.

7.2 Discussion

Whether the 94 snow measurement points used in this study are representative of the basin as a whole can be questioned. Elder et al. (1997) used a sampling network of 709 points that was thought to be representative of the elevations, slopes, and aspects of the their study area. Johnson et al. (1998) describe data difficulties including inconsistent monthly sampling, added and removed stations, and possibly a few moved or otherwise altered snow courses. Of critical importance for the regression analyses in this research is that the same dataset was not used for any of the models. From one week to the next, there were different datasets. The location of the points in each of the models is therefore very important. There may be situations where there are a large number of points, but they may be clustered together. Later in the snow season there is also a greater possibility that many of the measurement points may already be snowfree. The lack of measured snow data at certain points (in some of the analyses) adversely affected the regression results. When these zero or no snow values were left out of the analysis procedures, results in the order of 70% explained variation were achieved.

After a sufficiently deep snowpack has developed, the role of curvature is no longer important in snow accumulation and redistribution processes. This is why the curvature variable was only important in April (after substantial melt had occurred) or when there was below normal snowfall.

The introduction of computers in spatial data handling has introduced a false sense of accuracy due to the use of spatial data at scales larger than that of the original document from which the data were derived (Thapa and Bossler, 1992). GIS have the potential to dramatically increase both the magnitude and importance of errors in spatial databases (Openshaw, 1989). The role that DEM error had on the regression results here is unknown. Kölbel-Deicke and Heuberger (1987) state that sufficiently pronounced morphology within a limited area leads to the development of snow and depletion patterns that occur in specific steps in consecutive years. These patterns also appear in the model results for the BNP. The role of avalanches in snow redistribution has not been considered in this study. This is especially true when one considers the ice chapel ("Eiskapelle") (Wolf, 1998) that is formed by snow being redistributed from higher to lower elevations.

Precipitation provides the basic input for hydrological studies, however it varies greatly in space and time within a range of mountains and also from one mountain range to another (Singh et al., 1995). Hydrological processes cannot be properly represented until the distribution of precipitation is known. Many snow variables might be obtainable from remote sensing but operational hydrological models have really only been developed for snow cover and also for SWE but in fairly level terrain. Some models are also very satellite data intensive, which can lead to higher costs depending on the size of the study area and the detail required in the data.

In deep mountain snowpacks, the active microwave spectral region may allow for direct estimation of water equivalence, but the presence of liquid water in the snow causes problems because water and ice have such different dielectric properties (Dozier, 1998). Topography also complicates the measurement because the signal is sensitive to incidence angle (Dozier, 1998). Seidel (1996) suggests a method of interpolating snowcover based on Elevation-Aspect-Slope (EAS) classes.

7.2.1 Integrating the Models with Existing Snowmelt and Runoff Models

Determining the initial SWE values in a basin is one of the biggest problems with a large number of snowmelt-runoff models. The usefulness of the models developed here which estimate the spatial distribution of SWE will be if they can be integrated into runoff models such as the SRM.

Many presently utilized snowpack runoff models require estimates of areal SWE. Remotely sensed data are used in a lot of the models to derive snow covered area and from this SWE is derived. Some of the methods used function quite adequately when climatic conditions are normal. Extreme rainfall on snow events or a lack of snowcover have adverse effects on the ability of researchers to accurately estimate SWE. The methods presented here can definitely support model functionality. They are not dependent on optical satellite data collected in the winter which is sometimes not obtainable due to cloud cover and other factors.

7.3 Conclusion

Overall, the applied methodology and techniques produced some quite satisfactory results for distributed snow modelling using multiple regression techniques. Multiple data sources were used successfully to derive important variables for input into the estimation models. In the months of January and February (independent of the type of snow winter it was), explained variation results were consistently better than 60%. In good snow winters with a deep and well distributed snowpack, regression results in the order of 88% explained variation were obtained for snow depth and SWE. The best snow depth regression model for January-February had an adjusted R^2 of 0.875 while the snow-water equivalent model had an adjusted R^2 of 0.880. Elevation, slope gradient, and TM band 4 were the independent regressors in both cases. The best March-April result was an adjusted R^2 of 0.832 for snow depth and SWE. The best overall regressor in every case was elevation. For snow depth, slope gradient and principal component two were very good regressors for the January-February period and solar insolation and TM band variables for the March-April period. Snow-water equivalent had solar insolation and TM variables for the January-February period and solar insolation and principal component two for the March-April period. For both snow depth and SWE, profile curvature was a good regressor but only during April which is well into the melt season.

The success and quality of these models is dependent on the available calibration data. In snow poor winters such as 1990-91 and 1993-94, the results are not as good as years where there was a normal snow winter or a snow rich winter. The regression results are generally 20 to 25 percent poorer. These estimation models are based on the concept that results in one area can be applied to other areas with similar topographic and climatic conditions. It is however unknown whether the models developed in the Berchtesgaden National Park can be applied to other areas. Using a GIS-based approach allowed for the model results to be applied in areas where there are similar conditions to the existing ones where the snow points are located.

Better results may have been obtainable with a more widely distributed snow point measurement network that encompassed all aspect, slope, and elevation zones within the Park and that had a greater number of total observations. Ambrosi (1996) states that data availability sometimes limits the project in terms of applying the optimum methodology. Integration of winter snow images, whether acquired from satellite or aerial photography would help in determing the exact snowline boundaries and snow free areas which could be used as masks within the GIS model procedures. The results indicate that when there is a fairly complete snow cover in the study area, good results can be obtained with the model inputs and techniques used in this research.

The 1991/92 winter was the best example of this where snowfall and temperatures combined for a fairly long snowcover period. In poor snow winters where temperatures are too warm for consistent snow cover at lower elevations, it may be better to utilize tree regression techniques to model the snowpack. This way it will be possible to have regression models for areas with snow while snow free areas would not be modelled.

Whether there would have been improved model results if techniques for topographic effects compensation were used is unknown. According to Banko (1997), optimal topographic correction accounts for:

* the geometry of the image (including sun position, landform parameters, and sensor characteristics), and
* the atmospheric parameters at the time of image acquisition (including reflection characteristics of the surface objects),

however models that consider all of these factors do not exist.

7.4 Suggestions for Further Research

This dissertation research brings together elements that are now used regularly in today's Geography. It relies on techniques from GIS and statistical modelling. Digital data sources were integrated with collected snow measurement data to form the basis for the analyses.

A sure sign of data multicollinearity was that the vegetation indices were interchangeable in the preliminary regression analyses. When one that was significant was excluded, another replaced it. Finding out what variables are closely correlated with each other so they can be excluded before regression procedures may be helpful.

A spatially-distributed radiation model (SRAD) was recently developed by McKenney et al. (1999). It generates estimates of incident, outgoing, and net irradiance, as well as surface and air temperatures for each point in the DEM. This is possible as it incorporates monthly atmospheric parameters including cloudiness. This type of radiation model can only serve to improve model estimation accuracy. When cloud cover can be integrated, this has great influence in determining the melt regime in snowpacks.

Hydrological models are either predictive or investigative and the development of both types of model has traditionally followed a set pattern involving the following steps:

* collecting and analyzing data,
* developing a conceptual model (in the researcher's mind) which describes the important hydrological characteristics of a catchment,
* translating the conceptual model into a mathematical model,
* calibrating the mathematical model to fit a part of the empirical data by

adjusting various coefficients, and

✳ validating the model against the remaining empirical data set (Blöschl and Sivapalan, 1995).

The model results obtained in this study now need to be applied in other areas where it is possible to test the regression model results against measured values. Adjacent areas in Austria for which snow data are available offer an immediate test area. This will allow for two things to occur: validation of the model parameters and estimation of the potential snowpack water content over a larger area. The time required to obtain the necessary snow data is the controlling factor of when and not if this occurs.

Squares and cross-products of independent variables were used to account for some of the non-linearity in the atmospheric circulation data (McGinnis, 1997). Terrain position (e.g., ridge, mid-slope, valley) is a potentially useful variable with which to model environmental parameters and processes using geographical information systems (Skidmore, 1990). These techniques and variables have been used in snow modelling procedures in the past and perhaps their integration could provide an increase in model efficiency. It would also be advantageous to obtain satellite data during the different times of the snow accumulation and ablation seasons to see how the boundaries of the model results compare with the actual physical conditions.

Process-based distributed snow models have the advantage that they can represent nonlinear snow processes, and that process controls such as solar radiation and terrain effects can be accounted for (Blöschl and Elder, 1998). The modelling techniques developed here can help to bridge the knowledge gap for models with uncertainties in forested areas due to forest canopy type and density. They provide estimates based on topographic, landcover and climatic/environmental factors for all areas of a basin where the original snow data were collected.

REFERENCES

NOTE: All WWW - URL links are current as of April 1999.

ALBERT, M. AND G. KRAJESKI. 1997. **A New Point Snow Melt Model for Use in Distributed Applications**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

ALEXANDER, S., C. CALLAGHAN, P.C. PAQUET, AND N.M. WATERS. 1996. **GIS Prediction Models for Habitat Use by Wolves (Canis lupus)**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

ALLERUP, P., H. MADSEN, AND F. VEJEN. 1997. **A Comprehensive Model for Correcting Point Precipitation**. *Nordic Hydrology*, Vol. 28, pp. 1-20.

AMBROSI, G. 1996. **The Use of a GIS in a Regional Geomorphic Landscape Assessment**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

ANDERSON, D. 1996. **Snow Stats - GIS and Snow Monitoring at the National Weather Service**. *GIS World*, May 1996.

ANDERSON, E.A. 1973. **National Weather Service river forecast system - snow accumulation and ablation model**. NOAA Tech. Memo. NWS HYDRO-17. US Department of Commerce. Silver Spring, Maryland.

ANDERTON, S., B. ALVERA, AND S. WHITE. 1998. **Terrain Characteristics and Snow Cover Variability in Mountain Areas: An Example from the Spanish Pyrenees**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

ANTCZAKV, J. 1999. **Commercial high-resolution satellite vanishes after launch**. Associated Press, Cable News Network. http://cnn.com/TECH/space/9904/28/AM-SatelliteLaunch.ap/

ASCHENBRENNER, J. 1992. **Orthophoto und Monoplotting in der Gletscherkartographie: Die Herstellung von Kartengrundlagen für die Hochgebirgsforschung am Bespiel des Stubacher Sonnblickkees, Hohe Tauern**. Unveröffentlichte Publikation. Institut für Geographie, Universität Salzburg.

ASSOCIATED PRESS (AP). 1999. **No end in sight for worsening drought**. Cable News Network. http://cnn.com/WEATHER/9904/19/worsening.drought.ap/index.html

ATKINSON, P.M. AND R.E.J. KELLY. 1997. **Scaling-up point snow depth data in the U.K. for comparison with SSM/I imagery**. *International Journal of Remote Sensing*, Vol. 18, No. 2, pp. 437-443.

BALK, B. 1998. **Estimating the Spatial Distribution of Snow Water Equivalence in a Mountain Watershed Using Geostatistical Methods**. In Proceedings of the 66th Annual Meeting of the Western Snow Conference. Snowbird, Utah. April 20-23, 1998.

BALK, B., K. ELDER, AND J. BARON. 1999. **Combining Binary Decision Tree and Geostatistical Methods to Estimate Snow Distribution in a Mountain Watershed**. In Proceedings of the 67th Annual Meeting of the Western Snow Conference. South Lake Tahoe, California. April 19-22, 1999.

BANKO, G. 1997. **Waldoptimierte Korrektur von geländebedingten Beleuchtungsunterschieden in Landsat-TM-Daten**. In: Angewandte Geographische Informationsverarbeitung IX. Salzburger Geographische Materialen, Heft 26. Department of Geography, University of Salzburg, Salzburg, Austria. July 2-4, 1997.

BASIST, A. 1997. **Monitoring Snow Melt with the SSM/I Instrument**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

BAUMGARTNER, M.F. AND A. RANGO. 1995. **A Microcomputer-Based Alpine Snow-Cover Analysis System (ASCAS)**. *Photogrammetric Engineering & Remote Sensing,* Vol. 61, No. 12, pp. 1475-1486.

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.

BERNHARD, L. AND R. WEIBEL. 1998. **Modelling Snow Melt Using a Digital Terrain Model and GIS-Based Techniques**. http://www.geo.unizh.ch/gis/dtm/papers/bernhard/bonn/

BERNIER, M., J.-P. FORTIN, Y. GAUTHIER, R. GAUTHIER, R. ROY, AND P. VINCENT. 1999. **Pre-Operational Determination of Snow Water Equivalent (SWE) using RADARSAT Data**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

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

BEVEN, K.J. AND I.D. MOORE, (eds.). 1993. **Advances in Hydrological Processes: Terrain Analysis and Distributed Modelling in Hydrology**. John Wiley & Sons Ltd. Chichester, West Sussex, England.

BLASCHKE, T. 1996. **GIS Techniques and Hybrid Parametric/Non-Parametric Image Classification: A Case Study Showing the Potential for Signature Training and Accuracy Assessment**. In the International Archives of Photogrammetry and Remote Sensing. Vol. XXXI, Part B2, pp. 15-19. Vienna, Austria.

BLASCHKE, T. 1995. **Analyse und Bewertung eines Ökosystems mit GIS Methodische Untersuchungen am Beispiel der bayerischen Salzachauen**. Unveröffentlichte Publikation. Institut für Geographie, Universität Salzburg.

BLÖSCHL, G. 1991. **The Influence of Uncertainty in Air Temperature and Albedo on Snowmelt**. *Nordic Hydrology*, Vol. 22, pp. 95-108.

BLÖSCHL, G. 1990. **Wiener Mitteilungen - Snowmelt Simulation in Rugged Terrain - The Gap Between Point and Catchment Scale Approaches**. Technische Universität Wien, Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft. Band 91 - Wien 1990.

BLÖSCHL, G AND K. ELDER. 1998. **Scaling Problems in Snow Hydrology**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

BLÖSCHL, G. AND R. KIRNBAUER. 1992a. **An Analysis of Snow Cover Patterns in a Small Alpine Catchment**. *Hydrological Processes*, Vol. 6, pp. 99-109.

BLÖSCHL, G. AND M. SIVAPALAN. 1995. **Scale Issues in Hydrological Modelling: A Review**. *Hydrological Processes*. Vol. 9, pp. 251-290.

BLÖSCHL, G. AND R. KIRNBAUER. 1992b. **Flächendetaillierte Modellierung der Schneeschmelze in einem Alpinen Einzugsgebiet**. Tagungspublikation. Internationales Symposion INTERPRAEVENT 1992. Bern, Schweiz. pp. 161-179.

BLÖSCHL, G. AND R. KIRNBAUER. 1991. **Point snowmelt models with different degrees of complexity - internal processes**. *Journal of Hydrology*, Vol. 129, pp. 127-147.

BLÖSCHL, G., R. KIRNBAUER, AND D. GUTKNECHT. 1991a. **Distributed Snowmelt Simulations in an Alpine – Catchment: 1. Model Evaluation on the Basis of Snow Cover Patterns**. *Water Resources Research*, Vol. 27, No. 12, pp. 3171-3179.

BLÖSCHL, G., D. GUTKNECHT, AND R. KIRNBAUER. 1991b. **Distributed Snowmelt Simulations in an Alpine - Catchment: 2. Parameter Study and Model Predictions**. *Water Resources Research*, Vol. 27, No. 12, pp. 3181-3188.

BOLSTAD, P.V. AND T. STOWE. 1994. **An Evaluation of DEM Accuracy: Elevation, Slope, and Aspect**. *Photogrammetric Engineering & Remote Sensing*, Vol. 60, No. 11, pp. 1327-1332.

BORDELEAU, P.A. AND D.J. GRATTON. 1998. **The Potential for High Mountain Snow-Melt Modeling Using Net Radiation Balance Computed from Remote Sensing Data**. Presented at the Canadian Geophysical Union - Hydrology Section Annual Meeting. Quebec City, Quebec. May 18-20, 1998.

BREWER, T. 1999. **Predicting Snowpack Using the Southern Oscillation Index**. In Proceedings of the 67th Annual Meeting of the Western Snow Conference. South Lake Tahoe, California. April 19-22, 1999.

BROOKS, K.N., P.F. FFOLLIOT, H.M. GREGERSON, AND J.L. THOMAS. 1991. **Hydrology and the Management of Watersheds**. Iowa State University Press. Ames, Iowa.

BRUENDL, M. 1998. **Measuring Branch Deflection and Calculating the Intercepted Snow Mass on Spruce Branches**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10.
http://www.crrel.usace.army.mil/snow98/publications.html

BRYANT, G. AND S. SCHMITZER. 1995. **Lawn Irrigation Return Flow Modeling Using GRID**. In Proceedings of the 1995 ESRI International User Conference. May 22-26, 1995.
http://www.esri.com/library/userconf/proc95/prochome.html

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

CAJINA, N.S., K.L. BRUBAKER, AND A. RANGO. 1999. **Implementing the Martinec/Rango Snowmelt Runoff Model in the USGS Modular Modeling System**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

CALIFORNIA COOPERATIVE SNOW SURYEYS (CCSS). 1999. **California Snow Page**. http://cdec.water.ca.gov/snow/

CANDY, J. 1996. **Adding the Time Element to Your GIS**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

CARRARA, A., G. BITELLI. AND R. CARLA. 1997. **Comparison of techniques for generating digital terrain models from contour lines**. *International Journal of Geographical Information Science*, Vol. 11, No. 5, pp. 451-473.

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.

CARTER, J.R. 1992. **The Effect of Data Precision on the Calculation of slope and aspect Using Gridded DEMs**. *Cartographica*, Vol. 29, No. 1, pp. 22-34.

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

CHANG, K.-T. AND B.-W. TSAI. 1991. **The Effect of DEM Resolution on Slope and Aspect Mapping**. *Cartography and Geographic Information Systems*, Vol. 18, No. 1, pp. 69-77.

CHAOIMH, U.N. 1998. **European Snow Cover and its Influence on Spring and Summer Temperatures**. *The Geographical Journal*, Vol. 164, No. 1, pp. 41-54.

CHAR, S.J. AND J.B. SEVERLING. 1995. **Preanalysis Processing of Continuous GRID Data Sets for Resolution Approximation**. In Proceedings of the 1995 ESRI International User Conference. May 22-26, 1995. http://www.esri.com/library/userconf/proc95/prochome.html

CLARKE, R.T. 1994. **Statistical Modelling in Hydrology**. John Wiley & Sons Ltd. Chichester, West Sussex, England.

CLINE, D. AND K. ELDER. 1998. **Modelling the Spatial Distribution of Snow Water Equivalence and Snowmelt in Mountain Basins**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

CLINE, D., K. ELDER, AND R. BALES. 1997. **Scale Effects in a Distributed SWE and Snowmelt Model for Mountain Basins**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

COHEN, W.B., M. FIORELLA, J. GRAY, E. HELMER, AND K. ANDERSON. 1998. **An Efficient and Accurate Method for Mapping Forest Clearcuts in the Pacific Northwest Using Landsat Imagery**. *Photogrammetric Engineering & Remote Sensing*, Vol. 64, No. 4, pp. 293-300.

COLBECK, S.C. 1997. **The Geophysics of Snow**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

COLBY, J.D. AND P.L. KEATING. 1998. **Land cover classification using Landsat TM imagery in the tropical highlands: the influence of anisotropic reflectance**. *International Journal of Remote Sensing*, Vol. 19, No. 8, pp. 1479-1500.

COLBY, J.D. 1991. **Topographic Normalization in Rugged Terrain**. *Photogrammetric Engineering & Remote Sensing*, Vol. 57, No. 5, pp. 531-537.

COLEE, M., R. HARRINGTON, T. PAINTER, AND J. DOZIER. 1998. **A High-Resolution Distributed Snowmelt Model in an Alpine Catchment**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

CONGALTON, R.G., J.M. STENBACK, AND R.H. BARRETT. 1993. **Mapping Deer Habitat Suitability Using Remote Sensing and Geographic Information Systems**. *Geocarto International*, (3), 1993.

COPPOLA, C. 1996. **Study's grim finding: We're running out of fresh water**. Cable News Network. February 9, 1996. http://cnn.com/EARTH/9602/water/index.html

CRANT, J.S., G. STAPLES, AND R. SANI. 1996. **The Integration of Radar Remote Sensing and Spatial Analysis for Rice Crop Monitoring**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

DADHWAL, V.K. AND V.N. SRIDHAR. 1997. **A non-linear regression form for vegetation index-crop yield relation incorporating acquisition date normalization**. *International Journal of Remote Sensing*, Vol. 18, No. 6, pp. 1403-1408.

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, R.E. 1999. **Aspects of Snow Extent and Water Equivalent Pertaining to Hydrologic Modeling in Complex Landscapes**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

DAVIS, R.E. 1998. **A Review of Spatially Distributed Modeling of Snow**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

DAVIS, R.E., J.P. HARDY, J.R. METCALFE, AND A.E. WALKER. 1998. **Spatial Variation of Snow Cover in the Boreal Forest**. In the Proceedings of the 55th Annual Meeting of the Eastern Snow Conference. Jackson, New Hampshire. June 3-5, 1998. http://www1.tor.ec.gc.ca/crysys/esc/abstracts.htm

DAVIS, R.E., C. WOODCOCK, J.P. HARDY, W. NI, R. JORDAN, AND J.C. McKENZIE. 1997. **Spatially-Distributed Modeling of Snow in the Boreal Forest**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

DERKSON, C., E. LeDREW, AND B. GOODISON. 1999. **Associations between the Principal Spatial Modes of North American Prairie Snow Water Equivalent and Low-Frequency Atmospheric Teleconnection Patterns**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

DERKSON, C., M. WULDER, AND E. LeDREW. 1998. **Associations between Spatially Autocorrelated Patterns of SSM/I-Derived Prairie Snow Cover and Atmospheric Circulation**. In the Proceedings of the 55th Annual Meeting of the Eastern Snow Conference. Jackson, New Hampshire. June 3-5, 1998. http://www1.tor.ec.gc.ca/crysys/esc/abstracts.htm

DOZIER, J. 1998. **Remote Sensing of the Alpine Snow Cover: A Review of the Techniques and Accomplishments from the Visible Wavelengths through to Microwave**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

DROBOT, S.D. AND D.G. BARBER. 1998. **Towards Development of a Snow Water Equivalence (SWE) Algorithm Using Microwave Radiometry over Snow Covered First-Year Sea Ice**. *Photogrammetric Engineering & Remote Sensing*, Vol. 64, No. 5, pp. 415-423.

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

EBERHARDT, R., R. BÖGEL, B. FRÜHWALD, AND A. LOTZ. 1997. **Modellbildung zur Raum- und Habitatnutzung terrestrischer Organismen am Beispiel von Steinadler und Gemse**. In: Angewandte Geographische Informationsverarbeitung IX. Salzburger Geographische Materialen, Heft 26. Department of Geography, University of Salzburg, Salzburg, Austria. July 2-4, 1997.

EBNER, H. 1992. **Digital Terrain Models and their Applications**. *Geo-Informations-Systeme (GIS)*, 3/1992.

EHLSCHLAEGER, C.R., A.M. SHORTRIDGE, AND M.F. GOODCHILD. 1997. **Visualizing Spatial Data Uncertainty Using Animation**. *Computers in GeoSciences*, Vol. 23, No. 4, pp. 387-395. http://everest.hunter.cuny.edu/~chuck/CGFinal/paper.htm

EINET. 1998. http://www.eurimage.it/

EKSTRAND, S. 1996. **Landsat TM-Based Forest Damage Assessment: Correction for Topographic Effects**. *Photogrammetric Engineering & Remote Sensing*, Vol. 62, No. 2, pp. 151-161.

ELDER, K., M. GRAY, P. MAJOR, B. BAKER, AND C. NYBERG. 1999. **Measuring and Monitoring Snow Depth Using the Global Positioning System**. In Proceedings of the 67th Annual Meeting of the Western Snow Conference. South Lake Tahoe, California. April 19-22, 1999.

ELDER, K., R. DAVIS, AND W. ROSENTHAL. 1998. **Using Binary Regression Trees to Estimate Snow Cover Under Clouds**. In Proceedings of the 66th Annual Meeting of the Western Snow Conference. Snowbird, Utah. April 20-23, 1998.

ELDER, K. AND D. CLINE. 1998. **Spatial Properties of Snow in an Alpine Basin, Colorado Front Range**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

ELDER, K., R. DAVIS, AND W. ROSENTHAL. 1997. **Estimating the Spatial Distribution of Snow Water Equivalence in a Montane Watershed**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

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

EL HADDI, A.A., S. SHEKHAR, R. HILLS, AND A. McMANAMON. 1996. **Mirror-Image Round Robin Spatial Data Partitioning: a Case Study With Parallel SEUS**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

ELSTON, D.A., G. JAYASINGHE, S.T. BUCKLAND, D.C. MACMILLAN, AND R.J. ASPINALL. 1997. **Adapting regression equations to minimize the mean squared error of predictions made using covariate data from a GIS**. *International Journal of Geographical Information Science*, Vol. 11, No. 3, pp. 265-280.

ENVIRONMENTAL NEWS NETWORK (ENN). 1999. **Landsat 7 begins viewing the world**. Environmental News Network. http://europe.cnn.com/NATURE/9905/04/landsat.enn/

ERDAS INC. 1997. **ERDAS Field Guide (Fourth Edition)**. ERDAS Inc. Atlanta, Georgia.

ESCHER-VETTER, H., M. WEBER, L.N. BRAUN. 1998. **Auswirkungen von Klimaänderungen auf den Wasserhaushalt alpiner, teilweise vergletscherter Gebiete**. Kommission für Glaziologie der Bayerischen Akademie der Wissenschaften - München. http://www.lrz-muenchen.de/~a2901ad/webserver/webdata/berichtkfg.htm

ESRI INC. 1993. **ARC Macro Language**. Environmental Systems Research Institute. Redlands, California.

ESRI INC. 1991. **Cell-based Modelling with GRID**. Environmental Systems Research Institute. Redlands, California.

FARNES, P.E., W.W. McCAUGHEY, AND K.J. HANSEN. 1997. **Historic Role of Fire in Determining Water Yield from Tenderfoot Creek Experimental Forest, Montana, U.S.A.** In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

FASSNACHT, S.R., N. KOUWEN, E.D. SOULIS, AND P.I. JOE. 1998. **Seasonal Estimation of Snowfall Using Weather Radar**. Presented at the Canadian Geophysical Union - Hydrology Section Annual Meeting. Quebec City, Quebec. May 18-20, 1998.

FASSNACHT, S.R., N. KOUWEN, E.D. SOULIS, AND T.P. RIDGWAY. 1997. **Direct Sublimation of a Seasoned Snowpack**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

FASSNACHT, S.R., E.D. SOULIS, AND N. KOUWEN. 1999. **Modelling the hydrology of a southern Ontario snowpack from weather radar precipitation**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

FELIX, R., K. PREISMEIER, O. WAGNER, H. VOGT, AND F. WILHELM. 1988. **Abfluß in Wildbächen, Abschlußbericht des Teilprojektes A2**. Münchener Geographische Abhandlungen Reihe B, Band B6. Department of Geography, University of Munich.

FELS, J.E. AND K.C. MATSON. 1996. **A Cognitively-based Approach for Hydrogeomorphic Land Classification using Digital Terrain Models**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

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.

FLORINSKY, I.V. 1998. **Accuracy of local topographic variables derived from digital elevation models**. *International Journal of Geographic Information Science*, vol. 12, No. 1, pp. 47-61.

FOODY, G.M. 1988. **Incorporating Remotely Sensed Data into a GIS: The Problem of Classification Evaluation**. *Geocarto International*, (3), 1988.

FORSYTHE, K.W. 1997. **Stepwise Multiple Regression Snow Models: GIS Applications in the Marmot Creek Basin, (Kananaskis Country, Alberta) Canada and the National Park Berchtesgaden, (Bayern) Germany.** In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997. http://snobear.colorado.edu/WSC/WSCref/1997.html#wayne

FORSYTHE, K.W. 1995. **Alpine Snow Modelling Using Geographic Information Systems**. Unpublished M.Sc. Thesis. Department of Geography, University of Calgary.

FORSYTHE, K.W., R.D. WHEATE, AND N.M. WATERS. 1995. **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, CANADA. June 13-15, 1995.

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): pp. 37-48.

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), pp. 49-56.

FRANZ, H.P. 1998. **Personal Communication**. GIS Manager. Berchtesgaden National Park Administration. Berchtesgaden, Germany.

FRANZ, H.P. 1997. **Digitale Daten - Daten auf herkömmlichen Medien**. Nationalparkverwaltung Berchtesgaden, Sachgebiet 560. Berchtesgaden, Germany.

FROHN, R.C., K.C. McGWIRE, V.H. DALE, AND J.E. ESTES. 1996. **Testing a Model of Deforestation with Remote Sensing, GIS, and Landscape Metrics**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

GAO, J. 1997. **Resolution and accuracy of terrain representation by grid DEMs at a micro-scale**. *International Journal of Geographical Information Science*, Vol. 11, No. 2, pp. 199-212.

GARBRECHT, J. AND L.W. MARTZ. 1994. **Grid Size Dependency of Parameters Extracted from Digital Elevation Models**. *Computers & Geosciences*, Vol. 20, No. 1, pp. 85-87.

GILES, P.T. 1998. **Personal Communication**. Assistant Professor. St. Marys University. Halifax, Nova Scotia.

GILES, P.T. AND S.E. FRANKLIN. 1996. **Comparison of Derivative Topographic Surfaces of a DEM Generated from Stereoscopic SPOT Images with Field Measurements**. *Photogrammetric Engineering & Remote Sensing*, Vol. 62, No. 10, pp. 1165-1171.

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

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

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. 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), pp. 1931-1940.

GONIMA, L. 1993. **Simple algorithm for the atmospheric correction of reflectance images**. *International Journal of Remote Sensing*, Vol. 14, No. 6, pp. 1179-1187.

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.

GOODISON, B.E. AND A.E. WALKER. 1993. **Use of snow cover derived from satellite passive microwave data as an indicator of climate change**. *Annals of Glaciology*, Vol. 17, pp. 137-142.

GOONETILLEKE, A. AND G.A. JENKINS. 1996. **Grid Cell Resolution and Its Implications to Surface Runoff Modeling**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

GOROKHOVICH, Y. AND L.L. JANUS. 1996. **GIS Applications for Watershed Management**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

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.

GRAYSON, R.B., G. BLÖSCHL, R.D. BARLING, AND I.D. MOORE. 1993. **Process, scale and constraints to hydrological modelling in GIS**. In the Proceedings of HydroGIS 93: Application of Geographic Information Systems in Hydrology and Water Resources. Vienna, Austria. April 1993. IAHS Publ. No. 211, 1993.

GREEN, K. AND D. WEINSTEIN. 1996. **Automated Change Detection Using Remotely Sensed Data**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

GRYGIER, J., J. STEDINGER, R. ENTRIKEN, J. MANEVAL, AND G. FREEMAN. 1997. **SWIFT: A Simple, Conceptually-Based Snowmelt and Rainfall-Runoff Model with Modest Data Requirements**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

GUNERIUSSEN, T. 1997. **Backscattering properties of a wet snow cover derived from DEM corrected ERS-1 SAR data**. *International Journal of Remote Sensing*, Vol. 18, No. 2, pp. 375-392.

HALL, D.K., M. ALLEN, AND A.B. TAIT. 1999. **Snow Mapping through Dense Forests using Multiple Satellite Data Sets**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

HALL, D.K., J.L. FOSTER, V.V. SALOMONSON, A.G. KLEIN, AND J.Y.L. CHIEN. 1998. **Estimation of the Errors in Snow-Cover Mapping in North America using Satellite Data**. In the Proceedings of the 55th Annual Meeting of the Eastern Snow Conference. Jackson, New Hampshire. June 3-5, 1998. http://www1.tor.ec.gc.ca/crysys/esc/abstracts.htm

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.

HARDISTY, J., D.M. TAYLOR, AND S.E. METCALFE. 1993. **Computerised Environmental Modelling**. John Wiley & Sons. Chichester, England.

HARDY, J., M. ALBERT, AND P. MARSH, (eds.). 1998. **Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems**. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

HARDY, J., R.E. DAVIS, R. JORDAN, C. WOODCOCK, AND W. NI. 1997. **Snow Ablation Modelling in the Conifer and Deciduous Stands of the Boreal Forest**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

HARTMAN, R.K., A.A. ROST, AND D.M. ANDERSON. 1996a. **Operational Processing of Multi-Source Snow Data**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

HARTMAN, R.K., A.A. ROST, AND D.M. ANDERSON. 1996b. **Spatial Distribution of Snow Water Equivalent Observations in Mountainous Terrain**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

HAWTHORN, R.S. 1996. **Data Delivery**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

HEDSTROM, N. AND J.W. POMEROY. 1997. **Accumulation of Intercepted Snow in the Boreal Forest: Measurements and Modelling**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

HEINZER, T., M. SEBHAT, W. GREER, D. HANSEN, AND C.B. JOHNSON. 1995. **The Building of a Geographic Information System Interface to Modflow Utilizing Arc/Info Grid 7.0**. In Proceedings of the 1995 ESRI International User Conference. May 22-26, 1995. http://www.esri.com/library/userconf/proc95/prochome.html

HELLSTROM, R.A. 1999. **Representation of Forest Cover in a Physically-Based Snowmelt Model**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

HENDERSON-SELLERS, A. AND K. McGUFFIE. 1987. **A Climate Modelling Primer**. John Wiley & Sons Ltd. Chichester, England.

HERRMANN, A. 1978. **Schneehydrologishe Untersuchungen in einem randalpinen Niederschlagsgebiet (Lainbachtal bei Benediktbeuern/Oberbayern)**. Münchener Geographische Abhandlungen, Band 22. Department of Geography, University of Munich.

HERRMANN, A. 1973. **Entwicklung der winterlichen Schneedecke in einem nordalpinen Niederschlagsgebiet**. Münchener Geographische Abhandlungen, Band 10. Department of Geography, University of Munich.

HILL, T.B. 1996. **Forest Biometrics from Space**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

HILLS, R., A. McMANAMON, AND R.K. HARTMAN. 1996. **Snow Estimation and Updating System** In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

HODGSON, M.E. 1995. **What Cell Size Does the Computed Slope/Aspect Angle Represent?** *Photogrammetric Engineering & Remote Sensing*, Vol. 61, No. 5, pp. 513-517.

HOOD, E.W., M.W. WILLIAMS, AND D. CLINE. 1998. **Sublimation from a Seasonal Snowpack at a Continental, Mid-Latitude Alpine Site**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

HOPKINSON, C. AND G. YOUNG. 1997. **The Impact of Glacier Recession Upon the Discharge of the Bow River Above Banff, Alberta. 1951-1993.** In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

HUANG, X. AND J.R. JENSEN. 1997. **A Machine-Learning Approach to Automated Knowledge-Base Building for Remote Sensing Image Analysis with GIS Data**. *Photogrammetric Engineering & Remote Sensing*, Vol. 63, No. 10, pp. 1185-1194.

HUTCHINSON, M.F. 1996. **A Locally Adaptive Approach to the Interpolation of Digital Elevation Models**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

IRWIN, A. 1998. **Sea levels rising as glaciers melt away faster than forecast**. International News, Electronic Telegraph. May 27, 1998. http://www.telegraph.co.uk. Search for "sea levels".

ISAACSON, D.L. AND W.J. RIPPLE. 1990. **Comparison of 7.5 minute and 1-Degree Digital Elevation Models**. *Photogrammetric Engineering & Remote Sensing*, Vol. 56, No. 11, pp. 1523-1527.

JENSON, S.K. 1993. **Applications of Hydrologic Information Extracted from Digital Elevation Models**. In: Beven, K.J. AND I.D. Moore, (eds.). 1993. *Advances in Hydrological Processes: Terrain Analysis and Distributed Modelling in Hydrology*. John Wiley & Sons Ltd. Chichester, West Sussex, England.

JIN, Y. 1997a. **Snow depth inverted by scattering indices of SSM/I channels in a mesh graph**. *International Journal of Remote Sensing*, Vol. 18, No. 8, pp. 1843-1849.

JIN, Y. 1997b. **Simulation of a multi-layer model of dense scatterers for anomalous scattering signatures from SSM/I snow data**. *International Journal of Remote Sensing*, Vol. 18, No. 12, pp. 2531-2538.

JOHNSON, T., J. DOZIER, J. MICHAELSEN, AND P. FOHL. 1998. **Statistical Analysis of Sierra Nevada Snowpack Accumulation Trends**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

KARIMI, H.A., B.H. HOUSTON, AND S. PRATT. 1996. **Analysis of Strategies for Integrating Environmental Models with GIS**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

KEEL, G.W. 1996. **Improvements in Differential GPS Accuracies: 1995-1996: What a Difference a Year Makes!** In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

KEMPKA, R.G., R.E. SPELL, A.T. LEWIS, F.A. REID, S. FLINT, AND K. LEWIS. 1996. **Targeting Wetlands Restoration Areas Using Multi-date Satellite Imagery and GIS**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

KIRNBAUER, R. AND G. BLÖSCHL. 1993. **Wie ähnlich sind Ausaperungsmuster von Jahr zu Jahr? (How similar are Snow-cover Patterns from Year to Year?)**. Deutsche Gewässerkundliche Mitteilungen, 37, H5/6, s. 113-121.

KIRNBAUER, R., G. BLÖSCHL, AND D. GUTKNECHT. 1994. **Entering the Era of Distributed Snow Models**. *Nordic Hydrology*, Vol. 25, pp. 1-24.

KLEIN, A.G., D.K. HALL, AND G.A. RIGGS. 1997. **Improving Snow-cover Mapping in Forests Through the Use of a Canopy Reflectance Model**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

KÖLBEL-DEICKE, H. AND H. HEUBERGER. 1987. **Large-Scale Snow Depletion Maps of the Gurgl Valley, Ötztal, Tyrol, Austria, Showing Habitat Variety in an Alpine Terrain**. *Mountain Research and Development*, Vol. 7, No. 4, pp. 387-404.

KOH, G. 1998. **FMCW Radar Applications for Snow-Cover Studies**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

KOUTSIAS, N. AND M. KATERIS. 1998. **Logistic regression modelling of multitemporal Thematic Mapper data for burned area mapping**. *International Journal of Remote Sensing*, Vol. 19, No. 18, pp. 3499-3514.

KOVATS, M. 1997. **A Large-Scale Aerial Photographic Technique for Measuring Tree Heights on Long-Term Forest Installations**. *Photogrammetric Engineering & Remote Sensing*, Vol. 63, No. 6, pp. 741-747.

KUHN, M. AND N. BATLOGG. 1998. **Glacier runoff in Alpine headwaters in a changing climate**. In the Proceedings of the HeadWater '98 Conference. Meran/Merano, Italy. April 1998. IAHS Publ. No. 248, 1998.

KUMAR, L., A.K. SKIDMORE, AND E. KNOWLES. 1997. **Modelling topographic variation in solar radiation in a GIS environment**. *International Journal of Geographical Information Science*, Vol. 11, No. 5, pp. 475-497.

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.

LAUER, D.T., S.A. MORAIN, AND V.V. SALOMONSON. 1997. **The Landsat Program: Its Origins, Evolution, and Impacts**. *Photogrammetric Engineering & Remote Sensing*, Vol. 63, No. 7, pp. 831-838.

LEAVESLEY, G.H., R.J. VIGER, L.E. HAY, AND S.L. MARKSTROM. 1998. **Estimation and Evaluation of Spatially Distributed Snowmelt Model Parameters Using the Modular Modeling system (MMS)**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

LEYDECKER, A. AND J.O. SICKMAN. 1998. **Distribution of Snow in the Upper Marble Fork Basin, California**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

LI, L. AND J.W. POMEROY. 1998. **Simulation of Snowcover Redistribution in Irregular Terrain**. Presented at the Canadian Geophysical Union - Hydrology Section Annual Meeting. Quebec City, Quebec. May 18-20, 1998.

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.

LOPEZ, C. 1997. **Locating some types of random errors in Digital Terrain Models**. *International Journal of Geographical Information Science*, Vol. 11, No. 7, pp. 677-698.

LYNCH, S.D. AND R.E. SCHULZE. 1995. **Techniques for Estimating Areal Daily Rainfall**. In Proceedings of the 1995 ESRI International User Conference. May 22-26, 1995. http://www.esri.com/library/userconf/proc95/prochome.html

LYON, J.G., D. YUAN, R.S. LUNETTA, AND C.D. ELVIDGE. 1998. **A Change Experiment Using Vegetation Indices**. *Photogrammetric Engineering & Remote Sensing*, Vol. 64, No. 2, pp. 143-150.

MAIDMENT, D.R. 1996. **GIS and Hydrologic Modeling - An Assessment of Progress**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

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), pp. 3029-3042.

MARSH, P. 1998. **Snow-Cover Properties and Processes**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

MARTINEC, J. AND A. RANGO. 1995. **Seasonal Runoff Forecasts for Hydropower Based on Remote Sensing**. In Proceedings of the 63rd Annual Meeting of the Western Snow Conference. Reno/Sparks, Nevada, USA.

MARTINEC, J., A. RANGO, AND R. ROBERTS. 1998. **Snowmelt Runoff Model (SRM) User's Manual**. Updated Edition, Version 4. Department of Geography. University of Berne. 65pp.

MÄTZLER, C., T. STROZZI, T. WEISE, D.-M. FLORICIOIU, AND H. ROTT. 1997. **Microwave snowpack studies made in the Austrian Alps during the SIR-C/X-SAR experiment**. *International Journal of Remote Sensing*, Vol. 18, No. 12, pp. 2505-2530.

McCLUNG, D.M. 1996. **Effects of temperature on fracture in dry slab avalanche release**. *Journal of Geophysical Research*, Vol. 101, No. B10, pp. 21,907-21,920.

McGINNIS, D.L. 1997. **Estimating Climate-Change Impacts on Colorado Plateau Snowpack Using Downscaling Methods**. *Professional Geographer*, Vol. 49, No. 1, pp. 117-125.

McKENNEY, D.W., B.G. MACKEY, AND B.L. ZAVITZ. 1999. **Calibration and sensitivity analysis of a spatially-distributed solar radiation model**. *International Journal of Geographical Information Science*, Vol. 13, No. 1, pp. 49-65.

METCALFE, R.A. AND J.M. BUTTLE. 1997. **Spatially-Distributed Snowmelt Rates In a Boreal forest Catchment**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

MEYER, O. 1995. **Schneedeckenkartierung und Abschätzung der schneeflächenvariabilitätsbedingten Strahlungsbilanzveränderungen mit Landsat-TM-Daten im Biosphärenreservat Berchtesgaden**. Unveröffentlichte Publikation. Geographisches Institut der Philosophisch-Naturwissenschaftlichen Fakultät der Universität Bern.

MEYER, P., K. STAENZ, AND K.I. ITTEN. 1996. **Semi-automated procedures for tree species identification in high spatial resolution data from digitized colour infrared-aerial photography**. *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol. 51, pp. 5-16.

MOLNAR, L., (ed.). 1990. **Hydrology of Mountainous Areas: IAHS Publication No. 190**. International Association of Hydrological Sciences (IAHS) Press. Institute of Hydrology, Wallingford, Oxfordshire, United Kingdom.

MOORE, C.A. AND W.W. McCAUGHEY. 1997. **Snow Accumulation Under Various Forest Stand Densities at Tenderfoot Creek Experimental Forest, Montana, U.S.A.** In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

MOORE, I.D., R.B. GRAYSON, AND A.R. LADSON. 1993. **Digital Terrain Modelling: A Review of Hydrological, Geomorphological, and Biological Applications**. In: Beven, K.J. AND I.D. Moore, (eds.). 1993. *Advances in Hydrological Processes: Terrain Analysis and Distributed Modelling in Hydrology*. John Wiley & Sons Ltd. Chichester, West Sussex, England.

MOORE, R.D. AND I.G. McKENDRY. 1996. **Spring Snowpack Anomaly Patterns and Winter Climatic Variability, British Columbia, Canada**. *Water Resources Research*, Vol. 32, No. 3.

MULUGETA, G. 1996. **Manual and Automated Interpolation of Climatic and Geomorphic Statistical Surfaces: An Evaluation**. *Annals of the Association of American Geographers*, Vol. 86, No. 2, pp. 324-342.

MÜLLER-WOHLFEIL, D.-I., W. LAHMER, V. KRYSANOVA, AND A. BECKER. 1996. **Topography-based hydrological modelling in the Elbe drainage basin**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

NAESSET, E. 1997. **Determination of mean tree height of forest stands using airborne laser scanner data**. *ISPRS Journal of Photogrammetry & Remote Sensing*, Vol. 52, pp. 49-56.

NAGLER, T. AND H. ROTT. 1998. **SAR Tools for Snowmelt Modelling in the Project HydAlp**. In the Proceedings of IGARSS '98. IEEE Catalog Number 98CH36174.

NAGLER, T., H. ROTT, AND G. GLENDINNING. 1998. **SAR-based Snow Cover Retrievals for Runoff Modelling**. In the Proceedings of the 2nd International Workshop on Retrieval of Bio- & Geo-physical Parameters from SAR Data for Land Applications. ESTEC, Noordwijk, The Netherlands. October 21-23, 1998. (ESA SP-441, December 1998).

NARUMALANI, S., J.R. JENSEN, J.D. ALTHAUSEN, S. BURKHALTER, AND H.E. MACKEY JR. 1997. **Aquatic Macrophyte Modeling Using GIS and Logistic Multiple Regression**. *Photogrammetric Engineering & Remote Sensing*, Vol. 63, No. 1, pp. 41-49.

NATIONALPARKVERWALTUNG BERCHTESGADEN (NPVB). 1998. **Nationalparkplan Berchtesgaden - Entwurf - Band II**. Nationalparkverwaltung Berchtesgaden und Bosch & Partner Gmbh. Berchtesgaden and Königsdorf, Germany.

NATIONALPARKVERWALTUNG BERCHTESGADEN (NPVB). 1997. **Nationalpark Berchtesgaden - Nationalparkgerechter Tourismus**. Nationalparkverwaltung Berchtesgaden. Berchtesgaden, Germany.

NATIONALPARKVERWALTUNG BERCHTESGADEN (NPVB). 1994. **National Park Berchtesgaden - A Nature Reserve in the alps combining tradition with new ideals**. Nationalparkverwaltung Berchtesgaden. Berchtesgaden, Germany.

NATIONALPARKVERWALTUNG BERCHTESGADEN (NPVB). 1993. **Nationalpark Berchtesgaden - Wimbachklamm und Wimbachtal**. Nationalparkverwaltung Berchtesgaden. Berchtesgaden, Germany.

NATIONAL PARK BERCHTESGADEN (BNP). 1992. **National Park Berchtesgaden Short Description**. National Park Berchtesgaden. Berchtesgaden, Germany.

NSIDC. 1998. **Breakup of Larsen B Ice Shelf May Be Underway**. *NSIDC Notes - June 1998*. National Snow and Ice Data Center. Boulder, Colorado.

NSIDC. 1996. **Snow Water Equivalent CD-ROM**. *NSIDC Notes - Winter 1996*. National Snow and Ice Data Center. Boulder, Colorado.

OPENSHAW, S. 1989. **Learning to live with errors in spatial databases**. In: Goodchild, M.F. (ed.). Accuracy of Spatial Databases. New York. Taylor and Francis. pp. 263-276.

ÖSKOG, A.E. 1996. **RESURS-01-Bridging the Gap**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

OSTERHUBER, R., F. GEHRKE, AND K. CONDREVA. 1998. **Snowpack Snow Water Equivalent Measurement Using the Attenuation of Cosmic Gamma Radiation**. In Proceedings of the 66th Annual Meeting of the Western Snow Conference. Snowbird, Utah. April 20-23, 1998.

PANGBURN, T., R.E. DAVIS, E. OCHS, W. ROSENTHAL, AND K. ELDER. 1997. **Issues in Integrating Remote Sensing and GIS in Operational Snow Hydrology: Perspectives from Recent Experience**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

PATTEN, R.S. AND D.H. KNIGHT. 1994. **Snow Avalanches and Vegetation Pattern in Cascade Canyon, Grand Teton National Park, Wyoming, U.S.A.** *Arctic and Alpine Research*, Vol. 26, No. 1, pp. 35-41.

POMEROY, J.W. AND D.M. GRAY. 1998. **Modelling Snow Processes for Prairie, Arctic and Boreal Forest Environments**. In the Proceedings of the 55th Annual Meeting of the Eastern Snow Conference. Jackson, New Hampshire. June 3-5, 1998. http://www1.tor.ec.gc.ca/crysys/esc/abstracts.htm

POMEROY, J.W., N. HEDSTROM, J. PARVIAINEN, AND D.M. GRAY. 1998. **Coupled Modelling of Forest Snow Interception and Sublimation**. In the Proceedings of the 55th Annual Meeting of the Eastern Snow Conference. Jackson, New Hampshire. June 3-5, 1998. http://www1.tor.ec.gc.ca/crysys/esc/abstracts.htm

PRICE M.F. AND D.I. HEYWOOD, (eds.). 1994. **Mountain Environments & Geographic Information Systems**. Taylor & Francis Ltd. London, England.

PUREVDORJ, Ts., R. TATEISHI, T. ISHIYAMA, AND Y. HONDA. 1998. **Relationships between percent vegetation cover and vegetation indices**. *International Journal of Remote Sensing*, Vol. 19, No. 18, pp. 3519-3536.

RACK, W., H. ROTT, T. NAGLER, AND P. SKVARCA. 1998. **Areal Changes and Motion of Northern Larsen Ice Shelf, Antarctic Peninsula**. In Proceedings of IGARSS '98. IEEE Catalog Number 98CH36174.

RANGO, A. 1992. **Worldwide Testing of the Snowmelt Runoff Model with Applications for Predicting the Effects of Climate Change**. *Nordic Hydrology*, Vol. 23. pp. 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.

RAU, R.G. 1993. **Höhenabhängige Variationen der hydrologischen Eigenschaften von Schneeschmelzabflüsse in den mittleren Breiten**. In: Der Geograph im Hochgebirge. Innsbrucker Geographische Studien. Band 20.

REUTERS. 1999. **Scientists: Antarctic ice shelves breaking up fast**. http://www.cnn.com/NATURE/9904/08/antarctic.ice.reut/index.html

RICHTER, R. 1997. **Correction of atmospheric and topographic effects for high spatial resolution satellite imagery**. *International Journal of Remote Sensing*, Vol. 18, No. 5, pp. 1099-1111.

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

ROMANOV, P., I. CSISZAR, AND G GUTMAN. 1999. **Towards Automated Multispectral Snow Mapping**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

ROSENTHAL, W. AND J. DOZIER. 1996. **Automated Mapping of Montane snow cover at sub-pixel resolution from Landsat Thematic Mapper**. *Water Resources Research*, Vol. 32, No. 1.

ROTT, H., M. BAUMGARTNER, R. FERGUSON, G. GLENDINNING, B. JOHANSSON, O. PIRKER, S. QUEGAN, AND G. WRIGHT. 1998. **HYDALP - A European Project on Snowmelt Runoff Modeling Using Satellite Data**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

ROTT, H. 1993. **Fernerkundungsverfahren für die Schneehydrologie**. In: Blöschl, G., D. Gutknecht, and R. Kirnbauer, Schneehydrologie-Modellierung der Schneeschmelze in Einzugsgebieten. Schriftenreihe der Forschungsinitiative des Verbundkonzerns. Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft, Technische Universität Wien.

ROTT, H., N. BATLOGG, T. NAGLER, W. RACK, AND O. PIRKER. 1998. **Projekt Mission Alpine Hydrologie**. Endbericht zum Forschungsauftrag GZ 79.063/2-II/5/95 des BMWV. Schriftenreihe der Forschung im Verbund Band 41.

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

SALZBURGER NACHRICHTEN (SN). 1997. **Unser Wasser für Europa**. Salzburger Nachrichten. June 11, 1997.

SALZBURGER NACHRICHTEN (SN). 1996. **Wassermangel heizt politische Krisen an**. Salzburger Nachrichten. September 16, 1996.

SANDMEIER, S. 1997. **Radiometrische Korrektur des Topographieeffekts in optischen Satellitenbilddaten – Vergleich eines semi-emperischen Verfahrens mit einem physikalisch-basierten Modell**. *Photogrammetrie Fernerkundung Geoinformation*, 1/1997, pp.23-32.

SAUNDERS, I.R. AND W.G. BAILEY. 1997. **Longwave Radiation Modeling in Mountainous Environments**. *Physical Geography*, Vol. 18, No. 1, pp. 37-52.

SCARBROUGH-LUTHER, P. AND B. COFFEY. 1995. **Use of ARC/INFO, GRASS, ERDAS, and SAS to Create ACSII Files and ARC/INFO Point Coverages For the Integrated Midwest Biomass Resource Analysis Project**. In Proceedings of the 1995 ESRI International User Conference. May 22-26, 1995. http://www.esri.com/library/userconf/proc95/prochome.html

SCHAAB, G. AND R. LENZ. 1997. **SORAM: GIS-basierte Einstrahlungsmodellierung**. In: Angewandte Geographische Informationsverarbeitung IX. Salzburger Geographische Materialen, Heft 26. Department of Geography, University of Salzburg, Salzburg, Austria. July 2-4, 1997.

SCHALLER, J. 1994. **Geographic information systems and ecosystem models as tools for watershed management and ecological balancing in high mountain areas: the example of ecosystem research in the Berchtesgaden area, Germany**. In: Price M.F. and D.I. Heywood, (eds.). 1994. *Mountain Environments & Geographic Information Systems*. Taylor & Francis Ltd. London, England.

SEGLENIEKS, F., E.D. SOULIS, AND N. KOUWEN. 1997. **Determination of Snow-Covered Area Using RADARSAT C-HH SAR Imagery on Two Small Test Sites in Southern Ontario**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

SEIDEL, K. 1996. **Use of Multisensor Satellite Data for Snow Cover Mapping**. Presented at the 1996 SRM Workshop. Berne, Switzerland. October 7-11, 1996.

SEIDEL, K., C. EHRLER, AND J. MARTINEC. 1997. **Effects of Climate Change on Water Resources and Runoff in Alpine Regions**. In Proceedings of the Western Snow Conference from the Joint Meeting of: the 5th Scientific Meeting of the Canadian Geophysical Union - Hydrology Section, the 65th Annual Meeting of the Western Snow Conference, and the 54th Annual Meeting of the Eastern Snow Conference. Banff, Alberta, Canada. May 4-9, 1997.

SIMS, R.A., D.W. McKENNEY, B.G. MACKEY, AND M.F. HUTCHINSON. 1996. **Construction of a New Digital Elevation Model for Canada**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

SINGH, P., S.K. JAIN, AND N. KUMAR. 1997. **Estimation of Snow and Glacier-Melt Contribution to the Chenab River, Western Himalaya**. *Mountain Research and Development*, Vol. 17, No. 1, pp. 49-56.

SINGH, P., K.S. RAMASASTRI, AND N. KUMAR. 1995. **Topographic Influence on Precipitation Distribution in Different Ranges of Western Himalayas**. *Nordic Hydrology*, Vol. 26, pp. 259-284.

SKIDMORE, A.K. 1990. **Terrain position as mapped from a gridded digital elevation model**. *International Journal of Geographical Information Systems*, Vol. 4, No. 1, pp. 33-49.

SLUPETZKY, H. 1998. **Die "Eiskapelle" im Griesbachgraben (Osterhorngruppe, Salzburg, Österreich) – temporäre Höhlen unter Lawinenkegeln.** In the Proceedings of the 4th International Symposium on Glacier Caves and Cryokarst in Polar and High Mountain Regions. Salzburger Geographische Materialen, Heft 28. Alpinzentrum Rudolfshütte, Salzburg, Austria. September 1-7, 1996.

SLUPETZKY, H., (ed.). 1998. **Proceedings of the 4th International Symposium on Glacier Caves and Cryokarst in Polar and High Mountain Regions**. Salzburger Geographische Materialen, Heft 28. Alpinzentrum Rudolfshütte, Salzburg, Austria. September 1-7, 1996.

SLUPETZKY, H. 1996. **Programm "Wasser- und Eishaushaltsmessungen im Stubachtal" (Massenbilanzmeßreihe vom Stubacher Sonnblickkees) Ergebnisbericht für 1994**. In the Mitteilungsblatt des Hydrographischen Dienstes in Österreich, Nr. 74, Wien 1996, pp. 75-90.

SLUPETZKY, H. 1995. **Programm "Wasser- und Eishaushaltsmessungen im Stubachtal" (Massenbilanzmeßreihe vom Stubacher Sonnblickkees) Ergebnisbericht für 1993**. In the Mitteilungsblatt des Hydrographischen Dienstes in Österreich, Nr. 73, Wien 1995, pp. 39-54.

SLUPETZKY, H. 1993a. **Programm "Wasser- und Eishaushaltsmessungen im Stubachtal" (Massenbilanzmeßreihe vom Stubacher Sonnblickkees) Ergebnisbericht für 1992**. In the Mitteilungsblatt des Hydrographischen Dienstes in Österreich, Nr. 70, Wien 1993, pp. 115-131.

SLUPETZKY, H. 1993b. **Programm "Wasser- und Eishaushaltsmessungen im Stubachtal" (Massenbilanzmeßreihe vom Stubacher Sonnblickkees) Ergebnisbericht für 1991**. In the Mitteilungsblatt des Hydrographischen Dienstes in Österreich, Nr. 69, Wien 1993, pp. 61-74.

SLUPETZKY, H. 1992. **Programm "Wasser- und Eishaushaltsmessungen im Stubachtal" (Massenbilanzmeßreihe vom Stubacher Sonnblickkees) Ergebnisbericht für 1990**. In the Mitteilungsblatt des Hydrographischen Dienstes in Österreich, Nr. 68, Wien 1992, pp. 25-37.

SLUPETZKY, H. 1991. **Programm "Wasser- und Eishaushaltsmessungen im Stubachtal" (Massenbilanzmeßreihe vom Stubacher Sonnblickkees) Ergebnisbericht für 1989**. In the Mitteilungsblatt des Hydrographischen Dienstes in Österreich, Nr. 64, Wien 1991, pp. 44-66.

SMYTH, J. AND K. GOITA. 1999. **Statistical Analysis of the Impact of Temperature and Vegetation Cover on Snow Water Equivalent using SSM/I data over New Brunswick**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

SPACE IMAGING EUROPE (SIE). 1998-1999. http://www.spaceimagingeurope.com/

STÄNDIGE ARBEITSGRUPPE DER BIOSPHÄRENRESERVATE IN DEUTSCHLAND (SABD). 1995. **Biosphärenreservate in Deutschland – Leitlinien für Schutz, Pflege und Entwicklung**. Springer-Verlag. Berlin, Germany.

STANITSKY-MARTIN, D. 1996. **Atmospheric and Environmental Influences on Wintertime Shortwave Radiation, San Juan Mountains, Colorado, U.S.A.** *Mountain Research and Development*, Vol. 16, No. 3, pp. 199-210.

STROBL, J. 1992. **Datenmanipulation und Datenanalyse**. In Kilchenmann, A., (ed.). Technologie Geographischer Informationssysteme. Berlin, Germany.

STROBL, J. 1988. **Reliefanalyse mit dem Computer**. *Geographische Rundschau*, 40, H. 5, s. 38-43.

SUSONG, D., D. MARKS, T. LINK, AND D. GAREN. 1998. **Methods for Developing Time-Series Climate Surfaces to Drive Topographically Distributed Snowmelt Models**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

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

TAIT, A. 1998. **High Frequency Passive Microwave Radiometry over a Snow-Covered Surface**. In the Proceedings of the 55th Annual Meeting of the Eastern Snow Conference. Jackson, New Hampshire. June 3-5, 1998. http://www1.tor.ec.gc.ca/crysys/esc/abstracts.htm

TANG, G.A. 1998. **Sensitivity Analysis of Error in Digital Terrain Models**. Unpublished Ph.D. Dissertation. Department of Geography. University of Salzburg.

THAPA, K. AND J. BOSSLER. 1992. **Accuracy of Spatial Data Used in Geographic Information Systems**. *Photogrammetric Engineering & Remote Sensing*, Vol. 58, No. 6, pp. 835-841.

TODD, S.W. AND R.M. HOFFER. 1998. **Responses of Spectral Indices to Variations in Vegetation Cover and Soil Background**. *Photogrammetric Engineering & Remote Sensing*, Vol. 64, No. 9, pp. 915-921.

TOUTIN, T. 1998. **SPOT and Landsat Stereo Fusion for Data Extraction over Mountainous Areas**. *Photogrammetric Engineering & Remote Sensing*, Vol. 64, No. 2, pp. 109-113.

TURPIN, O., R. FERGUSON, AND B. JOHANSSON. 1998. **Integration of Remote Sensing Techniques into the Snowmelt Component of Hydrological Models**. In: Hardy, J., M. Albert, and P. Marsh, (eds.). 1998. *Abstracts from the International Conference on Snow Hydrology - The Integration of Physical, Chemical, and Biological Systems*. U.S. Army Cold Regions Research and Engineering Laboratory. Hanover, New Hampshire. Special Report 98-10. http://www.crrel.usace.army.mil/snow98/publications.html

VAN DRIEL, N. AND T. LOVELAND. 1996. **The U.S. Geological Survey's Land Cover Characterization Program**. In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

VEREGIN, H. 1997. **The Effects of Vertical Error in Digital Elevation Models on the Determination of Flow-path Direction**. *Cartography and Geographic Information Systems*, Vol. 24, No. 2, pp. 67-79.

WAGNER, W. 1995. **Application of Low-Resolution Active Microwave Remote Sensing (C-Band) over the Canadian Prairies**. Unveröffentlichte Publikation. Institut für Allgemeine Physik der Technischen Universität Wien.

WALD, L., T. RANCHIN, AND M. MANGOLINI. 1997. **Fusion of Satellite Images of Different Spatial Resolutions: Assessing the Quality of Resulting Images**. *Photogrammetric Engineering & Remote Sensing*, Vol. 63, No. 6, pp. 691-699.

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.

WALKER, A.E. AND J.R. METCALFE. 1999. **Investigation of Seasonal Snow Cover Variations in Eastern Ontario using Airborne Microwave Radiometry**. In the Proceedings of the 56th Annual Meeting of the Eastern Snow Conference. Fredericton, N.B., Canada. June 2-4, 1999. http://www1.tor.ec.gc.ca/crysys/esc/esc99-agenda.html

WALSH, S.J., D.R. LIGHTFOOT, AND D.R. BUTLER. 1987. **Recognition and Assessment of Error in Geographic Information Systems**. *Photogrammetric Engineering & Remote Sensing*, Vol. 53, No. 10, pp. 1423-1430.

WARD, A.D. AND W.J. ELLIOT, (eds.). 1995. **Environmental Hydrology**. CRC Press Inc. Boca Raton, Florida.

WARDOYO. AND G. JORDAN. 1996. **Assessing Management of Forest Landscapes with ARC/INFO and EASI/PACE**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

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

WIESINGER, C. AND H. SLUPETZKY. 1996. **Das Klima im Gebiet von Altenmarkt/Zauchensee**. Ortschronik Altenmarkt im Pongau. Band 1. Gemeinde Altenmarkt (Hrsg.). pp. 45-53.

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

WILSON, J.P. 1996. **GIS-based Land Surface/Subsurface Modeling: New Potential for New Models?** In Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Fe, NM. January 21-26, 1996. Santa Barbara, CA: National Center for Geographic Information and Analysis. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

WINSTRAHL, A., K. ELDER, AND R. DAVIS. 1999. **Implementation of Digital Terrain Analysis to Capture the Effects of Wind Redistribution in Spatial Snow Modeling**. In Proceedings of the 67th Annual Meeting of the Western Snow Conference. South Lake Tahoe, California. April 19-22, 1999.

WOLF, A. 1998. **Die Eiskapelle beim Königssee, Watzmann (Berchtesgadener Alpen)**. In the Proceedings of the 4th International Symposium on Glacier Caves and Cryokarst in Polar and High Mountain Regions. Salzburger Geographische Materialen, Heft 28. Alpinzentrum Rudolfshütte, Salzburg, Austria. September 1-7, 1996.

YAZDANI, R., D. MINTY, B. REID, AND G. WEIR. 1996. **Land Cover Classification by Integrating LANDSAT TM, SPOT, and Topographic Digital Data**. In Proceedings of the GIS'96 Conference (CD-ROM). Vancouver, British Columbia. March 19-21, 1996.

YIN, Z. AND T.H.L. WILLIAMS. 1997. **Obtaining Spatial and Temporal Vegetation Data from Landsat MSS and AVHRR/NOAA Satellite Images for a Hydrologic Model**. *Photogrammetric Engineering & Remote Sensing*, Vol. 63, No. 1, pp. 69-77.

ZHAO, L. AND D.M. GRAY. 1998. **Snowmelt Infiltration into Frozen Soils: Some Recent Progress**. Presented at the Canadian Geophysical Union - Hydrology Section Annual Meeting. Quebec City, Quebec. May 18-20, 1998.

ZUSAMMENFASSUNG

Entwicklung von Schneedecken-Modellen an einem Beispiel in den Kalkhochalpen (Nationalpark Berchtesgaden, Deutschland)

Die Schneedecke hat in den Gebirgen der mittleren Breiten eine grosse Bedeutung und wirkt sich vielfältig auf die Trinkwasserreserven, Wasserkraftwerke, Bewässerungen und auf die Freizeitgestaltung aus.

Die Schneedeckenverteilung und Schneehöhen sind in gebirgigen Gebieten aufgrund der Topographie, Vegetationsbedeckung und klimatischer oder Umweltfaktoren sehr unterschiedlich. Geographische Informationssysteme (GIS), digitale Geländemodelle (DGM), Fernerkundungstechniken und Statistikmethoden (Multiple Regression) haben eine immer wichtigere Bedeutung in der Erfassung der Schneedecke.

Während DGM-Daten die Bestimmung von topographischen Faktoren ermöglichen, sind Satellitendaten nutzvoll für die Abschätzung der Vegetationsbedeckung bzw. des Oberflächenzustandes und der schneebedeckten Flächen. Die in dieser Untersuchung angewandten Forschungsmethoden wurden entwickelt, um die Schneedeckenverteilung zwischen Messpunkten grössenordnungsmässig interpolieren zu können, wobei statistische Modelle angewandt wurden. Dahinter steht die bekannte Tatsache, dass Gebiete mit ähnlicher topographischer, landschaftlicher und klimatischer Bedingungen ähnliche Schneedeckenverhältnisse aufweisen. Die Anwendung dieser Methoden und Kenntnisse haben grosse Vorteile in Problemzonen wie in Waldgebieten, steilem Gelände und in Schattenflächen, wo Satellitensensoren die Schneedecke nicht direkt und/oder nur schwer erfassen.

Die Daten für die angewandten Regressionsmodelle stammen von einem Messnetz mit 94 Schneemeßstellen, wo jeweils Schneehöhe und Wasseräquivalent zwischen Jänner und April von 1989 bis 1994 gemessen wurden. Die Schneedaten wurden zu wöchenliche Gruppen zusammengefasst (es sind nicht immer alle Schneepegel gemessen worden). Die Schneedaten wurden mit Daten von Satellitenbildern - “Landsat Thematic Mapper” (TM) - und des 25m-DGM kombiniert, sowie in weiterer Folge mit verschiedenen, davon abgeleiteten Variablen, als Vorbedingung für die

Regressionsanalysen. Masstabs- bzw. Deckungsprobleme wurden dadurch minimiert, dass das 25m-DGM und die georeferenzierten und eingepassten Satellitenbilder mit einer Auflösung von 25m verwendet wurden. Dabei wurde ein Modell für die Sonnenstrahlung integriert, das die Abschätzung der potentiellen kurzwelligen Strahlung auch in den Abschattungen ermöglichte.

Die Methode der schrittweisen multiplen Regression wurde angewandt, um empirische Gleichungen für die nachfolgende Modellierung der Schneedeckenparameter zu erhalten, wobei die Grundlage dafur die mit *Arc/Info* GIS gewonnenen Dateien waren. Für die Monate Jänner-Februar ergab das beste Schneehöhenmodell einen multiples Bestimmtheitmaß (R^2) von 0.875, d.h. es erklärt 87.5% der Variationen in den Daten, während die Beziehung für den Wasserwert 0.880 beträgt. Seehöhe, Hangneigung und TM Band 4 waren die unabhängigen Variablen, mit denen die Variabilität der Schneehöhe und des Wasseräquivalents am besten zu erfassen waren. Für die Monate März-April wurde für beides ein maximaler multiples Bestimmtheitmaß (R^2) Werte von 0.832 gefunden.

Der allerbeste Zusammenhang mit einer einzigen Variablen in den Schneemodellierungen ergab sich für die Seehöhe. Es ergaben sich sehr gute Ergebnisse bei der Verwendung von Schneehöhe, Hangneigung und „Principal component two“- Werten (hergeleitet von den TM Satellitendaten) bei den Regressionsberechnungen für die Jänner-Februar Monate. Kurzwellige Einstrahlung und die Variablen der TM Bänder waren die beste Regressionskomponenten für März-April. Die Variabilität des Wasseräquivalents der Schneedecke für die Monate Jänner-Februar war am besten mit der kurzwelligen Einstrahlung und den Variablen der TM Bänder in Beziehung zu setzen, und die kurzwellige Einstrahlung und „principal component two“- Werte betreffend März-April. Für beide, Schneehöhe und Wasseräquivalent des Schnees, war die Oberflächentopographie bezüglich konvexer und konkaver Formung (profile curvature) ein weiterer guter Weg für die Verhältnisse im April, aber auch für Modellierungen bei geringen Schneehöhen. Die Gleichungen - als Ergebnis der Analysen - wurden im „Map Calculator“ des *Arcview GIS* verwendet, um eine weitere Annäherung an die räumlichen Charakteristika der Schneeverteilung zu gewinnen.

Der Erfolg und die Qualität dieser Modelle hängt von den Schneedeckenverhältnissen und auch der Art der erhältlichen Daten ab. In schneearmen Wintern wie z.B.1990/91 und 1993/94 sind die Ergebnisse nicht so gut im Vergleich zu einem normalen (1992/93) oder einem schneereichen Winter (1991/92). Die Beziehungen sind generell 20 bis 25% schlechter. Dies kann zumindest teilweise auf fehlenden Schnee zumeist bei den tiefer gelegenen Messpegeln zurückgeführt werden. Der Prozentsatz von Messpunkten mit einem Nullwert ist meistens über 25. Dies kann einen ungünstigen Einfluss auf die Ergebnisse im Falle nur weniger gemessener Punkte haben.

Insgesamt konnten in dieser Arbeit mit den angewandten Methoden und Techniken durchaus zufriedenstellende Ergebnisse erzielt werden. Gute Zusammenhänge wurden zwischen der Schneedecke und Variablen, die aus dem DGM und den Satellitendaten stammen, gefunden. Es wird erhofft und erwartet, dass diese Techniken in der Modellierung des Schmelzewasserabflusses Verwendung findet. In vielen Fällen zeigten sich Probleme mit der Erfassung und Abschätzung der Ausgangsverteilung des Wassergehalts in der Schneedecke.

Es gibt einige interessante Aspekte für die Fortsetzung dieser GIS-gestützen Forschungrichtung in der Zukunft.