Predicting Water Availability in the Antarctic Dry Valleys using Geographic Information Systems and Remote Sensing

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Abstract

Water is one of the most important ingredients for life on Earth. The presence or absence of biologically available water determines whether or not life will exist. Antarctica is an environment where abiotic constraints, particularly water, strongly influence the distribution and diversity of biota. As Antarctic biology is relatively simple when compared to more temperate climates, it is a prime location for researching constraints on biodiversity, and what may be the impacts of changes to these constraints resulting from climate change and human disturbance. This research uses Geographic Information Systems (GIS) and remote sensing to develop a relative water availability index of three Dry Valleys in Southern Victoria Land, Antarctica. This study area is being used for the IPY Terrestrial Biocomplexity project, an international collaboration researching the distribution, diversity and complexity of biology in the Dry Valleys. The development of a predictive water availability model will contribute greatly to their research goals.

This thesis describes the sources of biologically available water in the Dry Valleys and its interaction with biota. Remotely sensed data of these sources is gathered and various methods of analysing the data are explored. This includes creating a mean snow cover distribution model from MODIS data over 4 summer seasons, and Landsat7 ETM+ surface temperature data. These data sets, combined with a high resolution LIDAR Digital Elevation Model and glacier and lake locations, are then analysed with GIS to produce a Compound Topographic Index (CTI), a model showing the likely accumulation and dispersal of liquid water given the spatial distribution of water sources and the flow of water over the terrain according to the influence of gravity. Visualisation techniques are used to validate the resulting model, including the use of 3D visualisation and comparison of drainage patterns using overlays of a high resolution ALOS image. This research concludes that GIS and remote sensing are valuable tools for predicting water distribution in Antarctica. Although cloud cover, varied illumination and differing spatial resolutions can create limitations, remote sensing’s cost effective and environmentally sound method of data capture and the computational and spatial modelling capabilities of GIS make their use well suited to the Antarctic environment.

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Acronym List/Glossary

Albedo – Light reflectance

ATM – Airborne Topographic Mapper

Biocomplexity – Biological organisms, their community structure and functional linkages

Biota – Living organisms (animals, plants etc.)

CTI – Compound Topographic Index, also referred to as Compound Terrain Index and Topographic Wetness Index

D8 – 8 Direction Flow Path Calculation Algorythm (O'Callaghan & Mark, 1984)

DEM – Digital Elevation Model

D-Inf – D-Infinity Flow Path Calculation Algorythm (Tarboton, 1997)

EDA – Environmental Domains Analysis

GIS – Geographic(al) Information System(s)

IPY – International Polar Year

LIDAR – LIght Detection And Ranging

Mixel – Mixed Pixel Element

MODIS – Moderate Resolution Imaging Spectroradiometer

NDSI – Normalised Difference Snow Index

NIR – Near Infrared

SWIR – Short Waver Infrared

Chapter 1. Introduction & Context

1.1 Introduction

Understanding what governs the distribution and diversity of biotic life is important to our knowledge of how biology has reached its current state in terms of distribution and diversity, as well as gaining foresight into what changes may occur in the future. The Antarctic environment has an important role in studying the governing constraints on life, as it is an environment where the abiotic constraints on life are highly influential. Antarctica's unique and limited biology make understanding how abiotic constraints impact on biological diversity and distribution much easier than in more complex systems. Being such a relatively stable environment, where life exists at extremes of cold and desiccation, any change to environmental constraints can lead to much more noticeable changes in biology than at lower latitudes. Knowledge gained from investigating Antarctica's biological diversity and distribution can then be applied to other, more complex, areas.

An important element in species distribution is water availability. In an arid environment such as Antarctica, the spatial distribution of water is an integral part of understanding the ecology. In this thesis the creation of a predictive water availability model of the Antarctic Dry Valley study area using Geographic Information Systems (GIS) and remote sensing is described. The aim of this model is to produce a relative index of liquid water available for biology using variables that influence the volume and distribution of water in the study area. This model can then be used as a significant part of a multivariate analysis of biocomplexity in the Dry Valleys exploring the ability to use abiotic environmental constraints to model likely biocomplexity.

The sources of water into this environment and its overland flow are modelled to determine the availability of water to sustain life. As well as the use of existing spatial data of glacier, lake and river locations, remote sensing is used to identify the availability of the spatially and temporally transient snow melt by calculating an average index of snow cover. Digital elevation data and hydrological flow algorithms are then used to determine likely flow and accumulation of liquid water.

This thesis is an exploration of methods and data that may be useful in the prediction of liquid water distribution. This research includes examining mathematical modelling of snow distribution, the use of remotely sensed thermal data, and various methods used when utilising remotely sensed data. The final outputs resulting from this project are a combination of the best suited and most practical data and methods. The following paragraph outlines how the creation of the model, the relevant knowledge and the experimentation with data and methods is structured in this thesis.

The remainder of this chapter will describe the environment of Antarctica and the Dry Valleys. Also outlined is the relationship of this project to the IPY Terrestrial Biocomplexity project and the contribution this research is making. A review of the current understanding of the nature of water and its relationship with biota is given in Chapter 2: The Importance of Water. Chapter 3: Spatial Data Modelling and Remote Sensing, is divided into two sections. The first section discusses why spatial modelling is useful for studying biology and describes key elements of hydrological modelling used in this research. The second section discusses remote sensing and its use for detecting snow. Chapter 4: Data Collection and Modelling, is a description of the steps taken to produce the predictive water model. This includes the software used to create the model, the Digital Elevation Model (DEM), and water flow model, as well as the acquisition and analysis of remotely sensed data. As this project is researching the methods of using remote sensing and GIS to model water availability in Antarctica, this chapter also presents the resulting model as well as its validation. Chapter 5: Discussion and Conclusion then covers the strengths and limitations of the model and its relevance to biocomplexity research. It also discusses further applications and additions that can enhance what has been achieved in this project, and revisits the objectives of this research.

1.2 Antarctica and the Ross Sea Region

Antarctica is perhaps the most unique and extreme environment on Earth. Often dubbed the continent of extremes, Antarctica's ice, climate, average altitude, wind, isolation, lack of liquid water and limited biology make up the distinctive and inhospitable continent. For these reasons Antarctica's environment is a setting for extensive scientific interest (Campbell, 2003). The extreme qualities have produced a location where biology is relatively simple and scarce, without long-term human occupation and influence (Peck, Convey, & Barnes, 2006; Powers, Ho, Freckman, & Virginia, 1998)

Antarctica is almost entirely dominated by ice with an average thickness of over 2 kilometres creating the highest average altitude of any continent. Antarctica's latitudinal location also means it is the coldest and windiest continent (Peck et al., 2006). Up to 2% (46,000km^2) of the Antarctic continent is ice free (Fitzsimons, Campbell, Balks, Green, & Hawes, 2001; McKnight et al., 1999; Peck et al., 2006). Approximately half of this ice-free ground occurs within the Ross Sea region, particularly in the McMurdo Dry Valleys of Southern Victoria Land, the continent's largest continuous expanse of ice-free ground (approximately 6000km^2) (Hemmings, 2001).

1.2.2 The Dry Valleys

The Dry Valley systems of Southern Victoria Land were formed by glaciers gouging deep valleys in generally an east-west orientation. These valleys were cut off from the flow of glaciers and ice from Antarctica's interior by the uplift of the Transantarctic Mountains. They remain ice-free through ablation of snow and ice which exceeds any accumulation

(Fitzsimons et al., 2001; Fountain et al., 1999; Friedmann, 1982; Hopkins et al., 2006; Horowitz, Cameron, & Hubbard, 1972).

The Dry Valleys of Antarctica contain alpine, piedmont and terminal glaciers, lakes mostly under permanent ice-cover, bare soils and stream channels (Gooseff, Barrett et al., 2003). Their mean annual air temperature is -20 to -25°C and in summer rarely rises more than 0°C. However the ground temperature may reach higher than 15°C for short periods during the day (Horowitz et al., 1972). For 2-3 months during the austral summer there is continual daylight and during the winter months there is continual darkness with valley floor temperatures falling as low as -40°C (Fountain et al., 1999). The cold temperatures vastly decrease water vapour content in the atmosphere and precipitation is scant (Horowitz et al., 1972), therefore qualifying the valleys as cold deserts (Peck et al., 2006). In the Dry Valley region the mean precipitation is limited to around 10 cm per year in the form of snow (Fountain et al., 1999). This aridity is enhanced in the Dry Valleys by the dry katabatic (down slope) winds off the Antarctic plateau increasing ablation and creating true desert conditions (Friedmann, 1982). Ventifacts and wind-drifted pebble ridges are created by these constant winds and, due to the low humidity, the snow often sublimes without any visible wetting of the ground (Horowitz et al 1972).

Bare rock makes up to 10% of the ice-free area and elsewhere poorly developed gravelly soils with mostly an absence of organic material are present (Hemmings, 2001). Most of the gravelly surface can be described as a ‘desert pavement’. This pavement is a relatively smooth layer of fine gravels, stone or rocks. It is formed mainly by surface weathering and winnowing. Rocks of all sizes are broken down over time and sorted by the wind and result in a stable aerodynamic surface of various particle sizes (Fitzsimons et al., 2001).

Widespread throughout the Dry Valleys is permafrost, a rock-hard mixture of permanently frozen ice and soil, from a few centimetres below the surface to over a meter depending on factors such as elevation and orientation (Fitzsimons et al., 2001; Horowitz et al., 1972; McKnight et al., 1999). The permafrost is divided into an active layer and true permafrost (Fitzsimons et al., 2001; McKnight et al., 1999). The active layer lies above the true permafrost to an average depth of approximately 0.5 meters; the true permafrost begins below this depth. The active layer differs from the deeper permafrost by the fact it freezes and thaws annually (Fitzsimons et al., 2001; McKnight et al., 1999).

Running through the desert pavement are stream channels of various sizes. The streams that create these channels are very different to most streams on Earth. These Dry Valley streams are fed by glacier melt and flow for up to 10 weeks a year (Fountain et al., 1999; McKnight et al., 1999). These streams vary in length from less than 1 kilometre to 30 kilometres and in width from 1 to 10 or more metres (McKnight et al., 1999). Liquid water only exists all year in ponds with high salinity or in large ice-covered lakes (Hemmings, 2001).

Life in Antarctica exists predominantly in areas such as the Dry Valleys were the land is free of permanent ice-cover. The latitudinal gradient of environmental conditions in the Ross Sea region has a distinct impact on biodiversity (Adams et al., 2006; Fitzsimons et al., 2001). Notable features of Dry Valley biology include the lack of terrestrial vertebrate animals and flowering plants. Primary producers are bryophytes, lichens, cyanobacteria and algae, and terrestrial fauna include collembola (springtails), mites and microscopic organisms such as protozoa, rotifers, tardigrades and nematodes. The largest terrestrial animals present in the Dry Valleys are the springtails and mites measuring only up to 2mm long (Adams et al., 2006; Fitzsimons et al., 2001).

According to the 2001 Ross Sea Region State of the Environment Report (Fitzsimons et al., 2001) biota in the Dry Valleys generally live in distinct forms of communities depending on their endurance of abiotic factors and reliance on other biota. These communities are outlined below.

Flush Vegetation

The first of these communities is 'flush' vegetation where water is reliably recurrent. This type of community is made of short moss cushions and turf subformations in regular patterns around the main watercourses, dominated by cyanobacterial crusts.

Algal Crust Communities

Surface communities of algal crusts vary from isolated patches a few centimetres in diameter to growths covering hundreds of square metres. Algal crust communities may contain various microorganisms, nematodes, tardigrades and protozoa. The growth of these communities depends on the regular availability of water during the short summer.

Desert Pavement Communities

Communities in the desert pavement most often occur near the coast and become increasingly absent in the drier areas inland. Distribution of these communities often occurs with regular snow patches. Microorganisms, particularly yeasts, are found at almost all but the driest sites. Springtails and mites also commonly occur in the desert pavement albeit much more scattered in their distribution.

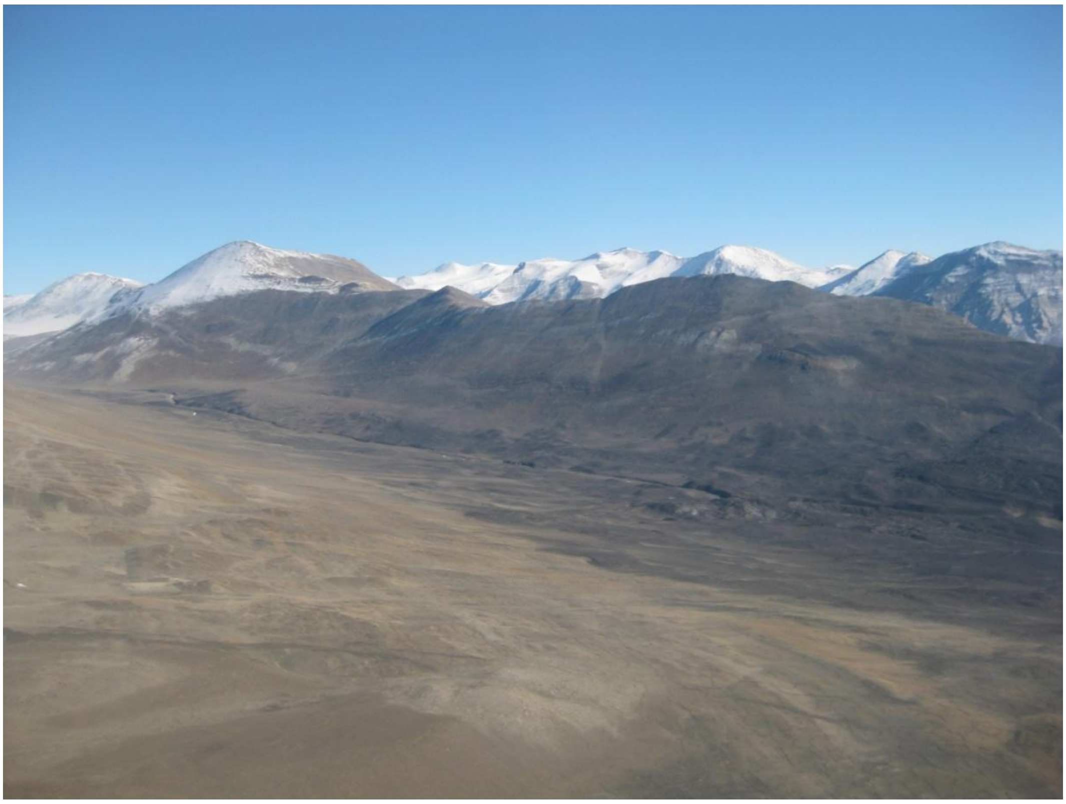
Rock Surface Communities

Rock surface communities are dominated by lichens along with some bryophytes in crevices and other sheltered microclimates. Crustaceous and foliose lichens are predominant and may develop anywhere that is protected from wind (which causes abrasion), has enough light and has a water supply from blown snow or melt.

Endolithic Communities

Endolithic communities are biotic communities occurring beneath the rock surface (hypolithic) or within rock fissures. Endolithic communities can grow on most north-facing rock surfaces with enough porosity that they receive exposure to the sun. On sunny days the temperatures within the endolith zone can reach much greater temperatures than the surrounding air temperature. This form of community is the most common vegetation community found in the Dry Valleys.

Figure 1.1 Marshall Valley, Southern Victoria Land



1.3 IPY Terrestrial Biocomplexity Project

There is currently underway an IPY Terrestrial Biocomplexity project (referred to as the IPY Biocomplexity project in this thesis) linking Canterbury, Massey and Waikato Universities along with numerous international collaborators intending to describe the biocomplexity of sites in the Dry Valleys, Antarctica. Biocomplexity is the biological organisms, their community structure and functional linkages. Determination of biocomplexity requires describing the biota at all levels within a community and discovering how the community structure can be influenced by the presence of key organisms and geochemical features. The main goal of this research is the development of an integrative multivariate model that allows for sensitivity analysis of systems of the biocomplexity in the Ross Sea region. The research is being funded by the Foundation for Research Science and Technology (FRST) as part of its International Polar Year (IPY) funding.

The *Protocol on Environmental Protection to the Antarctic Treaty (1991)* (British Antarctic Survey, 2007) designates Antarctica as "a natural reserve devoted to peace and science" (Hemmings, 2001). New Zealand is committed to conservation of Antarctica and the Southern Ocean for the present and future generations of New Zealanders and the World (Peterson, 2004). As such knowledge about biodiversity and the linkages and interactions of biota and the environment are important for implementation of such goals. Little is still known of the full complexity of biological communities and the factors controlling the diversity of these communities. Key research questions outlined in the Antarctica New Zealand Science Strategy include: what is the terrestrial biodiversity at ecosystem, species and genetic level of the Ross Sea region and how does the polar environment affect physiological and biochemical aspects of animal behaviour? (Peterson, 2004). This study therefore is an important step in answering these questions.

The results of this project will contribute to New Zealand's active role of responsible stewardship under the Antarctic Treaty in conserving, protecting, and understanding the biodiversity of Antarctica (Peterson, 2004). Before planning for environmental protection can take place, knowledge is required for understanding what steps need to be taken to conserve the unique biology in the Dry Valleys. This research will enable end users, in particular government agencies, to identify and protect the current biodiversity of the Ross Sea Region and to manage environmental impacts within the highest international forums.

Not only can the impacts of localised variables such as the movement of personnel and equipment and the establishment of research bases be identified but the effects of greater scale environmental change, such as climate change, can be identified. The Antarctica New Zealand Science Strategy also has key questions asking: how sensitive are Antarctic organisms and communities to climate variability and climate change; and have Antarctic species responded quickly or slowly to environmental change? (Peterson, 2004). Climatic constraints are chiefly responsible for Antarctica's current diminutive ecosystems. Biotic constraints such as predation and competition are very minor. As such, an increase in ambient temperature, water availability, or light regime will promote the development of new effects on ecosystem functions (Kennedy, 1995). What may be small variations in temperate regions would have far greater impact in polar regions (Barrett et al., 2006). This magnification is known as polar amplification (Fountain et al., 1999). The Dry Valleys are particularly sensitive because small changes can lead to greater variations in the hydrologic regime (Fountain et al., 1999). Any climate warming is therefore predicted to modify the spatial pattern of Antarctica's biota. Species currently limited by certain environmental intolerances may extend their range of development southwards and to higher altitudes (Kennedy, 1995).

1.3.2 Denton Hills Study Area

The IPY Biocomplexity project is currently undergoing field reconnaissance and sampling over the 2008/2009 austral summer in the Dry Valleys collecting data in preparation for the development of the model. The study area includes three main valleys in the Denton Hills area, the Garwood, Marshall and Miers Valleys, as well as surrounding areas, totalling an area of approximately 300km², lying within 163°20'52"E 77°59'55"S and 164°32'26"E 78°11'58"S. These valleys are smaller than the large Dry Valleys further north making extensive sampling more viable, yet the diversity of these valleys is greatly representative of the Antarctic Dry Valley environment. Five main glaciers influence the hydrological regime in the study area. The Garwood and Joyce Glaciers in the north and north-west form melt rivers into Garwood Valley and Shangri-la. In the south-west, the Miers and the Adams Glaciers feed streams into Miers Valley and Lake Miers. The Marshall Glacier at the western end of Marshall Valley feeds the Marshall Stream, and many smaller glaciers and permanent snow patches are scattered predominantly along the western ends of the ridges between the valleys. Coursing through the valleys are ephemeral streams that will flow during the summer once the glaciers, lakes and snow begin to melt, and will then freeze and sublime during the winter. Three main lakes, Lakes Buddha, Miers and Colleen, are in the study area, as well as a number of smaller lakes and ponds. Being glacier gouged valleys, the valley sides are steep and rocky, and at the eastern ends have rugged moraine formed floors. These valleys do receive a greater maritime influence as they are coastal and open out to the Ross Ice Shelf not far south of its northern edge. They are sheltered from the Antarctic Plateau by the Royal Society Range in the west and thus can receive less katabatic influence. The elevation of these valleys ranges from sea level to approximately 1300m.

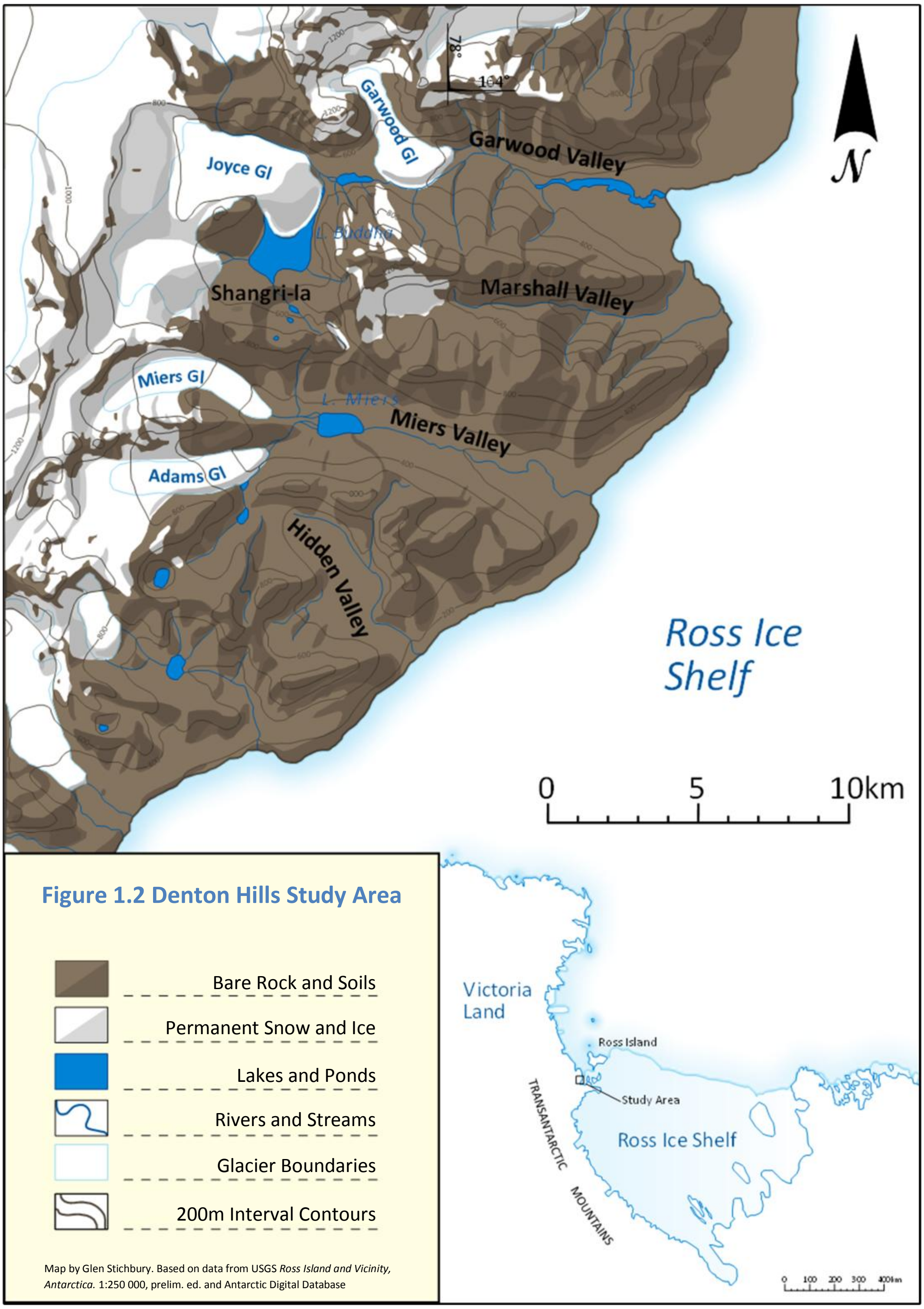


Figure 1.2 Denton Hills Study Area

Map by Glen Stichbury. Based on data from USGS *Ross Island and Vicinity, Antarctica.* 1:250 000, prelim. ed. and Antarctic Digital Database

1.4 My Contribution

GIS provides an ability to analyse and explore parameters contributing to biocomplexity in ways that would otherwise be too costly, too time consuming and too intense for manual computation. This is no truer than for the study area in this project where isolation and extreme environmental conditions are considerable limitations to in situ observations. GIS and remote sensing will provide a means for gathering and analysing data with little need of field validation. My contribution to the project described in this thesis is the combined use of GIS and remote sensing to gather data for and develop a model of the predicted location of biologically available water in the Dry Valleys.

The widespread use of remotely sensed data is relatively new in Antarctica and data acquisition can be difficult. This project requires the investigation of the availability and use of data for GIS applications. This will include searching for data that will fit into the frame of this project in terms of being readily available and free to access. Numerous data sources from multiple remote sensing systems will be examined for their suitability. Once the data is obtained, further preparation for analysis may be required using remote sensing and GIS software. This may include the conversion of the images to suitable formats and pre-processing to display corrected data. Once ready, the data can then be combined into a model using GIS that predicts the spatial location of water in the Dry Valleys. This will provide data for the wider multivariate model as well as provide data on the various water variables for further study.

Research Goals

Overall research goal:

- Evaluate the potential for GIS and remote sensing to be used to predict biologically available water in Antarctica.

To achieve this overall goal, several objectives must be achieved:

- Examine current understanding of water in Antarctica and its relationship with biota.
- Explore various remotely sensed data for use in predicting water distribution within the context of this study.
- Experiment with various methods of preparing and analysing the data using GIS.
- Produce a predicted water availability model of the study area, as well as various datasets for further multivariate analysis of biocomplexity.

This study is quantitative in nature and examines empirical data. Quantitative geography is taken to be an empiricist, positivist approach to the discipline (Sheppard, 2001). GIS is seen as inherently quantitative and therefore empiricist as its computational roots are in Boolean mathematics and its manipulation of empirical spatial data (Sheppard, 2001). Study in physical geography is also reliant on other sciences such as physics and chemistry which are also widely rooted in positivism (Thorn, 2003). Positivism was given its theoretical identity by Auguste Comte (1798-1857). Comte claimed that positivism was however based on all who contribute to science, particularly Bacon, Descartes and Galileo. Comte suggested our knowledge should be based on physical phenomena/empirical data, gained through observation and experience (Mill, 1961).

Positivism is seen by many geographers (particularly human geographers) as an outmoded theoretical philosophy. This is particularly due to its narrow view of the source of knowledge. Although a positivist approach suits this research project, the shortfalls of positivism, particularly the inescapability of subjectivity and human bias must be acknowledged. Many decisions made in this project may include a degree of subjectivity but such decisions are justified with logical arguments. The strengths and weaknesses of this will be discussed more in Chapter 5.

Chapter 2. The Importance of Water

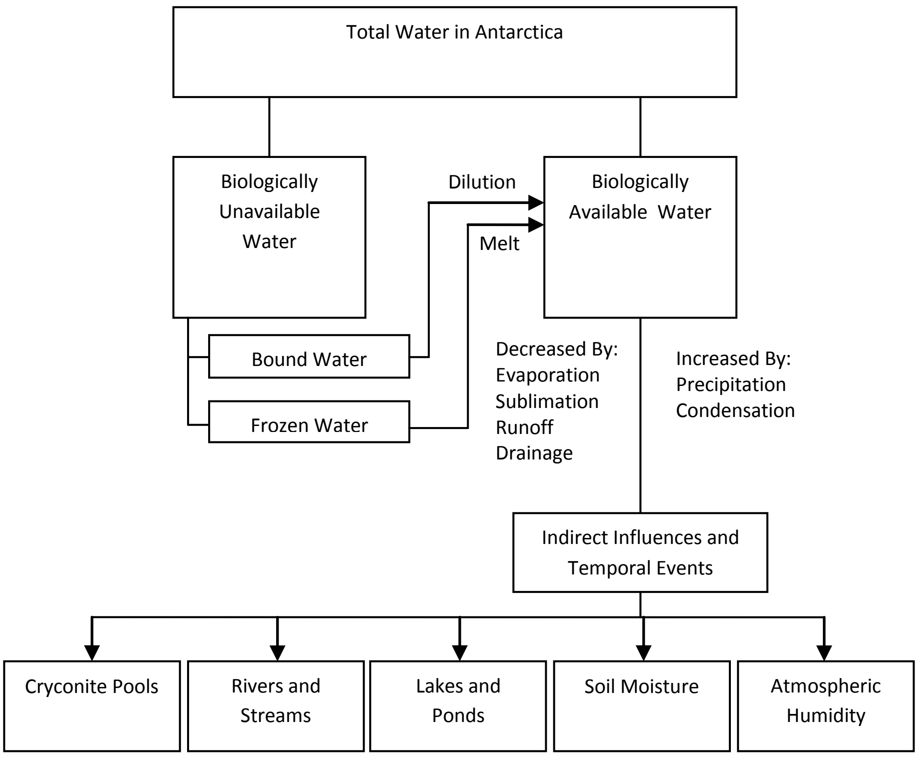
This chapter discusses Antarctic researcher's current understanding of water in the Dry Valleys and its relationship with biology. It discusses the importance of water, the small array of water sources in the Dry Valleys and the nature of its availability. It then explains what causes such relatively small quantities of available water in the Dry Valleys, finishing with its implications for Dry Valley biota.

2.1 Water in Antarctica

The key ingredient looked for when searching for life, no matter whether it is on Earth or on a moon of a distant planet, is water. The ecological axiom goes: 'where there is water, there is life.' This is true in Antarctica also, a continent containing a vast store of ice with an average thickness of over 2 kilometres covering over 95% of the continent (Peck et al., 2006). It is surprising to some then to learn that even though Antarctica has this enormous store of ice and snow that it is also the driest continent on Earth (Kennedy, 1993). This is due to the latitudinal location of Antarctica, situating the continent in a very cold climate where only coastal areas may receive an air temperature above 0°C for rare short periods in the austral summer (Horowitz et al., 1972). As it is so cold, water that would otherwise be in a liquid form is frozen in the form of ice or snow. Kennedy states that in ecology the nature of water can be divided into two forms: biologically unavailable water (water that is frozen or attached to other molecules) and biologically available water (water in a liquid state or unattached to other molecules)(Kennedy, 1993). As such, the great majority of water stored in Antarctica is unavailable to support life.

In the few ice-free areas of continental Antarctica, melt water runoff is vitally important because of the desert environment (Hemmings, 2001). Within the Dry Valleys large amounts of liquid water may exist in rivers, lakes and pools for short periods of the summer (Kennedy, 1993). Soil moisture (water occupying space between soil particles (Strangeways, 2003)) can also exist in varying - although believed mostly very limited - quantities. All of these sources of liquid water are governed by various environmental characteristics. Exposure to wind and sun, aspect and shadows, proximity to snow, surface colour and stoniness, slope gradient and seepage all influence the availability of water (Campbell, Claridge, Balks, & Campbell, 1997; Kennedy, 1993). Figure 2.1, based on a model produced by Kennedy, gives a visual portrayal of the variables and relationships that influence the nature of water in Antarctica. In the following sections the main water source variables will be investigated further, including snow, glaciers, rivers, lakes, permafrost and other less easily quantifiable factors.

Figure 2.1 Water in Antarctica



(Based on a figure by Kennedy, 1993)

2.1.2 Snow

Snowfall in the Dry Valleys is perhaps one of the easiest spatially and temporally transient sources of water that can be located using GIS and remotely sensed data. It may also be one of the most difficult to have its influence on water availability quantified. The scant precipitation that falls in the Dry Valleys falls mainly as snow - although small amounts of rain have been known to occur during the summer (Fountain et al., 1999). This precipitation is brought by easterly winds as low pressure systems pass over the open water of the Ross Sea. As the systems travel west over the Dry Valleys and rise over the Transantarctic Mountains it will precipitate, although precipitation becomes less common the further west it travels (Fountain et al., 1999). Snow also accumulates in the Dry Valleys, particularly in the winter, from being blown in off the Antarctic plateau and Transantarctic Mountains with westerly winds. This snow will accumulate in depressions, leeward areas and along the faces of glaciers (Gooseff, Barrett et al., 2003).

It is generally accepted that the influence snow has on water availability is limited due to the high rate of sublimation in the Dry Valleys (Campbell, 2003). Sublimation is the conversion of ice crystals directly to vapour without melting (Jacobson, 2005). The rate of sublimation is high due to two interlinked causes. The first is the extremely low air humidity caused by the cold climate. This is then coupled with the strong katabatic (down slope) winds descending into the valleys from the Antarctic plateau. These winds are cold and have high speeds which further decreases air humidity (Doran et al., 2002). Because of this low humidity, snow patches can sublime without visibly wetting the ground (Horowitz et al., 1972). The strong and in some areas nearly constant katabatic winds also decrease the ability for snow to provide melt water by shifting snow without it having time to supply moisture to the soil (Bockheim, Campbell, & McLeod, 2007; Campbell et al., 1997).

When snow does melt its supply of liquid water can vary. Generally it is smaller snow patches that provide soil moisture, particularly around the edges of the snow patch (Campbell, Claridge, & Balks, 2000). Melt is more likely to occur on north-facing areas than on areas with a southern aspect due to an increased amount of solar energy received on northern faces (Gooseff, Barrett et al., 2003), increasing the available energy to melt snow rather than ablate through sublimation. Snow melt is less likely to contribute to melt-water streams. However, in the spring, snow that has been deposited against the faces of glaciers or has drifted off the top of the glaciers do contribute to streams before disappearing in the early summer (Fountain et al., 1999).

Although the amount of biologically available water produced by snow melt may be limited, it is none the less an important water source requiring investigation. Seasonal snow patches may be used to predict biocomplexity controls as it provides moisture, insulation and hinders deposition of marine aerosols (Gooseff, Barrett et al., 2003). Surface soil horizons have the greatest increase of moisture content after snowfall, although within two days moisture content normally returns to ambient levels (Campbell, 2003; Campbell et al., 2000). If a snow patch remains for longer periods and slowly melts, water moisture levels may remain high for a number of weeks (Campbell, 2003; Campbell et al., 2000). Snow increases soil moisture levels not only at the edges or beneath the snow cover but can also raise moisture levels in a zone a few meters around it through the capillary flow of water laterally through the soil (Campbell, 2003). Snow's effects on microclimate can also increase moisture levels as melt water beneath a snow patch can be protected from evaporation (Gooseff, Barrett et al., 2003). Snow cover can provide insulation from the plummeting air temperatures during Antarctica's winter and also offer protection from wind desiccation (Tappeiner, Tappeiner, Aschenwald, Tasser, & Ostendorf, 2001). Snow cover may also be disadvantageous to a site's favourability to biota. Snow cover reduces soil temperatures due to its high albedo (reflectance), reflecting solar energy that could otherwise heat soils (Gooseff, Barrett et al., 2003). Melt water, particularly small amounts such as from snow patch melt, can increase the effects of freeze/thaw cycling and therefore use more solar energy to melt frozen water than heat the soil (Campbell, 2003).

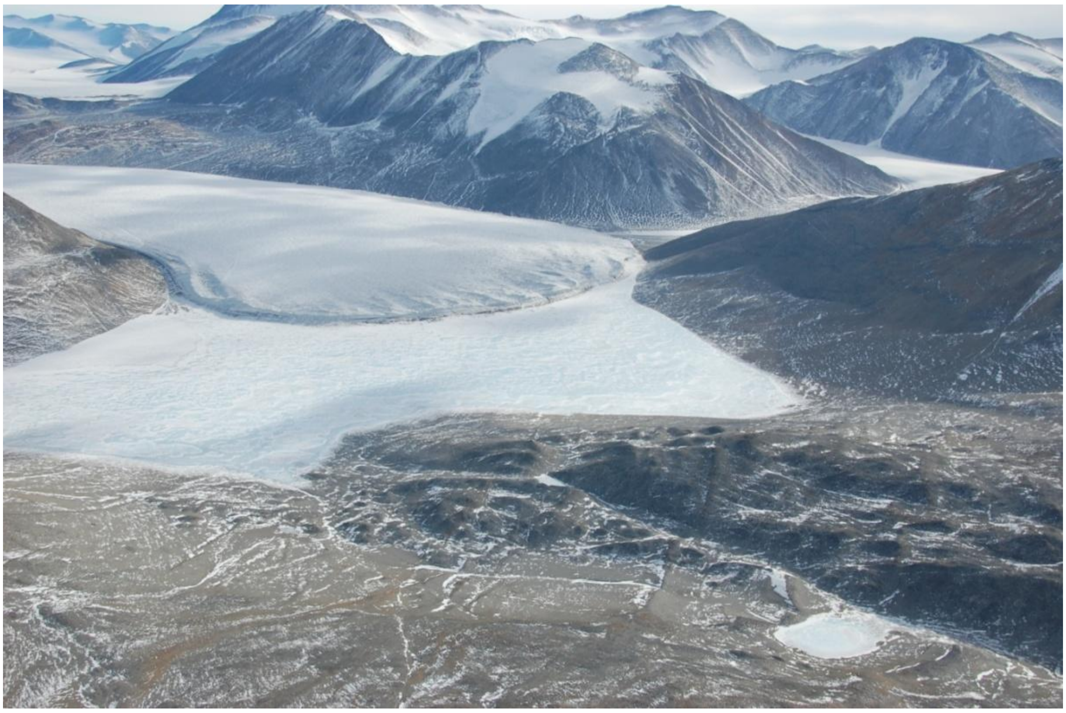
Figure 2.2 Snow Melt Runoff in Upper Garwood Valley

2.1.3 Glaciers, Lakes and Rivers

There are a number of glaciers, lakes and river channels throughout the study area and all of the Dry Valleys. These all form important sources of water for short periods during the austral summer. Glaciers in the Dry Valleys are made up of various types including alpine, piedmont and terminal glaciers (Gooseff, McKnight, Runkel, & Vaughn, 2003) in a variety of sizes. Differences in glaciers are a result of topographical differences. Glaciers are larger where there are greater snow accumulation areas (generally in the western end of the valleys where the altitude is greater and the terrain more mountainous). Glaciers on northern aspect slopes receive more solar radiation and are therefore generally smaller (Fountain et al., 1999). Glaciers provide the greatest and most regular source of water in the Dry Valleys, feeding melt water streams which in turn feed the various lakes (Doran et al., 2002; Fitzsimons et al., 2001). Melting of glaciers can occur from early in the summer as the vertical faces at the periphery of the glaciers are more perpendicular to the lower sun angle and therefore receive a greater amount of solar radiation, and occurs for the same reason in the late summer (Fountain et al., 1999).

Dry Valley lakes have received much scientific interest. However in this project it is the periphery of the lakes that are of importance. Dry Valleys lakes are commonly covered permanently by ice, often between 4 and 5 metres thick (Gooseff, McKnight et al., 2003; Peck et al., 2006). Some lakes can even be completely frozen although when there is enough transparency in the ice to allow light through, sediments within the ice may be heated enough to maintain surrounding liquid water. It is during the late summer however when moats of liquid water can form around the edges of lakes allowing the interchange of water and nutrients around the periphery of the lakes (Peck et al., 2006).

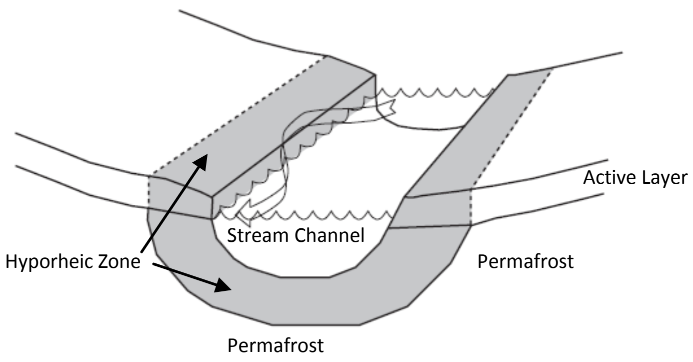
Figure 2.3 Lake Buddha and Joyce Glacier, Shangri-la



For up to 10 or so weeks every summer, melt water streams become an important feature within the barren Dry Valleys (McKnight et al., 1999). During the winter they will drain, evaporate or freeze and sublime (Kennedy, 1993). The streams flow down the sides of the valleys and along the valley floors carrying water, solutes and sediments to the lakes (McKnight et al., 1999). The amount of water flow varies daily depending on temperature, and channel courses can vary every year. Fountain et al. (1999) list a number of common features of Dry Valley Streams. At the source glacier, the streams will flow along the moraine, there can be little or no alluvium and the steams may be covered by a thin layer of ice. In areas of steep gradient, the active channel may be 5 – 10 metres across with steep banks and a bed containing large rocks and deposited sediment at the margins of the active channel. Moderate gradient streams have a bed of flat stone pavement, steep banks and less sediment deposition. Shallow gradient areas near lakes or second order steams in the valley floors have sandy braided channels and low banks. The biochemistry of the streams is influenced by the physical and chemical processes within the valley watershed (Runkel, McKnight, & Rajaram, 2003).

At either side of the stream channel is a zone where water seeps out laterally forming dark bands. These areas are known as the hyporheic zone, defined as a porous area of the stream bed and bank where water, previously in the stream, mixes with subsurface water before returning to the stream, although in the case of Dry Valley streams it is more the saturated alluvium adjacent to the stream. (Gooseff, McKnight et al., 2003; McKnight et al., 1999; Runkel et al., 2003) The depth of the hyporheic zone is limited by the depth of the active permafrost layer (discussed in 2.1.4), so as the summer progresses and the active permafrost layer thaws to deeper levels, so too can the hyporheic zone become deeper (Fountain et al., 1999; McKnight et al., 1999). The lateral extent of the hyporheic zone can be quite substantial due to the porous nature of the alluvium and the vertical boundary created by permafrost.

Figure 2.4 Hyporheic Zone



(Based on figure by McKnight et al., 1999.Copyright, American Institute of Biological Sciences)

The porous nature of the alluvium also allows for a rapid rate of exchange between the stream and hyporheic zone (Gooseff, McKnight et al., 2003; McKnight et al., 1999). Along with providing a saturated zone as an available short term habitat, the hyporheic zone feeds dissolved nutrients into the streams and lakes. Although previous studies on hyporheic zones limit this area to stream banks, the type of hyporheic zone defined above in the Dry Valleys could also refer to areas around lakes where melt water moats form and seep out laterally and so are included in this study.

Melt water from glaciers, lakes and rivers provide the greatest proportion of biologically available water every summer in the Dry Valleys. Within the melt water streams biotic communities can thrive. Microbial biota, primarily cyanobacteria, as well as chlorophytes and diatoms are common. Fauna include nematodes, rotifers and tardigrades. Algal mats that grow in these streams can live through long periods of desiccation and can develop high biomass (McKnight et al., 1999). Other areas of 'flush' vegetation, such as moss cushions, can exist around main water sources and damp areas (Kennedy, 1993; Waterhouse, 2001). Such communities in streams and other 'flush' areas lay dormant and are, as McKnight et al. put it, 'turned on' by the arrival of water and nutrients as glaciers melt and create streams of melt water which carry nutrients as they flow towards lakes (McKnight et al., 1999).

Figure 2.5 Main River Channel, Garwood Valley

2.1.4 Permafrost

Bockheim and Hall define permafrost as soil and/or rock that remains below 0°C for at least two consecutive years, and as such moisture in the form of water or ice does not necessarily need to be present. Two forms of permafrost are present in the Antarctic Dry Valleys: in coastal areas where there is a greater availability of moisture, ice-cemented permafrost is prevalent, whereas inland valleys dominantly contain dry-frozen permafrost, a form of permafrost possibly unique to Antarctica (Bockheim et al., 2007; Bockheim & Hall, 2002). The Dry Valleys of the Denton Hills area, the study area of this project, contain predominantly ice-cemented permafrost, however in the upper Miers Valley there is a zone of dry-frozen permafrost. The total ice-cemented permafrost of the study area makes up about 98% of the region with 1% dry-frozen permafrost and the other 1% made up of ground ice (made from the grounding of glaciers) (Bockheim et al., 2007).

Permafrost can also be divided vertically into two distinct layers, true permafrost and an active layer, the difference between the two being the active layer freezes and thaws annually (McKnight et al., 1999). As such ice-cemented permafrost can possibly be a source of moisture for biota and temperature may have a direct link to the availability of this water source. This active layer is more important in coastal areas such as the valleys of the study area where the climate is warmest, precipitation is greatest and soils are the youngest which all contribute to a higher water content in the permafrost (Campbell et al., 2000). The thickness of this active layer varies depending on elevation and proximity to the coast, with a range of 30-60cm in coastal areas to 15-20cm near the polar plateau (Bockheim & Hall, 2002). In the Denton Hills area the estimated active layer depth is 20-45cm (Bockheim et al., 2007).

Surface albedo plays an important role in determining the active layer depth. Areas with darker coloured rocks and soil absorb more solar radiation than lighter coloured surfaces and so have higher soil temperatures influencing active layer permafrost melt. This can fluctuate daily as temperatures change and clouds may cover the area. Other influences on active layer depth include snow cover, relief, vegetation, hydrology and glaciers (Bockheim & Hall, 2002). As an example, areas of northern aspect would be expected to have a higher soil temperature due to increased solar radiation increasing active layer depth, whereas snow cover insulates the surface from solar radiation and so would reduce active layer depth.

In general the active layer will melt in early to mid November and refreeze early in February. During most of the thaw period, the upper active layer may remain above freezing temperatures and so there may be few freeze/thaw cycles. However as soil depth increases the effects of changing temperatures and the period of thaw diminish (Campbell, 2003). As such, the availability of water varies vertically as well as horizontally from other sources such as streams and snow (Kennedy, 1993). Permafrost thaw as a source of water for biology is likely a far smaller factor than that of melt streams and precipitation; however it may be a regular contributor to soil moisture and micro-climate each summer.

2.1.5 Other Factors

There are other variables that may influence the availability of biologically available water in the Dry Valleys. The movement of moisture within soil can be influenced by topology, salinity, freezing fronts and ice-cemented layers (Campbell et al., 2000). Vapour and microclimates are also localised variables that provide enough relief from desiccation in such an arid environment. Topological variables can influence the energy balance relationships at a given site, such as the amount of solar energy being received by the site according to aspect, slope and albedo. The type of surface (e.g. porosity) can also influence the potential for trapping moisture or evaporation (Campbell et al., 1997). Low clouds and fog and microclimate humidity within the soil may also be important factors which influence vapour availability within soils (Campbell et al., 1997). Studies done by Campbell find that weather is an important factor in changing soil microclimate as fluxes occur after snowfalls and in different temperature and humidity levels (Campbell, 2003). Friedmann suggested that relative humidity within airspaces of rocks and soils are probably the best indicator of the availability of water (Friedmann, 1982). Salts are another important factor influencing the availability of biologically available water as salts attract water and lower its freezing point. In fact it is only in highly saline pools that water exists in a liquid state year round in Antarctica. As precipitation is so low in the Dry Valleys there is a lack of leaching within the soils and so this leads to the accumulation of salts in the soils (Powers et al., 1998). These salts can increase water levels to 10 times the amount of surrounding areas (Campbell, 2003) and prolong the time water is present in a liquid form (Campbell et al., 1997). However as water becomes increasingly saline it become decreasingly biologically available as biota reach limits in their ability to live on salt water.

Figure 2.6 Clouds Across Lake Colleen, Upper Garwood Valley

(Clouds and vapour can provide moisture to dry upper slopes for vegetation such as lichen)

2.2 The Cause of Water Scarcity

As stated in previous paragraphs, it is a combination of climatic forces that severely limit the availability of liquid water in the Dry Valleys. During the winter, coastal areas are encased in vast expanses of ice and temperatures remain so low that water remains in a constantly frozen state, evaporation and the condensing of vapour is non-existent and so leads to no precipitation. Any ablation of ice is only through sublimation as there is virtually no solar radiation to cause melting. As summer air temperatures will remain below 0°C most of the time, air humidity will also remain extremely low. This has two main effects. Firstly, precipitation is sporadic and sparse (Kennedy, 1993). Any snowfall that does occur and melts will only have a limited temporal impact on water availability (Campbell et al., 1997). Secondly, combined with the strong and persistent katabatic winds which aid the driving down of air vapour content, there is a greatly increased rate of sublimation (Campbell et al., 1997; Fountain et al., 1999; Kennedy, 1993).

Not only is there limited input of water into the system due to the climate, the high porosity of the ahumic mineral soils cause fast draining and therefore contribute to the limited temporal stability of liquid water (Kennedy, 1993). Overall the loss of water through ablation in the Dry Valley systems greatly outweighs the input of water resulting in a negative net water balance (Kennedy, 1993).

2.3 Biological Effects of Water in the Dry Valleys

McKnight et al. (1999) extend the ecological axiom “where there is water, there is life”, to suit the situation of the Dry Valleys. “Where there has been and will be water, there is life” is much more apt for life in the Dry Valleys. In the past, the extremely low temperatures of continental Antarctica were seen as the primary determinant of the sparse terrestrial life in Antarctica and, in a way, this is still true. However, the extreme cold is the primary cause of what may truly be the main limiting factor of terrestrial life in Antarctica: the scarce existence of biologically available water. Water is the essential ingredient of all terrestrial ecosystem functions, including chemical and physical change, nutrient transportation and leaching, and biological activity and interactions (Campbell et al., 1997). Even in warmer climates if water is not available then life will not exist. Therefore the freezing and melting of water in the Dry Valleys can be seen as a binary switch, turning off and on areas as habitats for terrestrial life (Fountain et al., 1999).

Temperature is still definitely an important factor on its own. Terrestrial biota need to be able to survive the stresses caused by extreme cold to exist in the Dry Valleys. Other factors, such as wind scouring and soil chemistry, are also notable limiting factors on terrestrial life. However studies have been carried out which separate out the influences of cold and desiccation (e.g. Janetschek, 1970, Kennedy, 1993). It is concluded that, at least at times, terrestrial life relies on the availability of water (Janetschek, 1970) and that terrestrial life fluctuates in accordance to water availability more than temperature change (Kennedy, 1993). Kennedy found that peaks in biotic populations did not coincide with maximum temperature. Instead the optimal growth period occurs during the spring thaw rather than at times of maximum temperature (Kennedy, 1993).

The latitudinal gradient of temperature decline is certainly a macro scale factor on the determination of species colonisation and survival. The extreme aridity of the soils of the Dry Valleys, increasing particularly as the valleys progress inland are another large scale effect on species location (Powers et al., 1998). At more mid and micro scales it is the moisture status at particular habitats, influenced by the various factors discussed previously, that determine the patterns of species existence, dominance and diversity in the Dry Valleys (Fountain et al., 1999; Hayward, Worland, Convey, & Bale, 2004).

As such, terrestrial biota are restricted in their distribution according to their ability to survive the stresses of desiccation (Convey, Block, & Peat, 2003; Powers et al., 1998). This limitation is more important than biotic factors such as predation (Hogg et al., 2006). Many species will remain dormant throughout the winter period when water is unavailable as the melting of any ice is beyond the capabilities of Dry Valley terrestrial organisms (Kennedy, 1993; McKnight et al., 1999). Species such as yeasts and Protozoa prevent water loss through encapsulation. Microarthropods possess waxy cuticles and live in soil profile, sublithic and endolithic habitats. Lichens can survive extreme amounts of water loss and absorb moisture from fogs, mists and low clouds (Kennedy, 1993).

As Campbell (2003) points out, there is, however, a negative effect on habitat favourability produced by the presence of water. Water can have a negative impact on the thermal regime of a habitat. Closer proximity to snow cover and permafrost produce lower soil temperatures. This also means more freeze/thaw cycles. Energy that would otherwise be used to heat soils is instead being used to melt ice, therefore making a less favourable soil temperature environment.

Chapter 3. Spatial Data Modelling and Remote Sensing

This chapter is divided into two sections. The first discusses the role of modelling in biological sciences and geography. This section begins with a discussion on why abiotic modelling is relevant to understanding biology in the Dry Valleys. It then introduces the use of computer modelling, in particular the hydrological modelling used in this research. It explains how the Compound Topographic Index works to show water availability and discusses two key considerations to be made when using this model – Digital Elevation Model resolution and the choice of flow path calculation method. The second section of this chapter discusses the use of remote sensing to capture data for this research. It gives a description of what remote sensing is, as well as its use in gathering data on snow. This section also gives an outline on another method initially explored for gathering such data.

3.1 Spatial Data Modelling

3.1.1Environmental Domains Analysis – Justification for Abiotic Study

The most comprehensive method for understanding biocomplexity at any given site is to observe and record all biota existing at that site. It is soon apparent the logistical requirements for any such operation at any site would prove the vast majority of such studies unfeasible. Therefore, another approach is needed to investigate biocomplexity that has less stringent requirements of time, funds, equipment and transportation. This involves understanding the limiting factors of a given site that may influence biocomplexity and categorising sites by these limitations. A commonly used term for this approach is environmental domains analysis. Environmental domains analysis (EDA) is the grouping of environments into categorical domains according to their limiting factors. These include climatological, hydrological, geological and biological factors. EDA is used as a means of grouping environmental factors to gain a prediction of likely biology at a given domain primarily for environmental management.

The basis for EDA are the principles of natural selection which dictates that the biological attributes of an organism are closely related to the environment in which it occurs (Kennedy, 1999). Shelford's law extends this logic to suggest that organisms have ecological maximums and minimums of tolerance, with a range in between (Spellerberg & Sawyer, 1999). Therefore the fitness of an organism to exist within an environmental domain is determined by a combination of biotic and abiotic selective forces that are defined by habitat characteristics (Peck et al., 2006).

The limiting factors discussed above can be both biotic and abiotic in character. Biotic limitations are generally competition, herbivory and predation (Hogg et al., 2006). Abiotic limitations include a vast range of environmental factors such as water availability, temperature, wind, soil and rock makeup and chemistry, slope, aspect, and solar radiation to name a general few. All of these limiting factors are interlinked and have various degrees of limitation depending on the given organism. EDA, however, focuses on the abiotic limiting factors. This is because environmental factors are much easier and cheaper to sample and are relatively temporally stable (Belbin, 1993; Leathwick, Oveton, Emmett, McLeod, & Lynn, 2001). Going back to the logic above, it follows that by characterising the specific environment by its constituent limiting factors, the biological characteristics needed to survive in that environment can be identified. Therefore species with these traits are more likely to be present in the environment than those without (Kennedy, 1999).

EDA's come in a variety of forms. This is greatly determined by the spatial framework determined by the analysis requirements. Clarkson and Stephens define a range of spatial filters from coarse to fine: ecological regions and districts, bioclimatic zones, hydrologic class, land systems, ecological class and ecological unit, ecosystem or vegetation type (Clarkson & Stephens, 2000). They also state that the scale of the investigation is always going to be important. The relationships between limiting factors that are evident at a coarser resolution may disappear at finer resolutions (Clarkson & Stephens, 2000).

The use of EDA in Antarctica is especially beneficial. The logistics required for any field scientific research is greatly exaggerated in Antarctica due to its isolation and extreme environmental characteristics increasing the difficulty and danger of travel to, from and within the continent. Antarctic travel requires large amounts of planning, medical fitness and finances for supply of the likes of equipment and fuel. Not only this, as Antarctica has had relatively little human occupation and is such a slowly changing environment, human activity in Antarctica has a high risk of negative environmental impacts. Although logistical constraints are a large limiting factor, scientific reasons also indicate that the use of EDA in Antarctica is particularly useful. As there is very little predation and competition, it is practical to attribute the determination of biota in Antarctica to abiotic environmental factors (Kennedy, 1999; Peck et al., 2006).

An EDA has been previously prepared for the Antarctic continent (Morgan, Leathwick, Price, & Keys, 2005). Other examples of large scale EDAs exist in New Zealand (Clarkson & Stephens, 2000; Leathwick et al., 2001) and globally (Bastian, 2000; Pojar, Klinka, & Meidinger, 1987). These classifications are at coarse resolutions. Although useful for wide scale understanding and management, these classifications become less useful as the resolution is increased. At these scales climate can be seen as a good starting point for determining the nature of terrestrial ecosystems (Pojar et al., 1987). Indeed Kennedy found that that the environmental stresses that limit biota increase with the distance south. Notably temperature, precipitation and solar radiation all decrease according to latitude (Kennedy, 1999). Although particularly important at a macro scale, these factors cannot alone determine the potential biocomplexity.

This project therefore requires environmental analysis at a finer resolution than that which is presently available. Local variations in topography or microclimate can strongly influence biota (Spellerberg & Sawyer, 1999), which is particularly the case in the Dry Valleys. As much of the limited water does not directly (or at all) come from precipitation, a greatly important factor is the spatial and temporal availability of water. As these factors have little representation in coarser resolution studies such as a continent wide EDA, the factors require investigation at a scale relevant to the IPY Biocomplexity project that this research contributes to. The utilisation of GIS for finer resolution analysis is useful for a number of reasons. These include the ability to store and compute large amounts of data and its ability to spatially model variables and predict distribution (Spellerberg & Sawyer, 1999).

Although this project will not, as such, be defining environmental domains, the logic behind it is the same as that being used to predict biocomplexity in the Dry Valleys. The IPY Biocomplexity study will use the underlying environmental factors that influence biocomplexity to predict levels of complexity at sites throughout the Dry Valleys. There are limitations to such a study however. Temporal change, either biotic or abiotic, that can influence biocomplexity may not be included in the limiting factors (Clarkson & Stephens, 2000). When factors are clustered together in order to categorise limitations, the centre of the cluster is going to be more representative than the periphery (Belbin, 1993). The Dry Valleys do compensate for these limitations. Temporal change in limiting factors has historically been slow. Indeed apart from direct human contact, climate change is seen as the only other factor that is having any noticeable impact on the Dry Valley environment (Kennedy, 1995). As the biology in the Dry Valleys is limited and simple there are also less biological variables that can create differences between predicted biocomplexity and in situ biocomplexity. As such the use of environmental limiting factors as identifiers for biodiversity seems a valid and rational avenue for approach in this project.

3.1.2 GIS Based Spatial Data Modelling

Modelling (or a model) is a common term in many academic circles. This project's aims are based around the creation of a model; therefore a definition of modelling, particularly GIS modelling, is required.

A model is a means of perceiving and communicating information. A model is a simplified representation of an object(s) of investigation (Wegener, 2000) and facilitates access to that object (Bailer-Jones, 2002). It is a structure that organises data in a way to make sense of the relationships between data (Kumar, Alameda, Bajcsy, Folk, & Markus, 2006). Often visualisation tools are used and can be used to predict results of changes to the relationships if they were to actually occur (Wegener, 2000).

Spatial models are data models used to understand spatial phenomena. They are an abstraction from the physical world represented using maps and symbolism (Bonham-Carter, 1994). The spatial scale of models can range from sub-molecular to astronomic (Wegener, 2000). In the creation of a spatial model, real world data must be described in terms of the model and a data structure chosen to fit the data model (Bonham-Carter, 1994). In the environmental sciences a spatial model may be a weather model, climate model, rainfall runoff model, ground water model or soil erosion model. Social science spatial models may be regional economic development models, housing market models, migration models or transport models (Wegener, 2000).

Wegener describes important categories and classifications of spatial models in his introduction to *Spatial Models and GIS*. Firstly there can be scale models, models representative of real world physical features; conceptual models, flow chart like models that outline components and relationships; and mathematical models, representing their components and interactions with mathematical formulae. Secondly there are deterministic models, models that generate repeatable results based on defined relationships and no random variables; probabilistic models which generate a range of possible solutions; and stochastic models, probabilistic models with conditional probability distributions. Thirdly models may be static, meaning they represent a steady state, or dynamic, showing a change over time. Lastly spatial models can be classified according to their resolution in space, time and attribute (Wegener, 2000).

Data models are not new scientific phenomena. Wegener gives early examples of models being used in both physical and social sciences. These include Lotka's *Analytical Notes on Certain Rhythmic Relations in Organic Systems* (Lotka, 1920), Volterra's *Leçons sur la théorie mathématique de la lute pour la vie* (Volterra, 1931), von Thünen's *Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie* (von Thünen, 1826) and Ravenstein's *The Laws of Migration* (Ravenstein, 1885/89) (Wegener, 2000).

It is the advent of the computer and their increasingly fast growth of processing capabilities that has created a means of easily computing data-hungry models (Wegener, 2000). This is especially important to spatial models with the development of specialised software specifically designed for the creation, management and display of spatial data. These software programs are collectively known as Geographic Information Systems (GIS). GIS have expanded analysts' ability to explore spatial data and modelling and have been developed for use in many different disciplines.

Hydrological modelling is one such discipline where the development of GIS and other computer software has expanded analysis capabilities. Although elements of hydrological modelling have existed for over a century longer than GIS, in the recent past they have greatly converged (Clark, 2000). Hydrological modelling (also termed hydrologic simulation or rainfall runoff modelling) is used to predict flow of water, sediments, chemicals, nutrients and microbial organisms, given observed precipitation and other variables at various time scales within a watershed, as well as predict the impact of human activity on these processes (Donigian Jr. & Imhoff, 2006; Singh & Frevert, 2006). Hydrological modelling draws on the geographic tradition that hydrology, catchment and fluvial systems interact closely and also causally in time and space (Clark, 2000).

3.1.3 Hydrological Modelling in the Dry Valleys: Compound Topographic Index

The hydrological model used in this project to represent the availability of liquid water is called a Compound Topographic Index (CTI), also referred to as a Compound Terrain Index or Topographic Wetness Index. A CTI is a steady state wetness index as a function of both slope and upstream contributing area per unit width into and out of a cell unit (Moore, Lewis, & Gallant, 1993; Yang, Chapman, Young, & Gray, 2005). CTI can be shown as:

$$\mathrm{CTI} = \ln(a/\tan\beta)$$

Where a = area value calculated as (flow accumulation +1)x(pixel area in m^2) and β is the slope expressed in radians (Evans, 2001/03).

Given the topological features of a watershed (derived from a Digital Elevation Model (DEM) of the area of interest), a CTI will compute the likely wetness of a given unit within the watershed by calculating the amount of water flowing into that unit. Initially water is assumed to be evenly distributed throughout the area of interest and flows overland according to steepest slope. However, the CTI can be modified to include an uneven distribution of water into the watershed, such as melt from snow cover and glaciers. This can be achieved by the use of a weight grid to represent the irregular distribution of water. For this reason the use of a CTI is applicable in this project. The CTI will represent an average probability of wetness over several seasons given the mean snowfall, temperature, glaciers, rivers and lakes locations.

When considering the use of a CTI in a watershed of interest there are two important decisions to be made which will vastly influence the results. These are Digital Elevation Model (DEM) resolution and method of flow path calculation.

3.1.4 DEM Resolution

The scale of the DEM used in a CTI is both very important and very difficult to choose. In general the rule is, the finer the resolution of the elevation model being used, the more accurate the CTI evaluation (given the DEM data is accurate). Primary DEM attributes required for the study that are calculable from a DEM are slope, aspect, curvature, flow-path length and upslope contributing area (J. P. Wilson & Gallant, 2000) and so the more detailed the DEM, the more micro scale influences can be included. However the various topological elements can themselves be at different scales. An example given by Schmidt and Hewitt is ridges are generally larger than hollows. As such the context of the study must often dictate the resolution used (Schmidt & Hewitt, 2004).

Digital elevation data is generally modelled in one of three data structures, regular grids (raster), triangulated irregular networks (TIN) and contour lines (J. P. Wilson & Gallant, 2000). For use in a CTI run on this project's software platform, the digital elevation data is required to be in a regular grid format. Wilson and Gallant recommend a 10m cell resolution DEM for hydrological applications, as they perform much better than resolutions coarser than this value and only slightly worse than for example 2m and 4m resolutions (J. P. Wilson & Gallant, 2000). While coarser resolutions do increase computation speeds and may be more appropriate for multiple or large scale watershed analysis, smaller streams can be excluded and the landscape artificially smoothed (J. P. Wilson & Gallant, 2000).

In the austral summer of 2001-2002 NASA's Airborne Topographic Mapper (ATM) system was used in Antarctica to collect almost 4000km² of data in several sites in the McMurdo Sound region. The ATM system uses "LIght Detection And Ranging" (LIDAR) from an aircraft platform to produce a highly detailed surface topography (T. Wilson & Csathó, 2007). LIDAR uses laser light for reflection, a high precision kinematic differential global positioning systems for position information and an inertial measuring unit for altitude calculations (Rubinstein, Needelman, Balduff, & Rabenhorst, 2004). As the LIDAR instrument passes over the study area laser light is reflected off the target surface and recaptured by the instrument. This measures the range from the aircraft to the ground and calculates the surface topography by mapping this using the global positioning system.

One of the areas targeted in the 2001-2002 operation was the Denton Hills region, the study area of this project. 600km² was mapped in the study area, flown along the lengths of the valleys with an average laser spot density of at least one point per 6m². The resulting data set is a grid DEM with a spatial resolution of 4m. The overall vertical accuracy of the operation was identified to be 0.2m (T. Wilson & Csathó, 2007). Although there were some missed areas within the study area (see 4.1.2 DEM Creation), this data set would provide for a CTI analysis with a greatly increased resolution than from DEM data previously available.

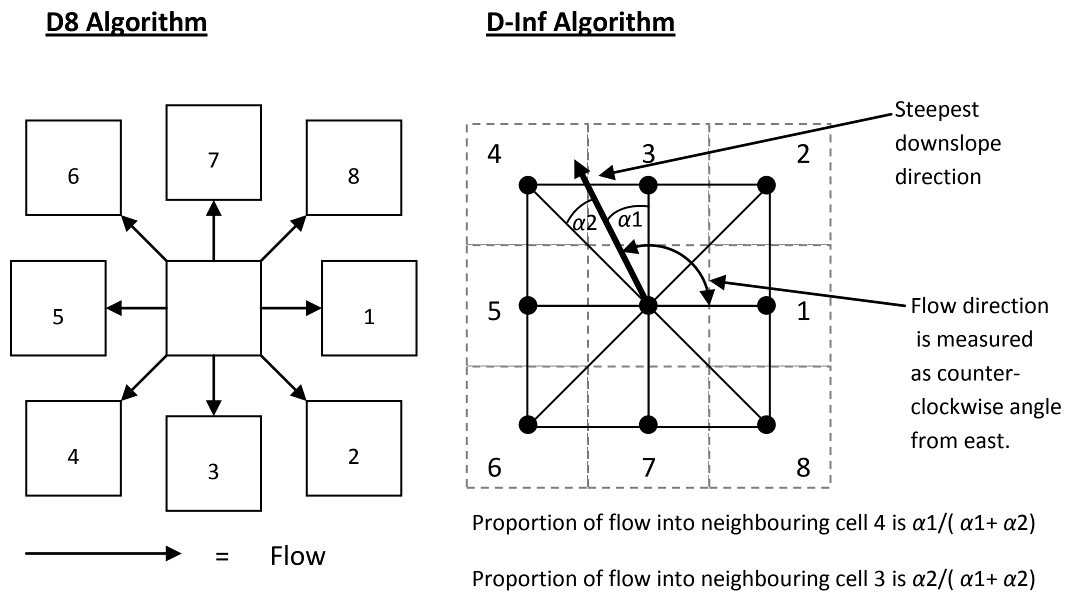
3.1.5 Flow Path Calculation

Water runoff can occur in two different ways, overland flow (pre concentration of water into recognised channels) and channel flow (Vieux, 2004). Various algorithms have been devised for the calculation of water flow paths for wetness indices, stream networking and other watershed analysis functions, including D8 (O'Callaghan & Mark, 1984), Rho8 (Fairfield & Leymarie, 1991), Multiple Flow (Quinn, Beven, Chevallier, & Planchon, 1991), DEMON (Costa-Cabral & Burges, 1994) and D-Infinity (Tarboton, 1997) (Endreny & Wood, 2001; J. P. Wilson & Gallant, 2000). All are different incarnations and approaches to calculating the direction of water flow and thus upslope contributing area. The various approaches above all follow the same principle that water will flow overland towards downslope areas according to gravity (J. P. Wilson & Gallant, 2000). Each, however, may use different methods of calculating the downslope direction depending on the subjectivity of its creators and its intended purpose. In this thesis, two of these approaches will be discussed further - O'Callaghan and Mark's D8 method and Tarboton's D-Infinity (D-Inf).

The choices made in flow path calculation are again very important as the various methods can have vastly different results. Tarboton lists the various desirable features of a flow path calculation method, including the need to avoid or minimize dispersion, the need to avoid grid bias and a certain robustness to cope with various and sometimes difficult data (Tarboton, 1997). Avoiding grid bias is perhaps the most sought after feature that the various flow path calculation methods attempt to achieve. Grid bias is the artificial influence that Grid based DEM cells have on the determination of water flow. In essence the size of the cells and orientation of the cell edges may produce an outcome different to reality where water flow is not influenced by grids. The zigzagging of water flow paths across the landscape is a typical indicator of this problem (J. P. Wilson & Gallant, 2000).

The D8 algorithm is the default ArcGIS method for calculating flow paths, see 4.1.1 Software Platform. D8 is a simple and widely used method, calculating flow into one of the eight neighbouring cells (Tarboton, 2008). This method is disadvantaged by this singular flow however as results may be striped or zigzag. This is because water must flow in one of eight directions (cardinal directions or the 45° angles between these) (J. P. Wilson & Gallant, 2000). On longer slopes this effect is more noticeable (Yang et al., 2005)(see figure 4.4 in section 4.1.3 Terrain Analysis using Digital Elevation Models). What is seen as a more robust approach to flow path calculation is the D-Inf algorithm (Evans, 2001/03; Yang et al., 2005). Unlike the D8 method, D-Inf allows for flow in any direction. D-Inf divides each 3x3 cell window (centred on the cell of interest) into eight triangular facets using the cell centres as vertices. From these facets slope, magnitude of flow and flow direction is calculated, flowing either down one of the 45° angles as in the D8 algorithm or proportionally into multiple downhill cells (Tarboton, 1997, 2008).

Figure 3.1 Flow Path Calculation Algorithms



(Based on figures by Tarboton, 2008)

3.2 Remote Sensing

3.2.1 Remote Sensing Overview

Remotely Sensed Data is the primary source of data used in this project. Remote sensing is the gathering of information about phenomena without physical contact. However, the more common use of the term, as employed in this project, is the use of airborne or spaceborne instruments for data capture (Rees, 2006). The use of remote sensing offers a way to complement and extend ground-based measurements (Goïta, Walker, & Goodison, 2003) and is becoming increasingly available and cost effective (Seidel & Martinec, 2004). A variety of systems and methods exist for this kind of remote sensing depending on available technology and target data. In this project, it is the differences in satellite systems that are of concern.

A primary division of satellite remote sensing systems is the way the system captures electromagnetic radiation, the importance of which increases when used to capture data at high latitudes. A passive system captures naturally occurring radiation, meaning the radiation is either reflected solar radiation or thermally emitted radiation. This is mostly confined to the visible and near infrared parts of the electromagnetic spectrum (roughly 0.35 to 2.5µm) (Rees, 2006). The other type of system is an active system which illuminates the Earth's surface and analyses the returned signal. This type of system primarily performs two functions. Ranging systems measure the distance to the Earth's surface, the other measures surface reflectance similarly to passive systems (Rees, 2006).

A second, and for this project, very important variation in satellite remote sensing instruments, is the spatial and temporal resolution. Spatial resolution is often closely related to the spectral band the data is being captured in (see next paragraph), but also is an effect of the technology available at the time of launch of the satellite the instrument's aboard, and what data the system has been designed to capture. Various spatial resolutions may be available from the same instrument if there are multiple outputs at different spectral bandwidths. As an example, the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument aboard the Terra satellite mission, the primary instrument used in this project, has a spatial resolution from 250m to 1km. A general rule is that optical systems can produce higher spatial resolutions, but are limited to daylight and cloud-free areas. Passive microwave systems generally have coarser resolutions but can operate at night and through clouds (Rees, 2006). Temporal resolution is how often data is captured of the same target area. The temporal resolution of a satellite remote sensing system is determined by a combination of the data capture swathe (the width of data capture) and the orbit of the satellite it is aboard. Most Earth observing satellites use circular, near-polar, sun-synchronous orbits where each orbit is phased out with its predecessor due to the Earth's rotation. Over several days the sensor's satellite will perform a cycle of orbits until it reaches its initial starting position, therefore observing the entire Earth's surface over that period. Satellites with these orbits have a higher rate of overlap in higher latitudes and so increase the temporal resolution in these areas.

A third differentiation between satellite remote sensing instruments is their spectral resolution and number of spectral bands. This can range from panchromatic and optical bands through to various infrared wavelengths. These variations determine what data can be captured and what kinds of analysis can be performed on the captured data. Further details of how these differences affect this project are described in the following sections.

The output of remotely sensed data in the terms of the satellite remote sensing used in this project is a digital image. A digital image is a two dimensional rectangular array (grid) of numerical values. These values are generally integers and each represents a quantity measured by the instrument. Each cell in the image is called a pixel (contraction of picture element) and its value is often referred to as its digital number or pixel value (Rees, 2006). The digital numbers in an image may represent any number of data. Raw data (data that has not been processed) will quite often contain values of reflected radiance reaching the instrument. From raw data, various levels of atmospheric and geometric corrections may be performed on the data, as well as various algorithmic functions to produce representations of the target object. Data from satellite remote sensing is available in a variety of digital formats and is increasingly becoming freely available for download via the internet.

Coarser resolution images often contain pixels containing several objects called mixed picture elements or 'mixels' (Seidel & Martinec, 2004). Mixels are of concern as analysis attempting to classify elements within an image may be confused by indistinguishable boundaries. In images of the Dry Valleys mixels are troublesome as a mixture of bare soils and snow produces shades of gray that may be interpreted as light snow cover, highly reflective soils or as cloud cover. This is discussed further in 4.2 Data Acquisition and Remote Sensing.

Table 3.1 Example Remote Sensing Systems

Satellite (Operator)	Sensor(s)	Spectral Resolution		Spatial Resolution		
		No. of bands & spectral distribution		Pixel size (m)	Swathe (km)	TR (days)
Landsat-5 Landsat-7 (USGS, USA)	TM / ETM+	7 / 8	1P	15	185	16
			1B, 1 G, 1 R, 1 NIR, 2 SWIR	30		
			1 TIR	120/60		
SPOT-2 SPOT-4 SPOT-5 (SPOT Image, France)	HRV-1,-2 / HRVIR-1, -2 / HRG-1, -2	4 / 5 / 5	1 P	10/10/2.5-5	60 – 117	3 – 26
			1 G, 1 R, 1 NIR	20/20/10		
			1 SWIR	20		
	HRS	1	1 P	5	120	
	Vegetation – 1 / 2	4	1 B, 1 R, 1 NIR, 1 SWIR	1165	2250	1
NOAA-15, -16, -17, -18/ (NOAA, USA) MetOp-A (ESA/EUMETSAT, EU)	AVHRR-3	6	1 R, 1 NIR, 2 SWIR, 2 TIR	1100 / 1090	2900 / 2940	1
IKONOS-2 / GeoEye-1 (GeoEye, USA)	Panchromatic	1	1 P	1 / 0.41	11.3 / 15.2	5 / 3
	Multispectral	4	1B, 1G, 1R, 1NIR	4 / 1.65		
TERRA (EOS AM) / AQUA (EOS PM) (NASA, USA)	ASTER	14	1 G, 1 R, 1 NIR	15	60	16
			6 SWIR	30		
			5 TIR	90		
	MODIS	36	1 R, 1 NIR	250	2330	2
			1 B, 1 G, 1 NIR, 2 SWIR	500		
			3B, 2G, 2R, 6NIR, 8SWIR, 8TIR	1000		
QuickBird-2 / WorldView-1 (Digital Globe, USA)	Panchromatic	1	1 P	0.6/ 0.5	16.5 / 17.6	5 / 2
	Multispectral	4	1 B, 1 G, 1 R, 1 NIR	2.4		
	IRMSS	4	1 P, 2 NIR	80	120	26
			1 TIR	160		
	HRC	1	1 P	2.7	27	130
	WFI	2	1 R, 1 NIR	260	890	5
			1 B, 1 G, 1 R	5.7	18	
ALOS or Daichi (JAXA, Japan)	AVNIR-2	4	1 B, 1 G, 1 R, 1 NIR	10	70	2 – 45
	PRISM	1	1 P	2.5	35 - 70	

(Ashraf, Brabyn, & Hicks, 2007)

3.2.2 Remote Sensing of Snow

Snow cover is one of the longest observed phenomena by satellite remote sensing. Snow cover has been monitored through optical imagery regularly since 1966 and through passive microwave imagery since 1978 (Hall, Riggs, & Salomonson, 2001; Rees, 2006). Snow cover is one of the most easily distinguishable features on the Earth's surface due to its high albedo (Fitzharris & McAlevey, 1999; Hall et al., 2001; Seidel & Martinec, 2004). This, coupled with its effects on hydrology and the more recent interest in climate change, are reasons why remote sensing of snow is a large and long term field.

It quickly becomes apparent that although snow may be easy to distinguish from other ground cover, other variables may impact on its distinguishability, namely atmospheric variables, but also local topology. The often near indistinguishability between snow cover and clouds is one of the most obvious problems faced by remote sensing scientists. This is more of a problem in maritime areas where cloud cover is more common. Other atmospheric gases and particles may also be a hindrance, particularly for making complex measurements or with instruments operating outside the visible spectrum. Local topology can particularly affect optical instruments as it alters the effects of light and shadow on observed areas. As an example, areas with a slope facing the sun will have a higher reflectance than areas in shade even if they have the same ground cover. The constant movement of the satellite and the cosmos means that these effects are often changing (Rees, 2006).

It is these variables that have helped lead to the use of multiple spectral bands, inside and out of the visible spectrum, for the detection of snow. Passive microwave radiation (between about 1GHz and 300GHz) is much less effected by atmospheric variables such as cloud and vapour (Tait, 1998). Wavelengths at this range are able to penetrate most clouds and are not sensitive to the effects of day and night (Goïta et al., 2003). Snow is also quite unique in its reflectance. Snow is one of the brightest natural phenomena in the optical and near infrared range when illuminated by the sun, but is quite dark in the medium infrared (Seidel & Martinec, 2004). Therefore a common approach to remotely sense snow is to use multispectral imagery consisting of a spectral band in the visible range and another in the near infrared at about 1.65µm. This is because snow and cloud are similar below 1µm, but they become increasingly different above 1µm to a maximum at about 1.55 to 1.75µm.

3.2.3 Normalised Difference Snow Index

Snow's strong visible reflectance and strong shortwave infrared absorbance is the basis for the use of the Normalised Difference Snow Index (NDSI) (Hall et al., 2001). This is a common technique that can be applied to many different phenomena and is based on the Normalised Difference Vegetation Index. The NDSI is a measure of the relative magnitude of reflectance characteristics between visible and shortwave infrared reflectance of snow (Hall et al., 2001). An example of how this works is as follows: A horizontal surface causes the radiance R1 in band 1 and R2 in band 2 of a sensor. If that surface was then tilted towards the sun, the radiance will increase by a factor of *n* similarly in band 1 and band 2. Therefore although there may be an increased difference between the two bands, the ratio remains unchanged (Rees, 2006). In other words, the difference between snow in bright sun light and bare soil in bright sun light should be about the same as the difference between snow in shadow and bare soil in shadow.

The MODIS instrument's version of the NDSI is:

$$NDSI = r4 - r6 / r4 + r6$$

where r4 is the reflectance in band 4 and r6 is the reflectance in band 6 (Hall et al., 2001; Rees, 2006). For the Landsat TM instrument the NDSI is:

$$NDSI = TM2 - TM5 / TM2 + TM5$$

where TM2 and TM5 are the reflectances in bands 2 and 5 respectively (Hall et al., 2001), virtually exactly the same as with the MODIS instrument.

An NDSI is valuable for its ability to operate without supervision and have minimal problems with the effects of variable lighting. The MODIS instrument is extensively used for mapping global snow cover and sea ice using the NDSI (http://modis-snow-ice.gsfc.nasa.gov/).

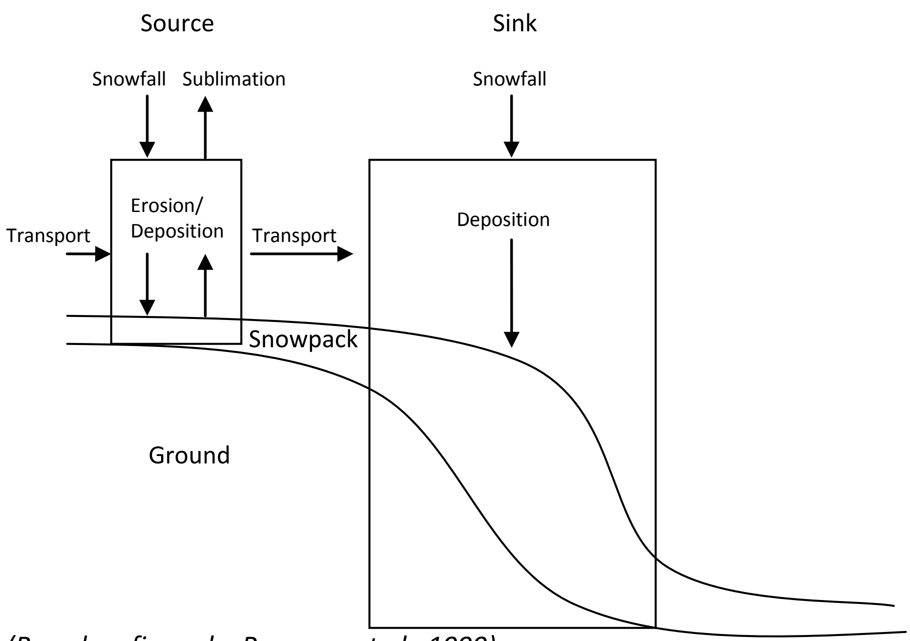
3.2.4 Alternate Approach: Snow Accumulation Modelling

Another method explored for its applicability in this project is the use of snow accumulation modelling. Snow accumulation modelling is the use of terrain analysis and mathematical computation to predict the location of blowing snow deposition. An underlying principle of snow accumulation modelling is that while snow melt's spatio-temporal dynamics rely on weather conditions, the spatial distribution is mainly influenced by the relatively stable topology (Tappeiner et al., 2001). Therefore, while snow cover is initially controlled by precipitation, it is also influenced by wind speed, wind direction and local relief (Ishikawa & Sawagaki, 2001).

The source of blowing snow can be from surface snow or from falling snow (Pomeroy, Marsh, & Gray, 1997). Blowing snow, causing heterogeneous distribution, occurs through saltation and suspension (Pomeroy et al., 1997; Walter, McCool, King, Molnau, & Campbell, 2004). Saltation is the movement of blowing snow in a layer a few centimetres thick, skipping just above the snow cover. Suspension is the movement of snow crystals supported in the air. Although suspended snow has a lower mass concentration than saltation, it can reach a layer thickness of several metres (Pomeroy et al., 1997). Snow becomes transported in the wind by being eroded and entrained as the wind stress reaches a point that will break the bonds of the surface snow crystals (Walter et al., 2004). Fetch and sublimation influence the amount of blowing snow as greater fetch increases the amount of blowing snow, while sublimation is increased by blowing snow's higher particle surface area to mass and a greater atmospheric water vapour deficit (Pomeroy et al., 1997).

Snow accumulation modelling works by converting the variables of blowing snow, particularly wind fetch, speed and direction, slope, aspect, angle and possibly temperature, altitude and vegetation into mathematical formulae (Tappeiner et al., 2001). Topology is particularly important as it influences the wind speed and thus the potential to erode or deposit snow. It is deduced that the separation of wind flow at the lee side of topological features and subsequent decrease of wind speed causes deposition of snow to these areas whilst windward areas can increase wind speed and thus increase erosion and transportation rates (Essery, Li, & Pomeroy, 1999; Ishikawa & Sawagaki, 2001; Pomeroy et al., 1997).

Figure 3.2 Basic Mechanics of a Blowing Snow Model



(Based on figure by Pomeroy et al., 1999)

This project has not included the use of snow accumulation modelling as it requires complex analysis of multiple variables (including wind, terrain, humidity, solar radiation etc.) Many of these variables are unavailable at levels of detail required for any quantitatively meaningful results. It seems far more viable to take a simpler approach by using remote sensing to observe actual snow cover over a number of summer seasons and use this information to create a mean index of snow distribution.

Chapter 4. Data Collection and Modelling

This chapter gives detail to the methods carried out to achieve a predictive water availability model of the Dry Valleys. These methods are described in a number of steps divided into three sections. The first section discusses the initial steps to be taken in developing the Compound Topographic Index involving the Digital Elevation Model. This involves describing the software used for the modelling, the creation of the Digital Elevation data and its use for calculating the flow directions. The second section describes the use of remote sensing in this project. This includes the choice of data and its manipulation and analysis for determining snow cover and surface temperature. The third section of this chapter covers the final steps in creating the model as well as its final output. It begins with describing how the various data on water sources were combined into a Weight Grid representing the various magnitudes of water sources in the study area. It then describes the calculation of water accumulation and dispersal using the Weight Grid and flow directions. Finally, the output model is described and shown in detail and its validation discussed.

4.1 Initial Steps: DEM Analysis

4.1.1 Software Platform

The over-arching aim of this project is to produce a spatial model of predicted liquid water biologically available in the Dry Valleys, Antarctica. This model will estimate the availability of liquid water based on the small array of possible water sources in the Dry Valleys. As part of a wider multivariate model, the analysis model in this project needs to have a degree of transferability. This is intended in two different ways. The model needs to be transferable to other study areas and require as little re-calibration as possible. The model also requires transferability with the wider data model meaning it needs to have the ability to readily ‘plug in’ to the wider biocomplexity model.

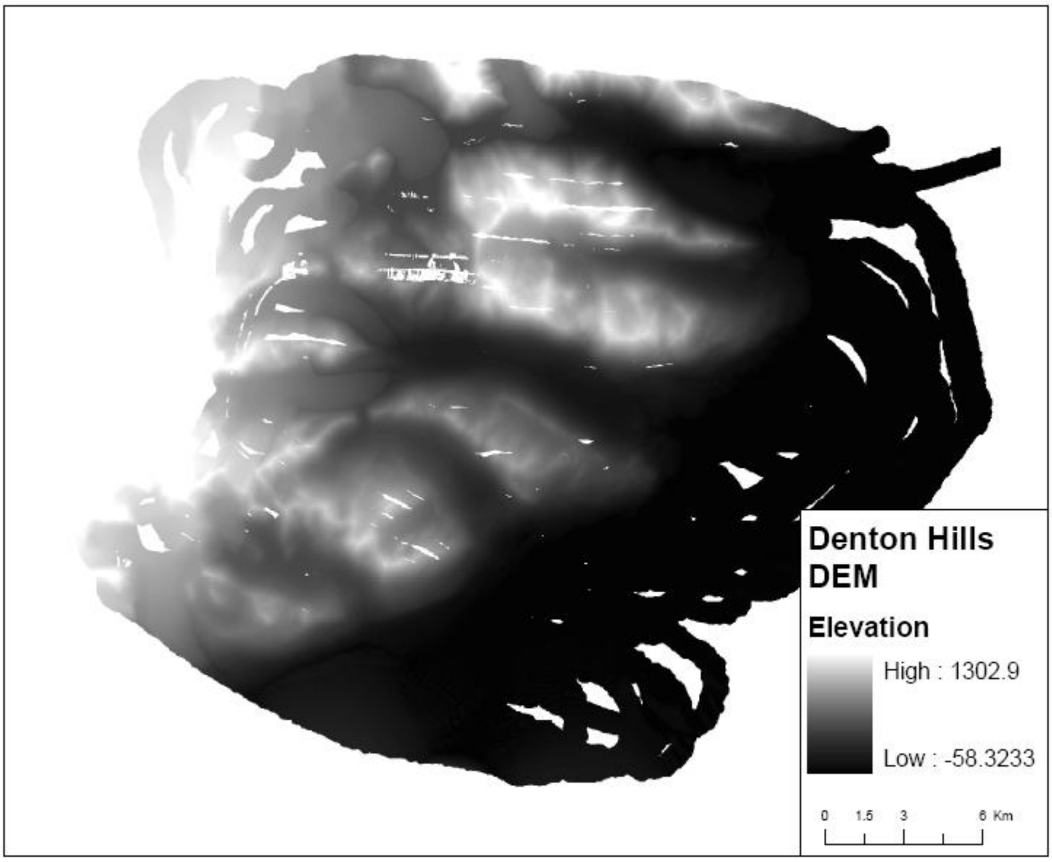
Environmental Systems Research Institute, Inc. (ESRI)'s ArcGIS software is a readily accessible and widely used GIS software. ArcGIS provides a variety of GIS platforms for numerous GIS applications. ArcInfo Workstation is a text command based platform suited to multiple input/output of data through the use of Arc Macro Language (AML) scripts. The ArcGIS software suite, particularly ArcInfo Workstation, was chosen for these reasons to be used for the majority of analysis in this project. However, as the satellite remote sensing data is in various formats that may not be immediately compatible with ArcGIS software, other software packages were also used to transform the data into formats compatible with ArcGIS. These were Leica Geosystems ERDAS Imagine 9.1 and HDF-EOS To GeoTIFF Conversion Tool (HEG) (http://newsroom.gsfc.nasa.gov/sdptoolkit/HEG/HEGHome.html).

4.1.2 DEM Creation

The first step in producing a modified CTI is to construct a DEM of the study area. A copy of the LIDAR DEM data (see 3.1.4 DEM Resolution) of the study area was obtained from Gateway Antarctica for use in this project. This data, at a 4m resolution, was a vast improvement on all other elevation data available for the study area. There were, however, problems with the original data as gaps of 'nodata' were present, particularly in parts of the Marshall Valley where the swath extent of the LIDAR had not overlapped as it captured the area. Therefore the first step required in this project was to attempt to 'fill' these gaps with interpolated data.

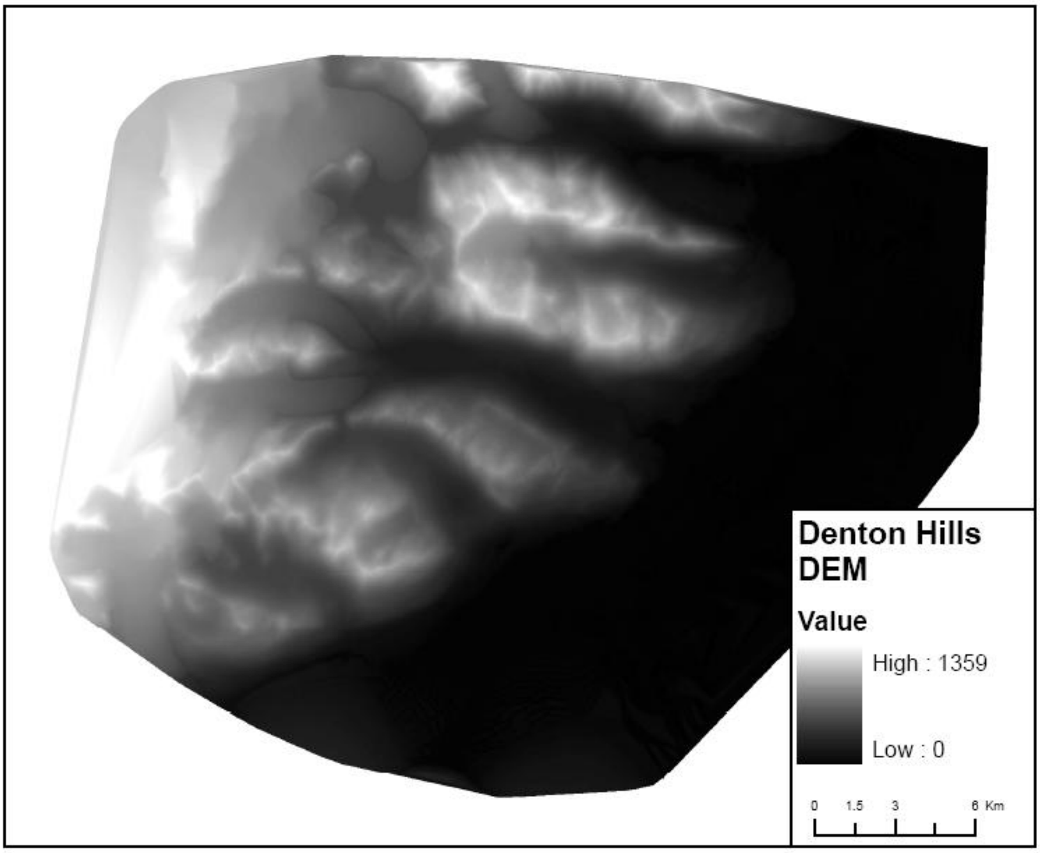
Areas not captured by the LIDAR instrument and areas of the Ross Ice Shelf contained the elevation value of -9999 when examined using ArcGIS software. This is a standard procedure to represent areas of no data. Using the SELECT command available in ArcInfo Workstation's GRID extension, all values above -9999 were extracted into a new data layer leaving gaps in the data where there had been the value -9999. The values of these gaps where then interpolated using a Triangular Irregular Network (TIN). A TIN is a surface model constructed by triangulating a set of points or vertices, connecting them with edges to form a network of triangles (ESRI, 2009b). To do this, the extracted layer was converted into a point shapefile in ArcMap, with each 4m cell being converted into a single point at the cell centre. These elevation points could then be used for creating the TIN. As the input data remain the same when creating a TIN and are all used, the precision of the original LIDAR data is preserved while gaps in the data are filled by joining the nearest nodes with an edge. At the periphery of the model the use of a TIN created incorrect elevation interpolations, particularly on the ice shelf and in the far western inland areas. As these areas are outside of the study area and do not influence analysis by being outside the study area watershed, they pose no problem.

Figure 4.1 Denton Hills DEM with 'no data' gaps



The output TIN with filled nodata gaps was then converted back to a raster DEM with a 4m cell size. The DEM was also resampled to 10m and 20m cell resolutions so the effects of cell size could be experimented with. Cell size is important to the analysis of flow paths (see 3.1.5 Flow Path Calculation), as well as impacting significantly on computational speed. The entire DEM was then raised by 57m. This was because at the sea level areas near the mouths of the valleys the elevation value was -57. By raising the entire DEM by 57m, the model would show correct base heights.

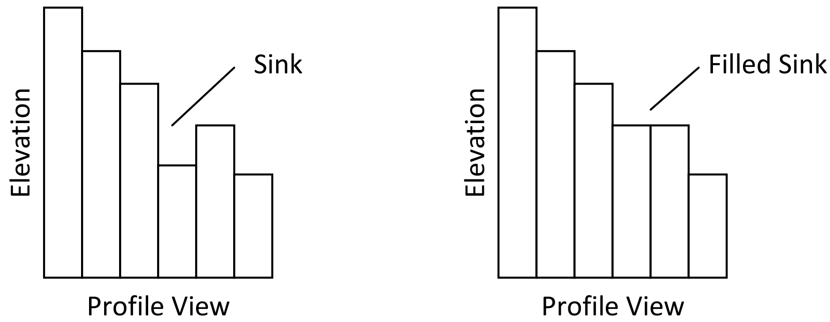
Figure 4.2 Denton Hills DEM



4.1.3 Terrain Analysis using Digital Elevation Models

The second step (or series of steps) required for the creation of a modified CTI is the calculation of the up slope contributing area. Various algorithms have been devised for the calculation of the contributing area (see 3.1.5 Flow Path Calculation). In this project I chose to use the D-Infinity algorithm by David Tarboton (Tarboton 1997), available for use in ArcMap using Tarboton's extension Terrain Analysis Using Digital Elevation Models (TauDEM)(Tarboton, 2008). The first step in the process of calculating the contributing area is to remove sinks in the DEM that will interfere with the routing of water flow across the DEM. Also known as pits, sinks are cells of low elevation in DEMs that are completely surrounded by higher terrain. This step identifies and raises these sinks to the level of the lowest pour point at their edge (Tarboton, 2008), see figure 4.3. Filling sinks is an iterative process, once sinks have been filled they may in turn cause new sinks and so the process continues until all sinks are filled to provide an optimal surface for the continuous delineation of water flow across the study area (ESRI, 2009b). Some 40161 sinks originally existed in the data and were iteratively filled.

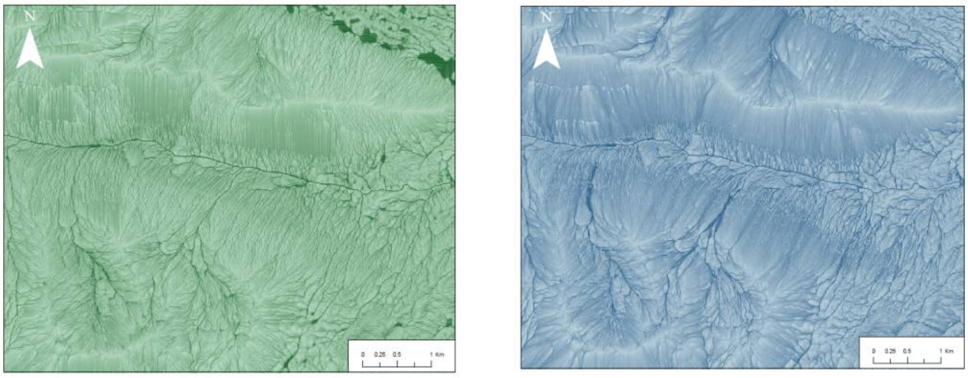
Figure 4.3 Filling Sinks



(Based on figure by ESRI, 2009)

The second step in the calculation of the contributing area is to calculate the flow direction on the surface of interest. This was done using the two methods discussed previously in 3.1.5 Flow Path Calculation**.** The D8 version of flow path calculation produced paths along 45° axis, which has the effect of producing stripes along the longer slopes of the valleys. The D-Inf method produced more realistic results because patterns of runoff formed streams on the valley sides that conform to observed areas of flush. As with all flow path algorithms, the valley floors may be less accurate due to the difficulty of calculating flow directions on flat areas, however, the D-Inf flow paths did show evidence of stream channels matching actual stream channels in the study area.

Figure 4.4 Compound Topographic Indices using D8 and D-Inf Flow Path Calculation



Both images show an unweighted CTI of the lower Marshall Valley, the left calculated using the D8 algorythm, the right using D-Inf. While the D8 versions shows evidence of stiping due to singular flow directions, the D-Inf version show smooth, more natural looking flow with more accumulation in gullies. Evidence of the repairs made to the DEM (see 4.1.2 DEM Creation) can be seen in the upper left.

Once the above steps are complete the model is ready for the addition of a weight grid representing the sources of water input into the study area.

4.2 Data Acquisition and Remote Sensing

4.2.1 Remotely Sensed Data Acquisition

There are numerous methods utilised in the identification of snow cover, which can be grouped into three categories; remote sensing, mathematical modelling and in situ observations. Due to the physical constraints, time and costs of long term in situ study and the difficulties of mathematical modelling (discussed previously in 3.2.4 Alternate Approach: Snow Accumulation Modelling), satellite remote sensing was chosen as the best avenue for investigation of snow cover for this project. A variety of instruments were considered for their use in this project, including various Landsat instruments, SPOT, Aster and MODIS. Three key requirements were necessary when choosing which instrument to use. These were data availability, spatial resolution and temporal resolution.

Data availability is an important requirement as the data used in this project must be acquirable and useable within the bounds of a Master of Social Science. This has two main meanings. Firstly the data must be free to access and use. Secondly, the data needs to be available to use immediately, meaning the data must already be captured as there is no time (or finances) to request data capture of the study area, particularly as data can only be captured during the austral summer months.

In terms of this project, spatial resolution is important for a number of reasons. The study area comprises of three valleys over an area of approximately 300km². Many existing snow mapping studies using satellite remote sensing are of larger areas such as at national, continental or global scales. This project requires a finer grain resolution to effectively map the changing snow cover in the study area, effectively meaning a required pixel size of less than 1km². Higher spatial resolution images would provide for a detailed delineation between snow cover and bare rock and reduce the occurrence of 'mixels'. Higher spatial resolution will also provide for the identification of smaller snow patches.

In this study, the temporal resolution of the remotely sensed data is also important. Often high temporal resolution is a trade-off for high spatial resolution and vice-versa. This is because the swath width (strip of the Earth's surface recorded, width being measured perpendicular to the longitudinal extent (Rees, 1999)), recorded by a high resolution remote sensing instrument may be small and not overlap with previous data captures. Also, the orbit of the satellite containing remote sensing equipment may not pass over the same location multiple times in relatively quick succession. In this study, a high temporal resolution is required to accurately record the temporal change of snow cover.

The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite has been chosen for use in this project (a second MODIS instrument is aboard the Aqua satellite). MODIS aboard the Terra mission observes the Earth during the morning (Aqua during the afternoon) and is part of the international NASA-centred Earth Observing System (Horrocks, 2008). As suggested in its name, MODIS combines a moderate resolution with a high temporal resolution. The MODIS instrument has 36 bands with a spatial resolution ranging from 250m to 1000m. The majority of the bands used in this study have a spatial resolution of 500m (bands 3, 4, 6 and 7), the other being 250m (band 1). The swath captured by MODIS is 2330km (cross track) by 10km (along track at nadir) and has a sun-synchronous, near-polar, circular 705km orbit. As such, the MODIS instrument will capture the study area of this project at least once daily, providing a greater chance of an un-obscured capture of the study area and greater potential to record patterns of snow accumulation and ablation (Maccherone, 2008). The MODIS instrument was chosen over the other systems investigated as it was the best in two of the three requirements. Although the other instruments may have a higher spatial resolution, access to their data must be paid for or the temporal resolution was much lower.

The *MODIS Rapid Response System* website (http://rapidfire.sci.gsfc.nasa.gov/) provides a daily subset of true-colour (MODIS bands 1: 620 - 670nm, 4: 545 - 565nm and 3: 459 - 479nm) and short-wave infrared (SWIR) (MODIS bands 3: 479nm, 6: 1,652nm and 7: 2,155nm) images of the study area. The subset begins in November 2004 and continues to be updated daily with images captured from the Terra and Aqua satellites. The images within the subset can be made up of stitched together scans as the MODIS instruments may capture parts of the image multiple times in one day. However, as MODIS is a passive system, images of the study area are only available from early September to early April coinciding with the austral summer. For the remaining months the study area is under constant darkness and so data cannot be captured with passive systems that rely on sun light to capture data. This period of no data capture does not pose a problem in this project as any liquid water only exists in the Dry Valleys during the summer when the data is being captured. Images were taken from the Terra mission only as the SWIR images were only available from this satellite (the MODIS instrument aboard the Aqua satellite has a malfunctioning band 6). The selection of images was event based as it required a clear view of the study area. The number of images can vary as the analysis is an average index of snow cover, however the greater the number of images the more representative the index will be. Of the four available summer seasons 167 dates provided a view of the study area unobscured by cloud and were obtained in Geotiff (.tif) format, both in true-colour and SWIR.

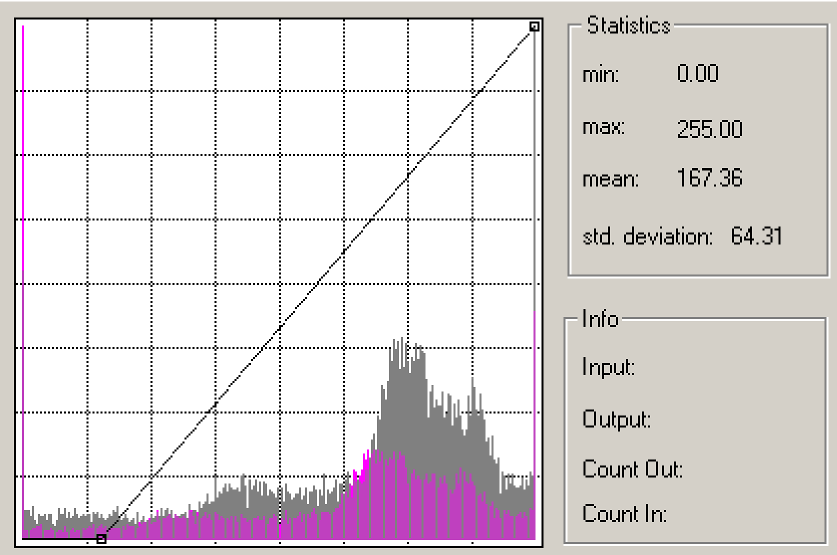
Once obtained, the images needed pre-processing to prepare them for further analysis. This involved the use of two AML scripts in ArcInfo Workstation. The first script set out the numerous variables required for each image before running the second AML script, such as defining the study area, which image is to be processed and output file names and locations. With the variables set, the second AML script would then be executed. This script would first set up the output locations by creating new workspaces. The image being processed would then be rectified (creating a new image by applying an affine transformation and optional clipping on the input image (ESRI, 2009a)) using the RECTIFY command. The new rectified image would be then converted to grid format (native to ArcGIS) for further analysis using the IMAGEGRID command. As the MODIS images are made up of three bands the output of this function are grid stacks, made up of three grids. As the input images used in IMAGEGRID were integers (containing whole numbers from 0-255), each grid in the output stack was also converted to floating point grids using the FLOAT function available in GRID (see Appendix B for this script).

4.2.2 Snow Method 1: Thresholding and Level Slicing

The spatial location of snow, particularly non-permanent snow, is an important factor when determining the location of liquid water in the Dry Valleys. The first method used to determine snow cover was the use of what can be termed gray-level thresholding or level slicing. The following method is a combination of both terms.

Contrast manipulations such as gray-level thresholding or level slicing are commonly used as a pre-processing technique. Gray-level thresholding segments an image into two classes according to their pixel value or digital number, one class below and one class above a threshold defined by the analyst. Level slicing is a technique of dividing the images' digital numbers into intervals or 'slices' determined by the analyst along the x axis of the image histogram (Lillesand & Kiefer 1994).

Figure 4.5 Sample Image Histogram for the MODIS red band, 28 Dec 2005

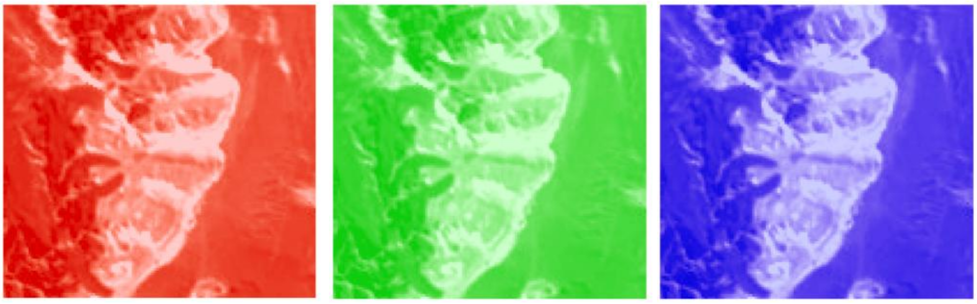


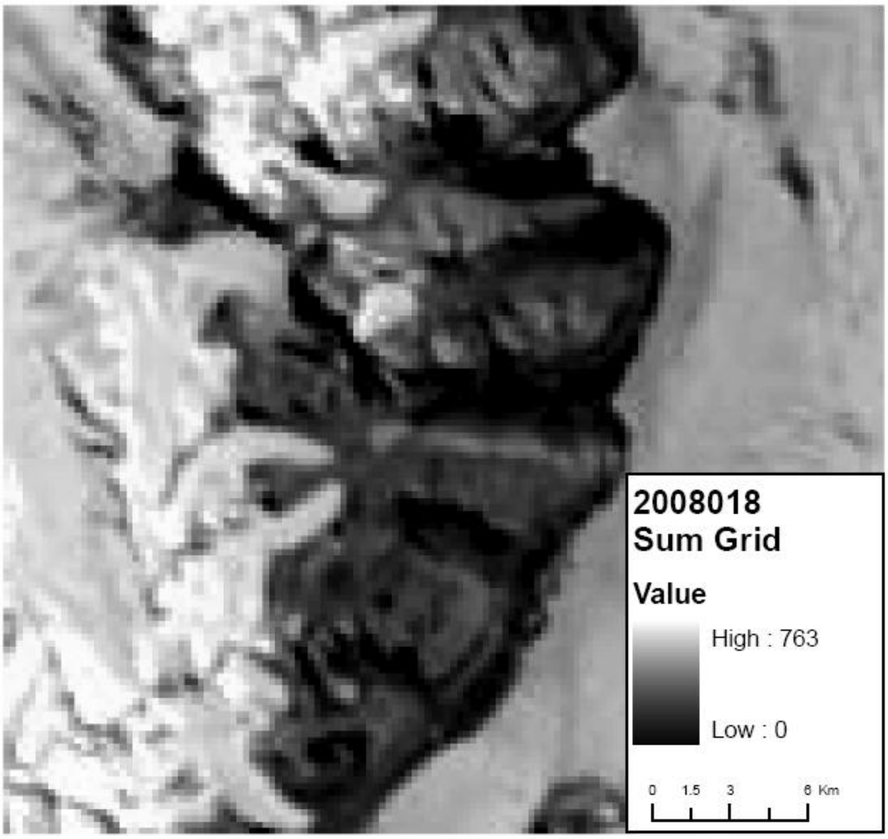
(X axis = gray level value, y axis = number of pixels with the gray level value. Histogram displayed using ArcMap 9.2)

When used as pre-processing techniques, these two contrast manipulations can be used to create masks or show discrete values for further classification. In the case of snow, this could be for identifying snow in an image before determining snow water equivalent or snow in different vegetation. As this project does not require these further steps, the pre-processing techniques are sufficient to be used in determining the spatial location of snow.

As the grid stacks of each true-colour image are made up of three separate grids, one each for the three colour bands red, green and blue (MODIS bands 1, 4, and 3 respectively), the first step of this method was to add the bands together to create a sum grid. To do this, the SUM command was evoked in the ArcInfo Workstation extension GRID. This command adds each spatially corresponding cell from each of the three grids together. By adding the digital numbers of the cells together, the difference between those cells whose values are three high numbers (making whiter colours such as for snow and ice cover) and those with lower values (darker browns such as rocks and soils) should be increased. This sum grid output was then used in a thresholding conditional statement where cells with a number equal to or greater than 550 (valid values could range between 0 and 765) would be classified as snow and ice (1) and all pixels falling below this value would be classified as other (0).

Figure 4.6 Red, Green, Blue and Sum Grid for 18 Jan 2008

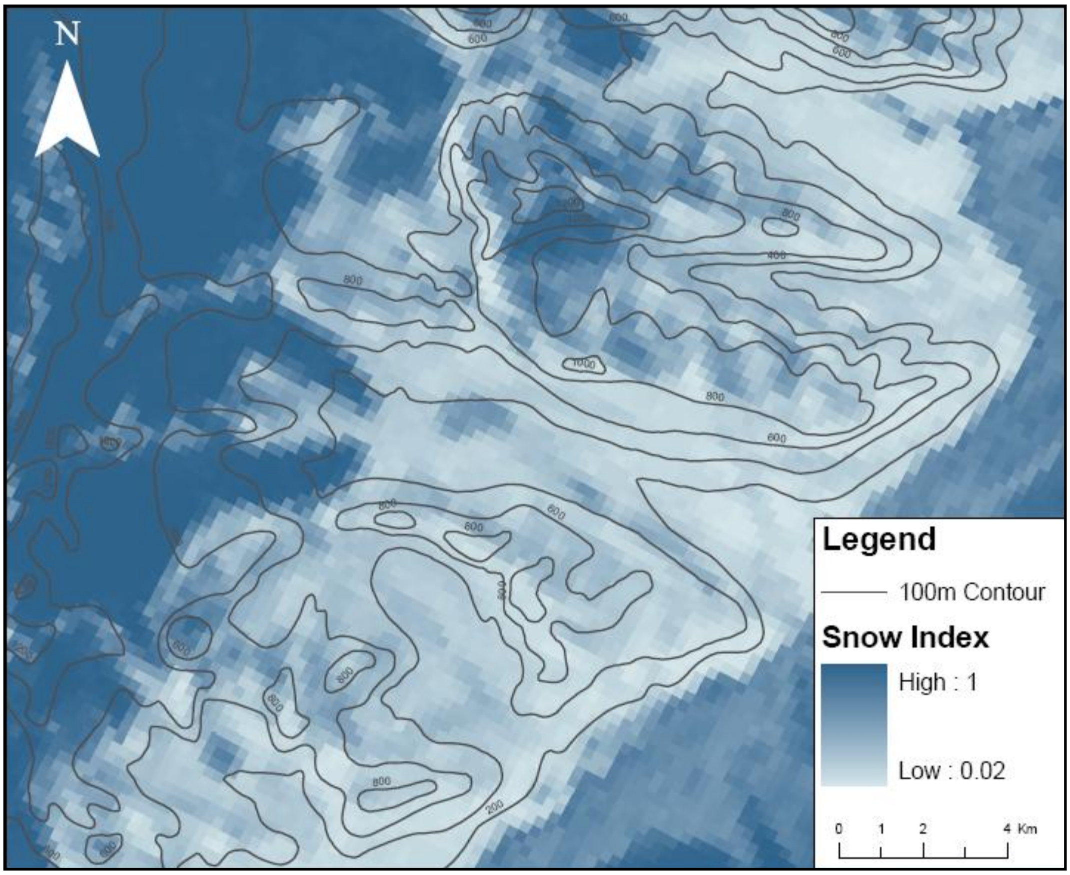




This single threshold was enough to detect snow and ice in sun-lit areas throughout the summer season but another step was needed to account for early and late summer lighting when the sun is lower towards the horizon or for images captured at times of the day that produced changing illumination and shadows of the study area.

To compensate for different lighting, two extra conditions were applied similar to what is termed level-slicing. Snow in shadow has a blue colour in the true-colour images so a conditional statement was added to apply to pixels not classified and snow and ice by the gray-level threshold. Grid cells classed as other than snow and ice were tested whether they had a high blue content but not too much red content. This was done by adding an equal to or greater than value on band 3 and a less than or equal to value on band 1. After numerous experiments, a digital number of 120 was used on the blue band 3 and 170 on the red band 1. These numbers picked out snow in shadow or partial snow cover with little confusion with rock reflecting in bright sun throughout the seasons. The 167 outputs of this method were averaged to produce an index from permanently bare rocks and soils to permanent snow and ice cover.

Figure 4.7 Snow Cover Index using Gray Level Thresholding and Level Slicing



4.2.3 Snow Method 2: Unsupervised Classification

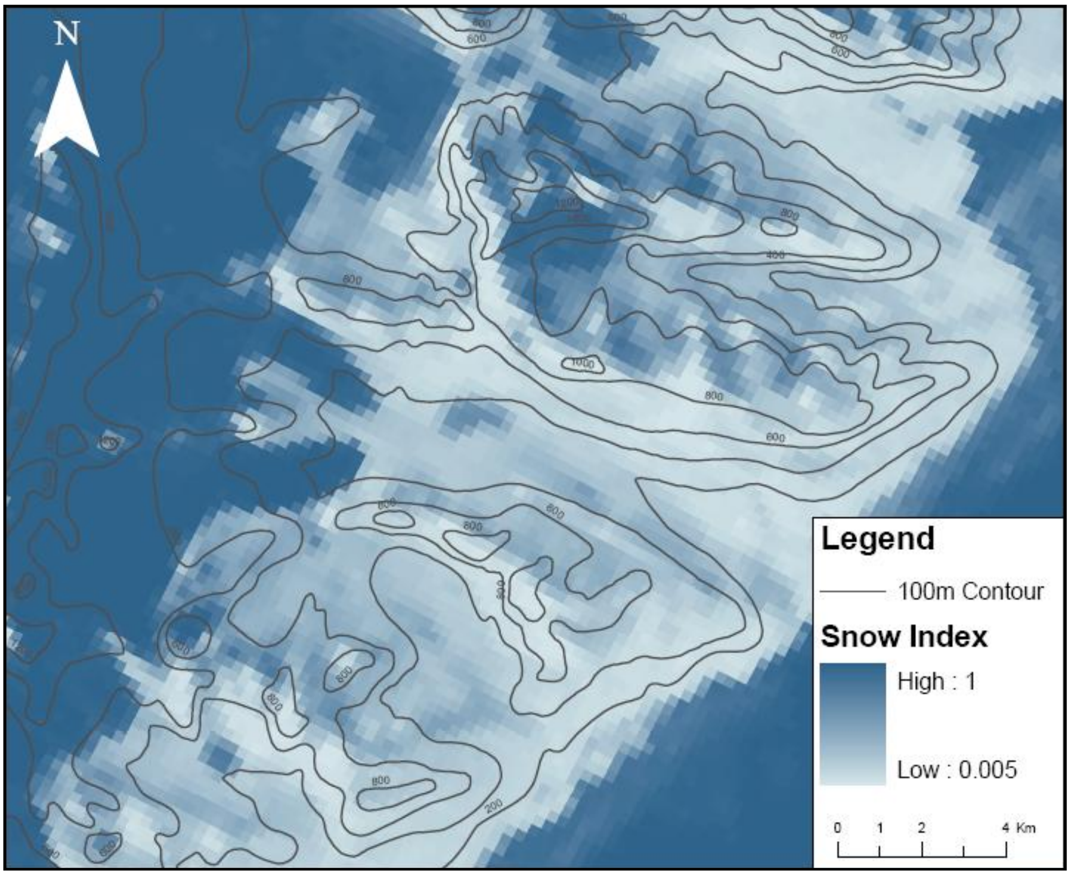
The second method used for determining the spatial location of snow cover was the use of ArcInfo Workstation's unsupervised classification function. Image classification invokes quantitative decisions on the data present in an image and groups pixels into classes representing ground-cover types. Unsupervised classification is the use of a clustering technique to assign the pixels to classifications (Rees, 1999).

In ArcInfo Workstation’s GRID extension, raster clustering is evoked using the ISOCLUSTER function. ISOCLUSTER uses the Isodata clustering algorithm. This algorithm divides each cell in a grid stack into clusters within the multidimensional space of the stack. The clustering process is iterative, meaning once each cell has been assigned to it’s nearest cluster mean, new means are then calculated based on the attribute distances of the cells within each cluster. Again each cell is assigned to it’s nearest mean cluster and the process should continue until the clusters become relatively stable (ESRI, 2009b).

In this project, multiple clustering variables were experimented with to identify the best possible combination to identify snow cover in the study area in the various lighting conditions. The final combination was 10 classifications, 5 iterations, a minimum class size of 10 cells and a sample interval of 10. Three images were used when experimenting with these variables: 2005261, 2006313 and 2008014 (YYYYDDD, day being Julian day number). 2005261 is early in the season when the sun is low and the effects of different lighting is exaggerated, 2006313 was captured the day after a snowfall and 2008014 is an image typical of the majority of the true-colour images used in this project. After numerous trials, the signatures provided by 2005261 were used from the above ISOCLUSTER variables as it provided exaggerated results that could span the various effects of lighting.

The output of the ISOCLUSTER function is a signature file containing the class signatures used by MLCLASSIFY, a function used in the GRID extension to classify raster data according to the ISOCLUSTER output. MLCLASSIFY finds the cluster signature with the maximum likelihood similarity for each cell in a stack and assigns the cell to that cluster’s classification. The output of this is a grid containing 9 classifications. Classes 1 and 2 signify bare rock, all other classes are snow and ice in various shades, with the higher class numbers being permanent snow and ice. This output then had a conditional statement applied to convert the 9 classes into 2, one for bare rock and soil (0) and the other for snow and ice (1). These were averaged over the four summer seasons to produce an index from permanently bare rock (0) to permanent snow and ice cover (1).

Figure 4.8 Snow Cover Index using Unsupervised Classification



At this stage the MODIS NDSI data (MOD10A1.5) for the study area were obtained from the EOS data pool at the National Snow and Ice Data Center (http://nsidc.org/index.html). However issues arose when examining the data for its use in this project. The incompatibility of using the MODIS NDSI in this project results from two main factors. While it is perfectly usable for larger area interest, at the periphery of the snow cover, in areas such as the study area of this project, surfaces may be confused with cloud or contain areas of no data. Being at the edges of the capture swath also means that the ridges between the valleys cast shadows over the valleys because of the angle from the instrument to the study area, resulting in no data in the valley floors.

4.2.4 Temperature Method

The third variable to be quantified using remote sensing for this project is surface temperature. Surface temperature can influence the availability of liquid water in two main ways. The ground surface can influence snow melt, increasing its likelihood when it rises above 0°C. Surface temperature can also influence the depth of permafrost melt, as warm ground temperatures will increase permafrost melt. The surface temperature is also an indicator of the level of solar radiation reception. Surface temperature can be quantified from satellite remote sensing using various thermal infrared bands. Depending on the Remote Sensing instrument being used, various algorithms exist to convert the digital numbers into temperature values.

The first attempt at creating a surface temperature data layer for this project was to use corresponding thermal images on the same dates as the snow images from the MODIS instrument aboard the Terra satellite. The data set chosen for surface temperatures was MODIS/Terra Land Surface Temperature/Emissivity Daily L3 Global 1km SIN Grid (MOD11A1) Version 5, available from the Land Processes Distributed Active Archive Center (LP DAAC) Data Pool (Land Processes Distributed Active Archive Center, 2008). The MOD11A1 data is downloaded in a HDF-EOS format so the HEGWin tool was used to convert the Land Surface Temperature daytime 1km grid into the Geotiff format for use in ArcGIS. The temperature data has a range of 7500–65535 and to convert the digital numbers into degrees Kelvin, the digital numbers had to be multiplied by a scale factor of 0.02 (Nickeson, 2008). All dates from the summer season of 2004-2005 were obtained and converted into the Geotiff format. Under closer inspection, the majority of the data showed areas of -273.15°C or absolute 0 in Kelvin throughout most of the study area. As temperatures are unable to reach this temperature naturally on Earth, these areas were considered to contain 'nodata'. There are two possible causes for these large gaps of 'nodata' in the study area. Firstly the MOD11A1 data is masked according to a global automated cloud cover data layer. Areas of the study area may have been wrongly classified as under cloud cover due to partial snow cover being confused with cloud. The other reason is that the valley floors may be shadowed by the surrounding mountains and ridges creating blind spots at the periphery of the data capture swath. This 'nodata' problem proved that the MOD11A1 data was unsuitable for the study area.

As the MODIS thermal data is unsuitable for the study area and the data from the i-button thermometers is yet to be recorded (see *Thermal Data Availability* in section 5.1.2), another source of remotely sensed thermal data was required for this project. Landsat 7 also captures thermal data of the study area, however the temporal resolution of this data is poor and accessing free data can be difficult. Three Landsat 7 ETM+ images of the study area were made available for this project by Gateway Antarctica. These images were level 1 data meaning the data has been processed to a degree of spatial and atmospheric correction and included all bands from 1 to 8 (including both high and low gain band 6, gain being the signal power used to capture data, low for expected high surface brightness and high for lower brightness). These images were captured on the 25/12/1999, 21/11/2001 and 27/12/2001. All three provided un-obscured captures of the study area. Landsat 7 ETM+ band 6 (10400-12500nm) is the instrument's thermal band. Band 6 is divided into two separate bands, one of high gain and one of low gain data in a 60m resolution. The data in the level 1 state requires an algorithm to convert the digital numbers into radiance then into temperature. This algorithm is available in the *Landsat 7 Science Data Users Handbook* (Williams, 2008). This algorithm was first performed using a model in ERDAS Imagine then converted into an AML script in accordance with the rest of this project.

The first step required in processing the Landsat images was to convert the images into a format compatible with ArcInfo Workstation. This was done using ERDAS Imagine's Import tool to import the .NLAPS files into the .img format native to ERDAS Imagine and accessible in ArcInfo Workstation. From this stage, the rest of the image processing can be done within the ArcInfo Workstation environment.

The script is set up to run through '*n*' times, once for each input image. The first step in the script is to set the variables and create the output file locations to be used in the upcoming operations. The next step rectified the images to the study area to avoid unnecessary computation as previously outlined in the image preparation of the MODIS images (see 4.2.1 Remotely Sensed Data Acquisition). The next stage of the AML script converts the image to a grid using the IMAGEGRID function, the output being two grids making up a stack, one of Landsat band 6 and the other of band 9.

The next part of the AML script performs the algorithm on the band 6 grid to create an output grid in degrees Celsius within the GRID extension. This algorithm is in two stages. This first stage converts the pixel digital numbers into radiance, represented as:

$$L_\lambda = \text{"gain"} * \text{QCAL} + \text{"offset"}$$

Or

$$L_\lambda = ((\mathrm{LMAX}_\lambda - LMIN_\lambda)/(\text{QCALMAX-QCALMIN})) * (\text{QCAL-QCALMIN}) + LMIN_\lambda$$

Where L_λ is the spectral radiance in watts/(m^2 * ster * µm), "gain" is the rescaled gain in watts/(m^2 * ster * µm), "offset" is the rescaled bias in watts/(m^2 * ster * µm), QCAL is the quantised calibrated pixel digital number, $LMIN_\lambda$ is the spectral radiance that is scaled to QCALMIN in watts/(m^2 * ster * µm), LMAX_λ is the spectral radiance that is scaled to QCALMAX in watts/(m^2 * ster * µm), QCALMIN is the minimum quantised calibrated pixel digital number and QCALMAX is the maximum quantised calibrated pixel digital number (Williams, 2008).

In this project the algorithm is:

Outgrid = ((12.65 – 3.2)/(255 – 1)) * (Band6_grid – 1) + 3.2

The second stage in the algorithm is to convert the radiance values to temperature in Kelvin then Celsius. This stage is represented as:

$$T = \frac{K2}{\ln\left(\frac{K1}{L_\lambda} + 1\right)}$$

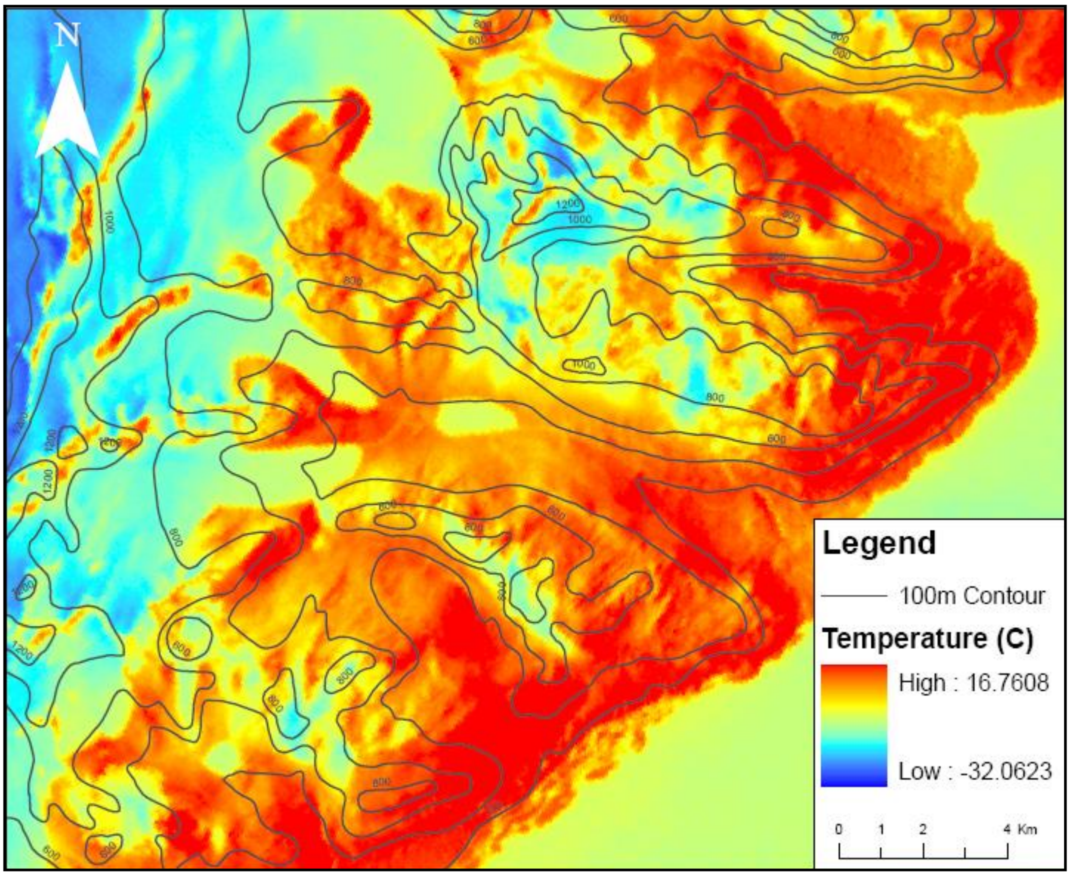
Where T is the effective at-satellite temperature in Kelvin, K2 is the calibration constant 2 in watts/(m^2 * ster * µm), K1 is calibration constant 1 in watts/(m^2 * ster * µm) and L is the spectral radiance in watts/(m^2 * ster * µm). To convert T into degrees Celsius the value needs to be subtracted by 273.15. In this project this stage of the algorithm is:

Outgrid = (1282.71 / (ln(666.09 / Radiance_grid + 1))) – 273.15

The next part of the AML script is to remove the areas left by the rectifying process that do not have a real thermal value. These areas contain the thermal value of -33.6018°C. The SELECT function available in GRID was used to select all values above -33.6018 to be used in the creation of a new output grid, ready for the last process run in the AML script.

Once all of the above processes have been run on each input image, a final step in the script creates a mean grid from all of the input images, using the MEAN function available in GRID. Figure 4.9 shows the final output mean grid produced for this project from the three input Landsat 7 images.

Figure 4.9 Surface Temperature Index



The thermal data described above was omitted in the final model creation due to two concerns. Firstly, there were only three available images to calculate a thermal index from. Although the processes shown above do show the validity of using remotely sensed thermal data in the study area, the limited data available for use meant that no truly representative average index of surface temperature could be created. Secondly, while all of the other variables being used in the model are direct sources of water, the surface thermal regime only influences these water sources and therefore it is difficult to produce a representative weight on the same scale as the water sources. For these reasons the thermal variable was not integrated with the final model, however future expansion of this model will provide an avenue for further investigation in this area, see Chapter 5. Discussion and Conclusion.

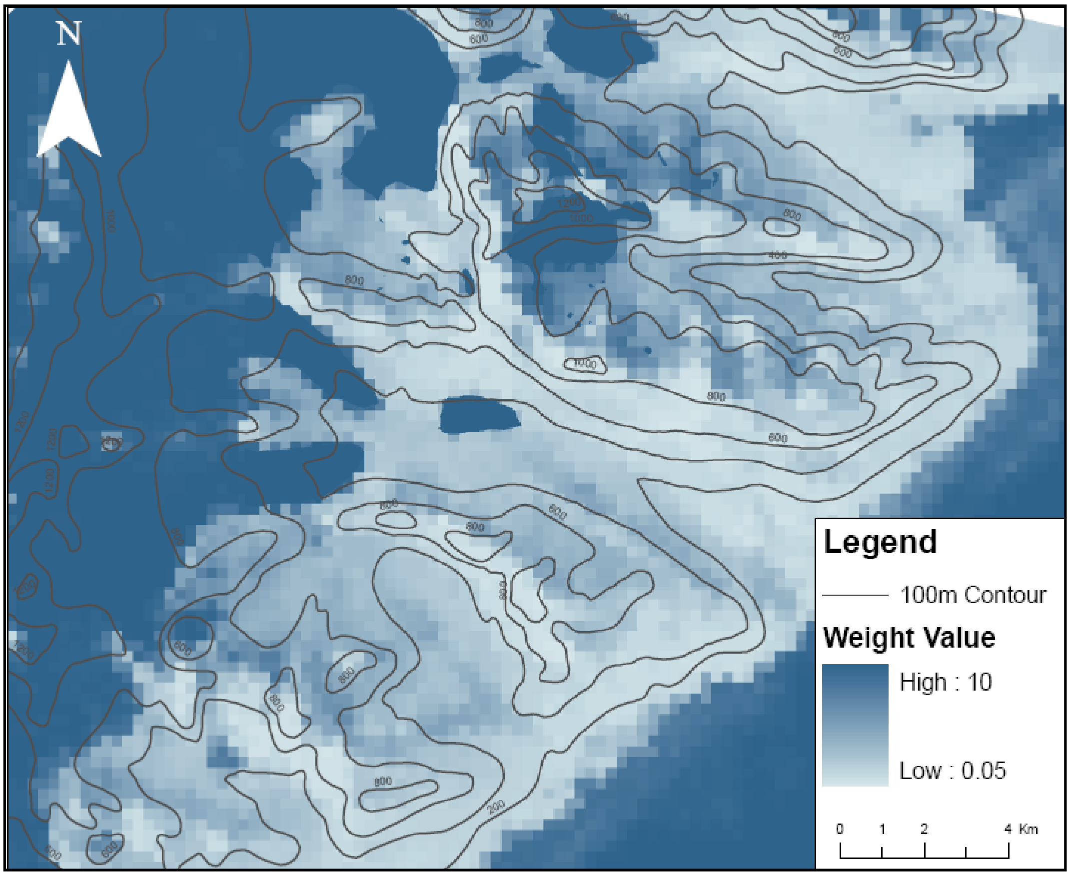
4.3 Final Steps and Results

4.3.1 Weight Grid

With the mean snow cover index calculated and the spatial data of glaciers and rivers in the study area obtained from Gateway Antarctica, the next step was the creation of a weight grid for calculating contributing area. The weight grid is used to represent the sources of water going into the Dry Valleys. First, the vector shapefiles of the Glaciers and Lakes were given a new weight attribute of 10 in ArcMap to represent the large quantity of water from these sources. They were then converted to raster grids using the TO RASTER conversion tool with a cell size of 10m and the weight attribute as their raster value. To create a snow weight, the snow index grid created by the unsupervised classification method described above in 4.2.3 was multiplied by 10 in ArcInfo Workstation to create cell values between 0.05 and 10, the highest values being equal to that of the glaciers and lakes. The snow weight grid was then resampled to a 10m cell resolution to match the glaciers, lakes and DEM grids. The glaciers, lakes and snow weight grids were then combined into a single weight grid in ArcInfo Workstation using the MERGE function available in GRID, with the analysis window and mask set to the study area DEM. The output weight grid contained values between 0.05 and 10 to represent the volume of water input likely in each cell.

This weight grid could then be used in the TauDEM extension to ArcMap for the calculation of contributing area. Contributing area calculated for each grid cell is taken as its own contribution plus the upslope cells that drain into that cell (Tarboton, 2008). Without the use of a weight overlay, each cell is counted as the weight value of 1. Each cell value is then calculated recursively to its value (1) plus that of the neighbouring cell(s) at the steepest upslope angle, determined in section 4.1.3. This method is the same in both the default D8 method used by ArcGIS and in the D-Inf method in TauDEM. However, in TauDEM, there is allowance for proportional flow into multiple cells depending on the direction of flow as discussed in section 3.1.5 Flow Path Calculation. The use of a weight grid changes the weight of each cell from 1 to a new value depending on what the weight represents. As stated above, the new weight values of the cells are between 0 .05 and 10 to represent the spatial distribution and volume of water sources. The recursive procedure calculates the cell values to their weight value plus the weight of the neighbouring cell(s) at the steepest upslope angle. The output of this step is a contributing area grid to use in the final calculation of the CTI.

Figure 4.10 Weight Grid For Contributing Area Calculation



4.3.2 CTI Calculation

The final step in the process of creating the model is the calculation of the compound topographic index. This is done through the use of an AML script *Compound Topographic Index* (Evans, 2001/03) obtained from ESRI's ArcScripts website:

http://arcscripts.esri.com. This script was run in ArcInfo Workstation using the GRID extension. The inputs used in running this script were the 10m resolution DEM of the study area and the optional contributing area grid calculated above. The 10m resolution DEM was used for two reasons. The calculation of the flow paths was only possible using a 10m resolution with the software used as a finer resolution would contain too many cells. The second, as outlined in 3.1.4 DEM Resolution, a 10m resolution would provide fast computational speed with minimal differences to finer resolutions. With the use of a pre-existing contributing area grid, five steps are taken in this script for the creation of a CTI model.

First the calculation of the slope of each cell using the SLOPE command, then converting this into radians:

$$Slope\ in\ Degrees * (\pi/2)/90$$

or

$$Slope\ in\ Degrees * 1.570796/\ 90$$

The output of this is then reclassed so values of 0 become 0.001 (or future calculations will not work). Next, the tangent of the reclassed radian slope grid is calculated using raster math. This is the tanβ variable in the final CTI equation. The area value variable *a* is then calculated again using raster math. To calculate *a*, the weighted contributing area grid created above is used:

$$(ca + 1) * \ cellsize$$

Where *ca* is the flow accumulation value from the weighted contributing area grid and, in the case of this model, the cell size is 10m.

With the *a* and tanβ grids completed, the final CTI equation can be run:

$$CTI = \ln(a/\tan\beta)$$

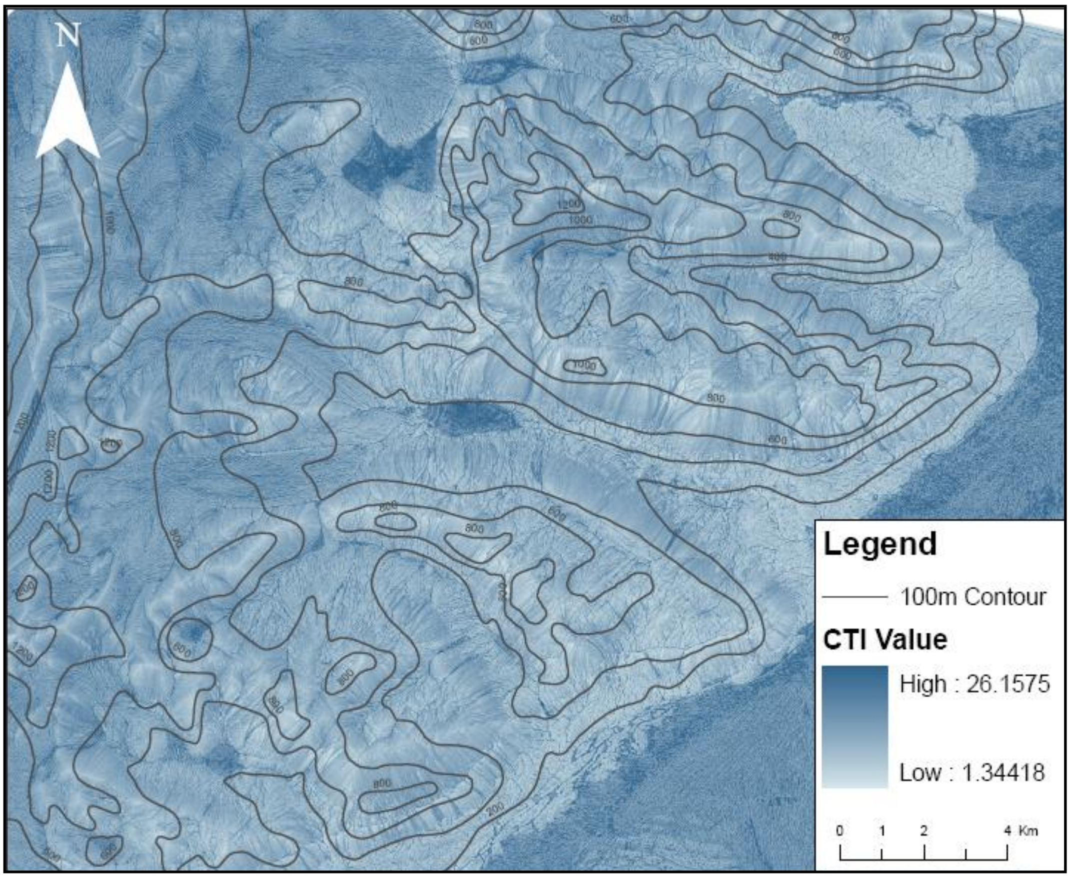
The output grid models the tendency of water to accumulate at any point of the study catchment (*a*) and the tendency of gravitational force to move water downslope (tanβ) (Quinn et al., 1991).

4.3.3 Final Output

The output model in this project is an index of the predicted spatial availability of liquid water, given the spatial distribution of water sources and the effects of gravity and topology. The index varies from 26.1575 at the wettest to 1.34418 at its driest. These numbers represent a relative scale of the accumulation and dispersal of water within the study area.

The model shows the increased likelihood of liquid water availability vertically downwards on the valley sides as water is pulled down slope by gravity. There is evidence of channels forming in many areas where a greater amount of water is accumulating. The lowest predicted water availability is on ridges except for small pools, although some of the smallest pools may have been omitted due to the pit filling process. The highest areas of accumulation are in the valley floor lakes and rivers.

Figure 4.11 Final CTI Model



This image shows the output weighted CTI model cropped to fit the study area. This model shows a steady state index of liquid water availability, using weight values to represent the sources of water entering the study area. Water from the different sources will flow over the terrain according to gravitational pull. Higher index values represent areas of accumulation; lower index values represent areas of greater dispersal. Notable areas of high accumulation show evidence of likely stream and lake formation, while the steep upper slopes on the valley sides show the highest areas of dispersal where liquid water is predicted to be limited.

4.3.4 Validation

A full scale quantitative validation of this model is currently unviable given the constraints of a one year Masters project. However future validation using the 437 soil moisture samples taken from the study area by the IPY Terrestrial Biocomplexity project could be used in a comprehensive comparison. Further verification of the model's use will be its inclusion in the IPY Biocomplexity project's multivariate analysis. When testing the abiotic constraints on biocomplexity, the use of this model will be verified if it becomes an explanatory variable with statistical significance. However, until the IPY Biocomplexity data becomes available, a qualitative assessment of the model using comparisons with visible drainage patterns and 3D modelling is a practical method of validating the results. Features looked for when assessing the model includes conformity to visible drainage patterns, downslope flow, and the impacts of various weightings – particularly snow.

To compare drainage patterns, an overlay of a high resolution (<4m²) Advanced Land Observing Satellite (ALOS) image captured on the 30/10/2007 was used (*see page 76 for copyright information). This high resolution image shows rills and gullies on the valley sides where melt water flush flows. Also visible are streams on the valley floors, alluvial fans, lakes and ponds. When compared with the model, these areas on the model should show higher wetness values than surrounding areas, with values increasing at lowering elevations and increased stream orders. Figure 4.12 shows a conformity of drainage on the slopes north of Lake Colleen and along Garwood Glacier, forming an alluvial fan before entering Lake Colleen. Figure 4.13 displays a number of small flush stream formations, forming lakes and ponds (outlined in white on the ALOS image) before draining into Lake Buddha. Figure 4.14 shows the effects of glaciers on the weighted CTI calculation, forming melt streams around the Miers and Adams Glaciers and flowing in braided channels to Lake Miers. Also clearly visible is the melt stream flowing from the gully in the top centre of the image. Figure 4.15 shows how the satellite image can be overlayed and "swiped" to show the underlying image using ArcMap's Effects toolbar. By clicking and dragging on the overlaying image layer, the data underneath is revealed. This is useful to make sure the drainage patterns are aligned, showing higher water accumulation in drainage streams visible in the ALOS image, as in the Figure 4.15 example.

The use of multi-angle 3D modelling in ArcScene enables an effective way to examine the flow of water over the terrain towards downslope areas. This downslope flow should produce dispersal on steep slopes at higher elevations and accumulation on lower, flatter areas and sinks. Figure 4.16 highlights the effects of downslope flow, with a view south-west over the Marshall Valley. The darker orange colour indicate the driest cells, changing to darker greens for wetter cells, dark blue being the very wettest. Figures 4.15 and 4.18 are overviews of the entire model, showing the three main valleys of the study area (from north to south: Garwood, Marshall and Miers), as well as Shangri-La at the western, inland end of the valleys and Hidden Valley to the south of Miers Valley. In these overviews many flush streams can be seen flowing down the valley sides, as well as the various lakes, ponds and rivers on the valley floors. Some small ponds can also be seen on ridge tops. Figures 4.19 and 4.20 are an example of how the ALOS image can also be used for 3D analysis. This view, looking north-west up Miers Valley, shows the conformity of the predicted lake and river with the observed phenomena.

A comparison with an unweighted CTI of the same watershed using the same calculation algorithms is used to test the influence of the various water source weightings. Figures 4.21 and 4.22 compare the model with an unweighted version. The unweighted CTI (Figure 4.22) shows a uniform input of water, with an even amount of dispersal and accumulation throughout the study area. In contrast to this, the weighted model (Figure

4.21) shows the influence of the various weights representing a heterogeneous input of water into the study areas. Areas around the various glaciers have a moderately high wetness value, with the highest values in the lakes and main river channels. The various ridges and slopes, particularly where snow cover is less common, contain low wetness values. These low values impact on water accumulation in the cells downslope, showing smaller areas of accumulation at the bottom of the slopes than in the unweighted version. Based on the visual comparison with drainage patterns shown in the ALOS image and the 3D views, the weighted CTI index appears to provide a realistic model of wetness.

Figure 4.12 Upper Garwood Comparison

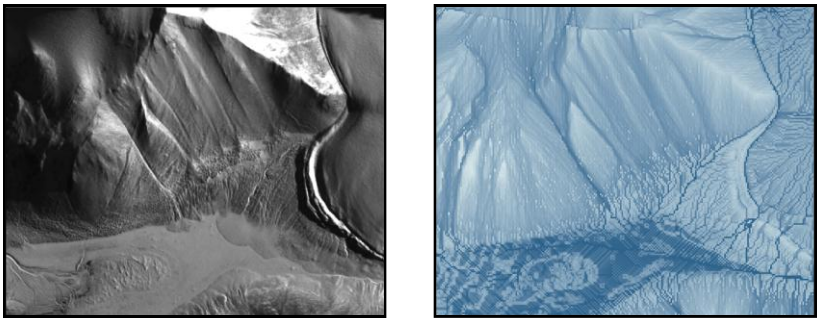


Figure 4.13 Shangri-la Comparison

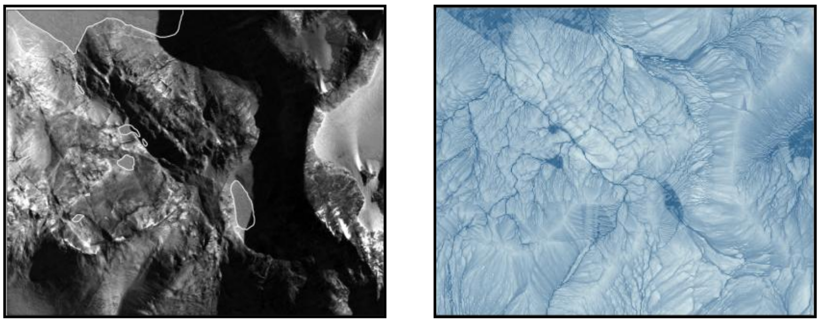


Figure 4.14 Upper Miers Comparison

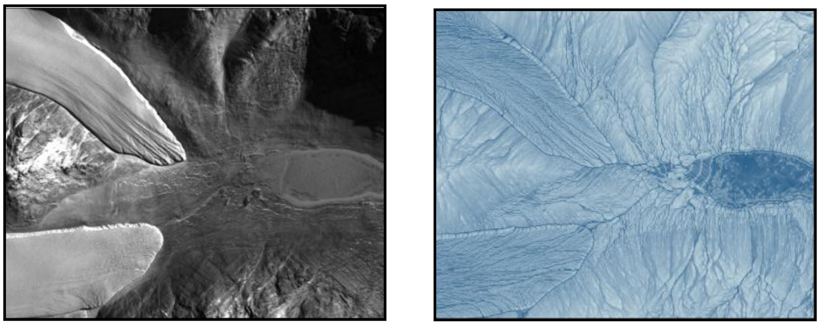


Figure 4.15 Upper Garwood Overlay

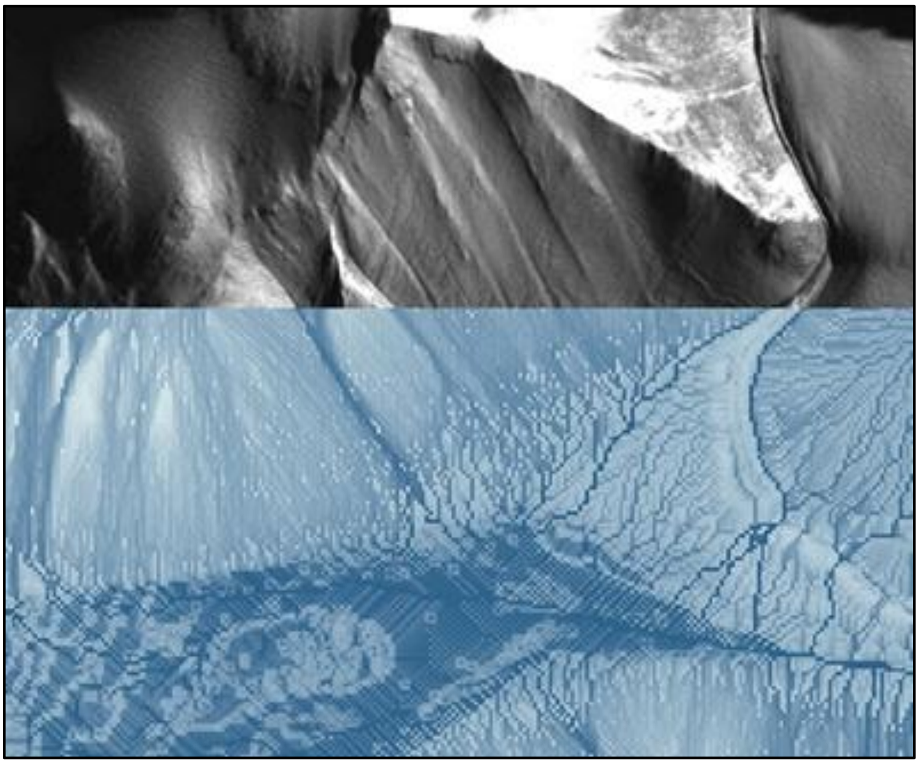


Figure 4.16 Down Slope Flow

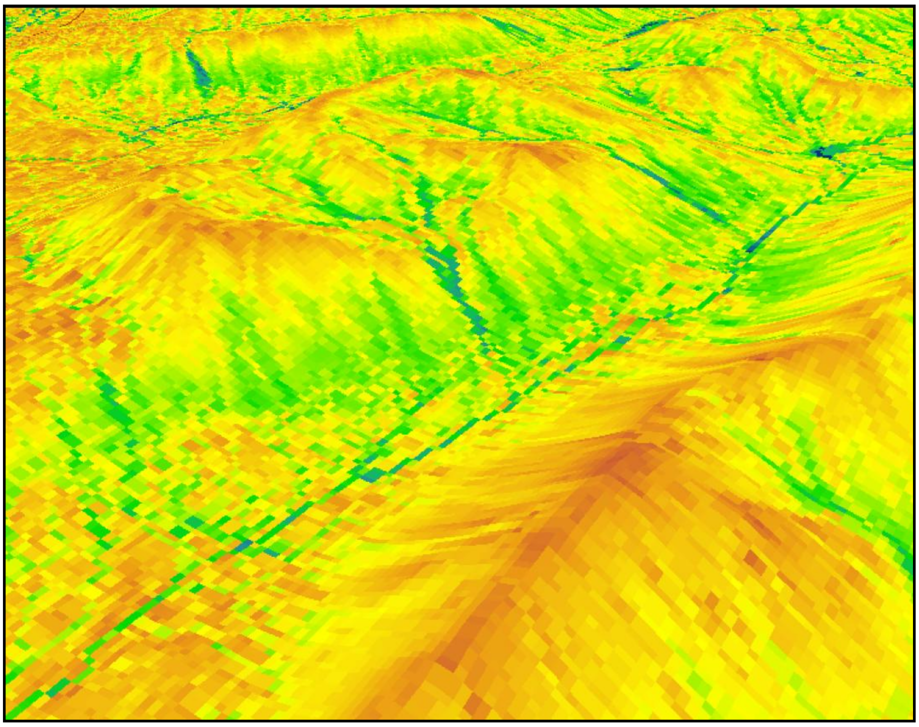


Figure 4.17 3D Overview A

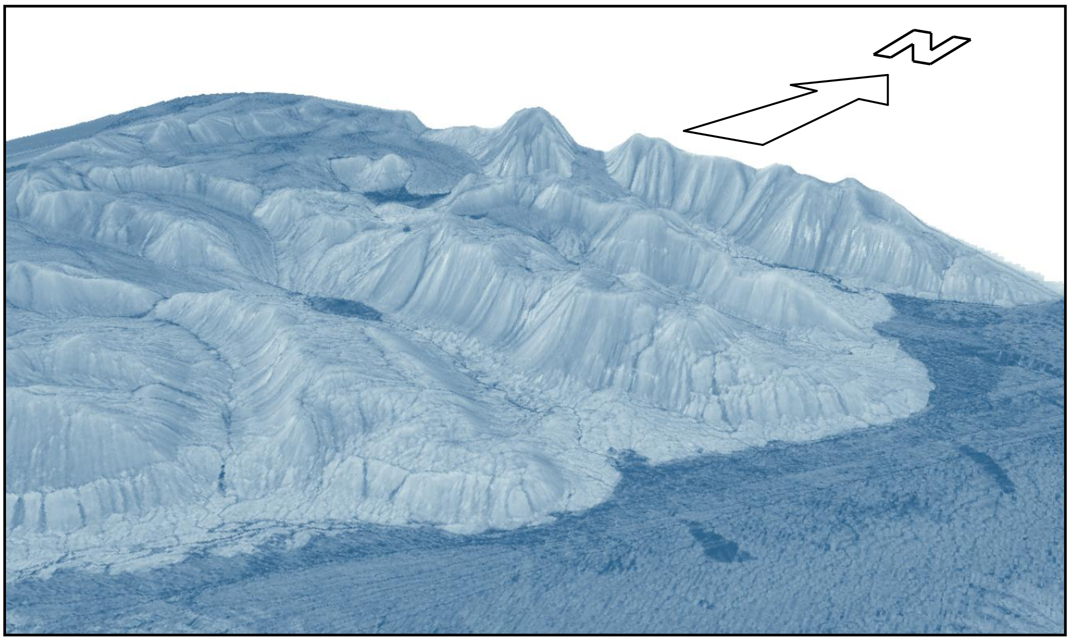


Figure 4.18 3D Overview B

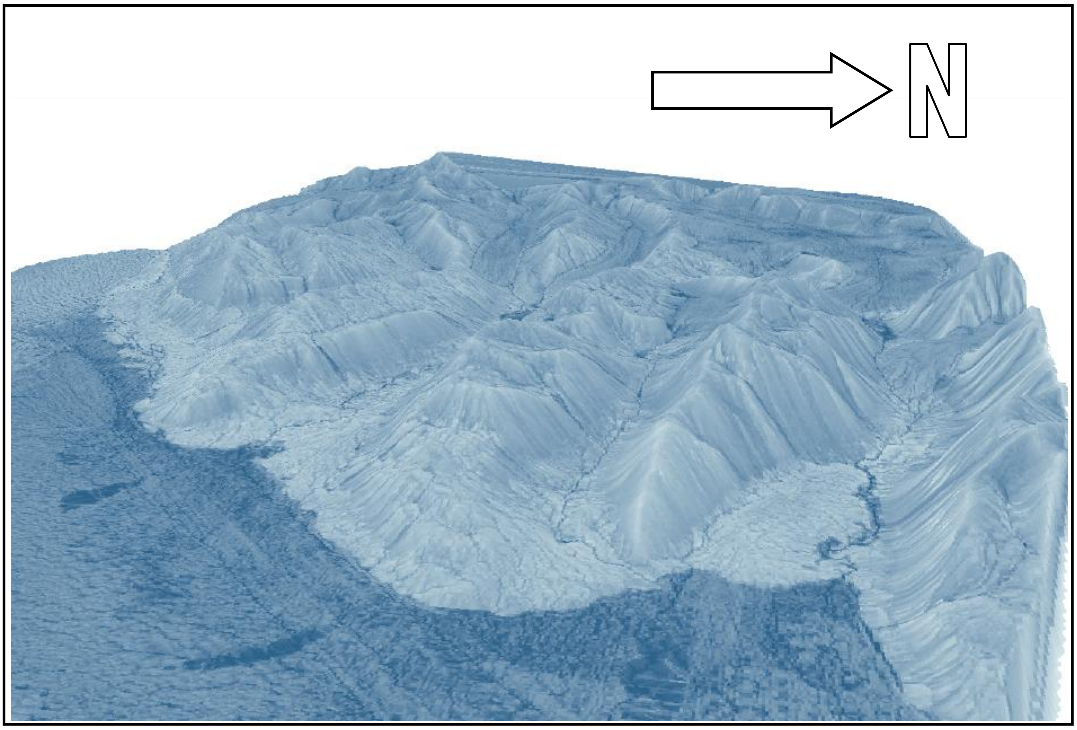


Figure 4.19 3D Miers Valley CTI

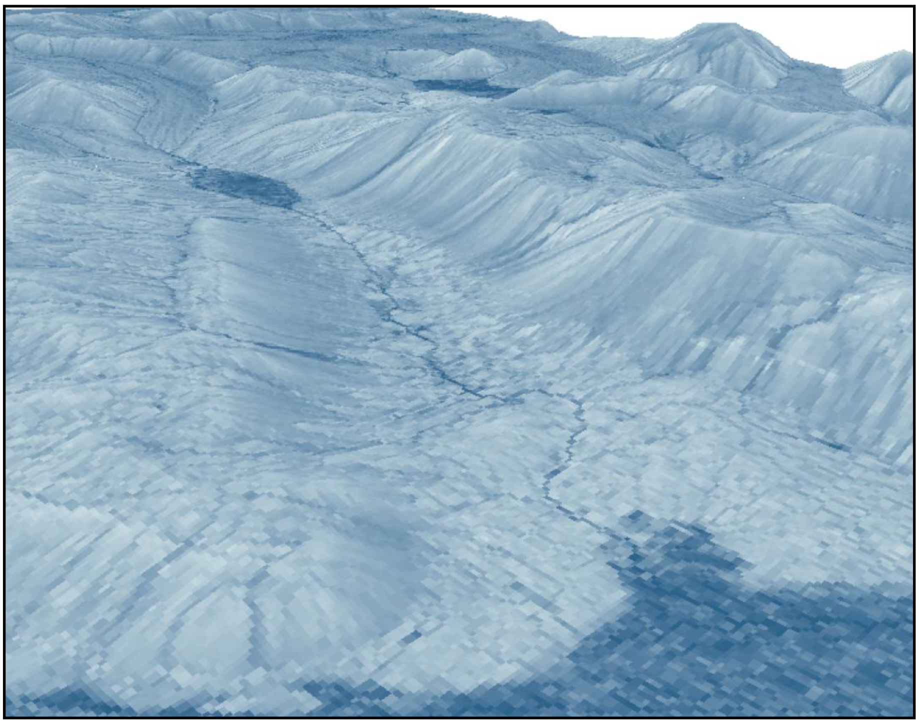


Figure 4.20 3D Miers Valley ALOS Image

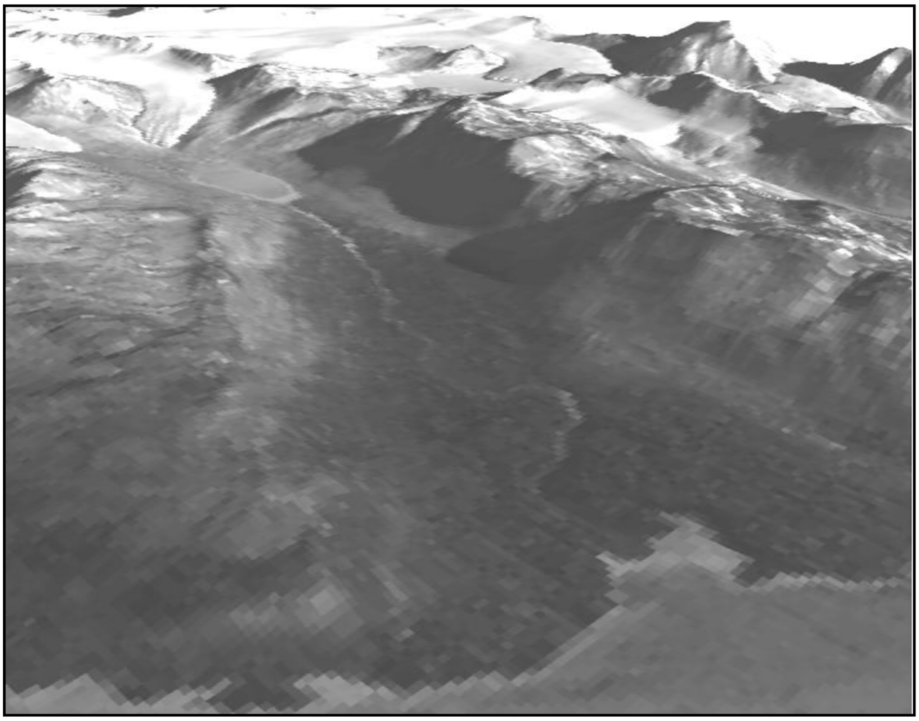


Figure 4.21 Weighted CTI Model

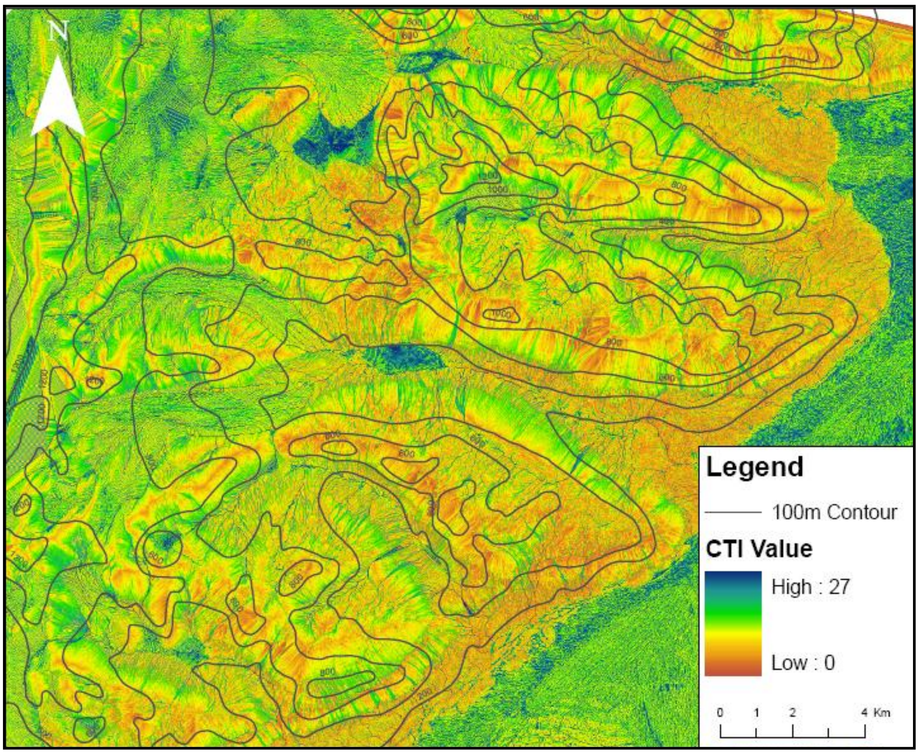
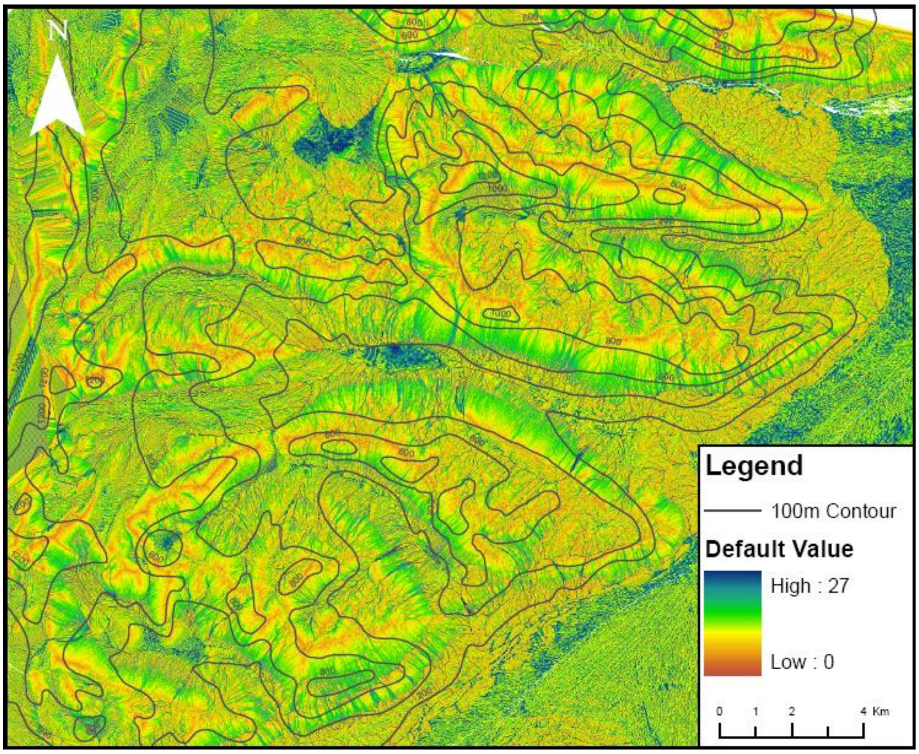


Figure 4.22 Unweighted CTI Model



Chapter 5. Discussion and Conclusion

The following chapter discusses the various strengths and limitations of the final output model, as well as the various data and methods used to achieve the output. Divided into two sections, the first will discuss the strengths and limitations of the model, as well as possible solutions and further avenues of investigation. The second section contains the concluding remarks, summarising the overall success, relevance and use of the model, and the achievement of the research goals.

5.1 Strengths and Limitations

5.1.1 Strengths

The model produced in this project is a new step in understanding water in the Dry Valleys of Antarctica. This model provides data for use in a number of fields in the physical sciences that require information on the distribution of water in the Dry Valleys, as well as possible applications in management and protection of these areas. In the past, measuring and mapping water availability has been sporadic, generalised and estimated due to the difficulty of data acquisition. The application of remote sensing and GIS to this area has provided data at a higher degree of accuracy, at a higher resolution, and over a larger area.

One of the strengths of the snow accumulation model using remote sensing is its simplicity and accuracy. In comparison, mathematical models predicting snow distribution involve the analysis of multiple variables, including various climate, wind and terrain variables, each of which requiring collection of data prior to analysis. Mathematically modelling the interaction of the variables to predict snow distribution is complex and the results are an estimation. Gathering remotely sensed data on past snow cover seems a far more logical method to create an average snow distribution index.

The use of remotely sensed data in this project has also provided an environmentally friendly contribution to the Antarctic knowledge base. Data acquired via satellite has removed the need for physically entering the unique and fragile Dry Valley environment. This reduces the effects of trampling and other human related impacts, as well as removing the risk of pollution and contamination to the area. This complies with the global effort for the protection and preservation of Antarctica. Field observations included in this project were carried out during the field collection of data for the IPY Biocomplexity project, when physical sampling was the only means for gathering data that will contribute to long term conservation goals. In this project remotely sensed data was primarily used for analysis, including the LIDAR generated DEM and daily satellite images of the Ross Sea Region captured by the MODIS instrument. This project illustrates one of the multitudes of ways such data can be utilised.

The data gathered for this research, as well as the various outputs of the analysis, all make useful contributions to the IPY Biocomplexity project. Each dataset (mean snow cover index, mean surface temperature index, corrected DEM and drainage) has its individual applications, but can also be combined to produce an overall predicted wetness index model. The IPY Biocomplexity project will be using multivariate regression analysis to predict the distribution of biota. The snow cover distribution, surface temperature and drainage variables developed in this thesis will be used in this analysis, and may possibly be important explanatory variables. As water availability is an important constraint on the spatial distribution of biota, the combined wetness index will likely prove to be a major contributing variable influencing the distribution and complexity of biota.

Not only are the datasets and model useful as they are, this project is also a proof of concept. The use of remote sensing to map snow cover, and CTI modelling to predict water distribution, are well established fields of research and analysis. Yet at present no other research has used both remotely sensed snow cover data and CTI modelling to predict water availability in Antarctica. In such an isolated environment where field research is difficult and water is such an influential constraint on biology, this research has proven to be a practical means of investigation. Further additions to this work, new study areas, and expanded applications using these methods can be done in confidence given the success of this project. Much of the data used in this project are freely accessible and the methods used in this project are fully explained (Chapter 4 and Appendix). As such, further work in this area or modifications of this work should be straightforward.

5.1.2 Limitations

Remote Sensing: Data Comparison

Choosing the appropriate data is an important decision when using remote sensing. This is illustrated in this project by the need to compromise between optimal spatial resolution, optimal temporal resolution and the cost of acquisition. The use of the Ross Sea Region subset available from the *MODIS Rapid Response System* website gave a high temporal resolution (daily) and free access but only moderate spatial resolution (250-500m^2). For large area analysis, such as comparing total daily snow cover between the various ice-free sites in Victoria Land, this data would be well suited. It did, however, cause a reduction in the potential spatial resolution of the analysis, as it did not allow for the full potential use of the high resolution DEM (4m^2). While the flow of water can be calculated to a high resolution previously unavailable for the study area, the snow weight modifier is only accurate to the moderate resolution of the snow cover data. It can be noted however that generally the distribution of snow cover is at a moderate scale (100s of meters). In this sense, the use of moderate resolution data to map snow cover distribution is appropriate. It is more the melt (and sublimation) of snow cover, and the flow of melt water over the terrain that occurs at a finer resolution. As the resolution used in this research to calculate flow paths is at a high resolution (10m²), the limitations of data resolution is reduced.

Perhaps the next step that should be taken to improve on this project is to obtain higher spatial resolution satellite images of the study area for snow cover analysis, such as Landsat or Aster. Increasing the resolution of the imagery increases the resolution of the weight grids that can be applied to the CTI. However the choice of high spatial resolution data must again be made with the temporal resolution of the data in mind. The positive outcomes of using high spatial resolution data include the ability to capture where snow accumulates in relation to smaller topological features and record to a higher degree of detail where snow patches endure for longer periods (such as in boulderfields). Another avenue for investigation would be to use the quantification of Snow Water Equivalent when determining the degree at which snow adds water to the Dry Valley systems. This type of investigation still does face the problem of having to quantify the effects of sublimation on the ablation rate of snow.

Melt Variations

The many interrelated variables influencing the melt rate of frozen water sources in the study area are highly complex and difficult to quantify. The rate of sublimation - the highest form of snow and ice ablation in the study area - is particularly influenced by humidity, wind and in the case of snow, the age of the snow patch (and therefore how compact it is). Attempting to quantify the effects of sublimation on the study area's hydrological regime is another research project in its own right. Other notable variables influencing melt rates, all interrelated with each other and with sublimation, are solar radiation reception, aspect, micro-terrain and soil variables (discussed further below), and temperature (surface and air). While these melt variables were not included in the model (for reasons such as data access, cost, time, or having no data available), the use of varying magnitudes on the weight grid - 0 having no recorded water source, to 10 for glaciers, lakes and permanent snow - provides a means of demonstrating the differing amounts of water produced if all frozen water sources melt at a similar rate. In the particular case of snow, the range of weights relate to the mean length of time the area is under snow cover. The more time spent under snow cover, the more potential there is for melt, and as such areas with a high mean snow cover index will have a high weight value and areas with low mean snow cover index will have a low weight value. The addition of melt variables, along with the use of higher resolution snow cover data to record the ablation patterns of snow in greater detail, could be an important next step in improving this model.

Cloud Cover

Field observations illuminated the scale of variability of snow melt in the study area. Numerous variables interact that determine the location and degree of melt. As discussed in Chapter 2**,** sublimation accounts for an enormous amount of snow ablation in the Dry Valleys. In weather events that deposit snow, the valleys can often be under cloud cover for extended periods. This has multiple implications. As there is much less solar radiation penetrating the cloud cover, temperatures remain cooler and there is less energy available to melt snow. Although there is cloud and precipitation in the air, humidity remains at extremely dry levels so sublimation continues at high rates while the melt rate is reduced. Cloud cover can remain for the duration of the snow cover period meaning that snow events can go unrecorded via satellite imagery due to disrupted visibility of the satellite remote sensor. The use of multispectral imagery, discussed in section 3.2.2, is a method to mitigate the effects of cloud cover on remote sensing.

Thermal Data Availability

The high resolution thermal data from the LANDSAT 7 ETM+ instrument was omitted from the final model produced in this study. While the use of such data was experimented with in the methodology chapter, the limitation at the time of having only three available datasets meant it was not sufficient to be included as a representative index. As data is increasingly becoming freely available, future inclusion of this data is highly plausible. Currently, I-Button temperature data loggers have been placed in arrays at various altitudes and aspects in each of the three valleys of the study area. This data too may be used in future analysis or for verification of surface temperature obtained from satellite images.

The addition of extensive thermal data to the model, either from weather station records or from satellite observations, could be used to predict the likely melt of snow as well as glaciers and lakes. Higher temperatures would mean an increased likelihood of melt, whereas lower temperatures would mean sublimation is increasingly likely to be the cause of any ablation. Wind records could also be factored into such investigations.

Terrain and Soil Variables

The terrain features covered by snow also influence the proportion of melt. Snow will generally ablate from northern aspects faster than southern aspect due to an increased amount of solar radiation received, resulting in a greater likelihood of melt. Snow on valley floors also tends to ablate faster, likely due to less shelter from the wind effects of sublimation and transportation. Snow cover accumulates most in lee areas. While depressions and leeward sides of ridges are obvious areas where snow will accumulate, areas such as boulderfields, common throughout the valley sides in the study area, collect snow and protect it from further transportation, providing numerous small, sheltered and moist microhabitats, particularly on northern slopes where the snow will be more likely to slowly melt. In these areas, microarthropods (springtails and mites), mosses and biotic crusts are likely to exist. Such areas are currently unidentifiable in this project, along with other small scale variables; therefore variables that influence water availability through snow melt are unrecorded. The possible use of roughness analysis on the high resolution DEM is a way of adding such variables to the model. Further investigations into soil characteristics (such as porosity, colour, salinity and horizon depth) and their influence on water flow and retention can also be factored into a water availability model.

Figure 5.1 Boulderfield Microhabitat

Subjectivity

Throughout the data collection and analysis process, subjective choices were made based on logical argument. While this leads to a degree of possible human error, the results produced can be verified using both field observations and data recorded by a weather station operating in the study area. The most important subjective decisions in this study were: (1) the weighting applied to the different water sources for the final CTI analysis, and (2) the model verification using visualisation techniques. The evaluation of the weightings is one of the numerous further investigations that can lead on from this project. Currently, soil moisture samples are being processed from many sites throughout the study area and the results of these could be used to verify the accuracy of the water availability predictions.

5.2 Concluding Remarks

As water is an important component required for life, a predictive model of water availability is integral to a study on biocomplexity in the Dry Valleys. The variables that influence the availability of water make up a large portion of the abiotic environmental characteristics that contribute to the determination of biota distribution. The model produced in this project, therefore, contains key information for the progress of the IPY Biocomplexity project. At the most basic level, the presence or absence of water will directly relate to the presence or absence of life. However, the amount of water available, the duration of its availability and the nature of its availability (e.g. flowing, pools or soil moisture) also directly influence which species will and will not be suited to that environment. The overland flow of water from higher areas, the formation of channels, and the accumulation of water in lower areas produce various microhabitats that cater for different species. While the drier upper slopes will more likely be limited to mostly lichens and other biota suited to surviving in highly desiccating areas, flush areas where water accumulates will likely be home to numerous species of cyanobacteria, algae, mosses, microarthropods and numerous microorginisms.

The methods and models described in this thesis show that the use of remote sensing and GIS for study in Antarctica is highly valid and a useful tool in both biotic and abiotic studies, as well as for managerial purposes. While this model has been created for use in the IPY Terrestrial Biocomplexity project, it is also useful for other applications such as hydrological modelling and environmental classification. Increasing our understanding of the Antarctic environment is important to the conservation and protection of this unique environment for future generations to study and explore. Remote sensing and GIS are integral to this as they can be used to produce knowledge without the need of direct contact and its negative implications. The data and methods used in this thesis are examples of only a few of the numerous and increasing uses of remote sensing and GIS.

The overall goal of this research was to evaluate the potential for GIS and remote sensing to be used for predicting biologically available water in Antarctica. To reach this goal, a number of objectives were set out. First, our current understanding of water in the Antarctic environment and its relationship with biota was investigated. This showed water is highly limited and is therefore a highly influential constraint on biology in Antarctica. Secondly, to gather data on the spatial distribution of water, various remotely sensed data sets and methods of analysis were examined for their relevance to this study. Daily MODIS images were used for their high temporal resolution and free access for snow cover analysis, Landsat7 ETM+ data was used for surface temperature, and a LIDAR generated DEM used for calculating water flow. Thirdly, various methods of analysis were experimented with using ArcGIS, including digital number conversion and image classification for the remotely sensed images, and flow path calculation and the development of a weighted Compound Topographic Index to predict water availability.

It can be concluded that such methods of data collection and analysis are highly valuable as they are environmentally friendly, cost effective, safe, and can easily analyse large areas. This research has produced valuable models and data sets for use in the multivariate Biocomplexity research. As the IPY Biocomplexity project continues, the degree of influence water has on biology and therefore the importance of the predictive water availability model will be revealed. This research has developed and demonstrated a new method for hydrological modelling in Antarctica that utilises both remote sensing and GIS. Given that water is a major constraint on biota in Antarctica, development of a wetness model will be important for predicting the distribution of biota in this significant location.

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Appendices

Appendix A: List of dates used for snow cover analysis

Dates given in year and Julian day (as from the MODIS Rapid Response System format): YYYYDDD

2004356	2005337	2006339	2007270
2004358	2005339	2006340	2007278
2005003	2005340	2006342	2007282
2005011	2005348	2006350	2007285
2005015	2005349	2006358	2007292
2005017	2005362	2006365	2007299
2005018	2005363	2007003	2007304
2005022	2006006	2007007	2007305
2005029	2006007	2007009	2007309
2005031	2006008	2007010	2007316
2005033	2006017	2007011	2007320
2005035	2006034	2007012	2007328
2005041	2006039	2007013	2007338
2005043	2006040	2007014	2007343
2005045	2006042	2007018	2007346
2005046	2006045	2007024	2007347
2005058	2006046	2007026	2007350
2005063	2006053	2007027	2007352
2005067	2006065	2007029	2007354
2005069	2006068	2007038	2007357
2005072	2006271	2007042	2007358
2005074	2006274	2007043	2007359
2005261	2006280	2007054	2008003
2005263	2006281	2007059	2008013
2005265	2006282	2007061	2008014
2005267	2006296	2007062	2008015
2005269	2006301	2007064	2008018
2005273	2006302	2007067	2008021
2005278	2006304	2007068	2008026
2005282	2006306	2007069	2008028
2005288	2006307	2007070	2008029
2005290	2006311	2007075	2008030
2005295	2006313	2007076	2008037
2005299	2006315	2007077	2008046
2005301	2006316	2007078	2008047
2005302	2006317	2007079	2008048
2005303	2006325	2007087	2008051
2005308	2006326	2007258	2008058
2005314	2006331	2007263	2008085
2005322	2006332	2007265	2008087
2005331	2006333	2007267	2008088
2005333	2006338	2007268	

Appendix B: Sample AML Scripts

Compound Topographic Index by Evans (2001/03)

(Preceding sections omitted as were not used in this research. Full copy available in Appendix C)

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...

&type /& Caculating Slope in Degrees /&
%tmp4% = slope(%tmp1%, degree)

&type /& Converting slope degrees to radians using: slope * (pi / 2) / 90 /&
%tmp5% = (%tmp4% * 1.570796) / 90

&type /& Caculating tangent of slope(radians) /&
%tmp6% = tan(%tmp5%)

&type /& Reclassing 0 slope values to .001 /&
%tmp7% = con(%tmp6% == 0, .001, %tmp6%)

&type /& Caculating upslope surface contributing area /&
%tmp8% = (%tmp3% + 1) * %cellsize%

&type /& Caculating Compound Topographic Index /&
%outgrid% = ln((%tmp8% / %tmp7%))

&type /& Cleaning Up Temporary GRIDS /&

&messages &off

kill (!%tmp1% %tmp2% %tmp3% %tmp4% %tmp5% %tmp6% %tmp7% %tmp8%!) all

&messages &on

&type /& Compound Topographic Index written to [upcase %outgrid%] /&

&end

&else &do

&if [exists %ca% -grid] = .FALSE. &then
  &return &inform Grid [upcase %ca%] does not exist!

&messages &off

describe %ca%

&messages &on

&s cellsize = %GRD$DX%
```

```
setcell %cellsize%
setwindow %ca%

&s tmp1 [scratchname -prefix xx1] /* Slope Radians
&s tmp2 [scratchname -prefix xx2] /* Slope Reclass
&s tmp3 [scratchname -prefix xx3] /* Slope Tangent
&s tmp4 [scratchname -prefix xx4] /* Area Value

&type /& Converting slope degrees to radians using: slope * (pi / 2) / 90 /&
%tmp1% = slope(%dem%) * 1.570796 / 90

&type /& Reclassing 0 slope values to .001 /&
%tmp2% = con(%tmp1% == 0, .001, %tmp1%)

&type /& Caculating tangent of slope(radians) /&
%tmp3% = tan(%tmp2%)

&type /& Caculating upslope surface contributing area /&
%tmp4% = (%ca% + 1) * %cellsize%

&type /& Caculating Compound Topographic Index /&
%outgrid% = ln((%tmp4% / %tmp3%))

&type /& Cleaning Up Temporary GRIDS /&

&messages &off

kill (!%tmp1% %tmp2% %tmp3% %tmp4%!) all

&messages &on

&type /& Compound Topographic Index written to [upcase %outgrid%] /&

&end
```

Image Preparation Part 2

```
***********************************************************************
            Image preparation for work in ArcInfo Workstation by Glen Stichbury

 This script requires a variables script to run, setting up the input file location
(%.inlocation%), output file location (%.outlocation%), image identifier (%.number%),
original image name (%.original%) including file extension eg .tif and a clip coverage for
the rectification (%.clip%).
 An example of the first two lines in the script would be:
&sv .clip                E:\Glen\Masters\workstation\NDSI\clip;        &sv .original~
RossSea.2004356.terra.250m.tif;        &sv .number    2004356;~
&sv .inlocation  E:\Glen\Masters\workstation\images;   &sv .outlocation~
E:\Glen\Masters\workstation\NDSI;       &r rectify.txt
 This script is set up to run processes on .tif files. Other image types
would require a universal change from .tif to the desired file extension.

**********************************************************************
&call workspace
&call Rectify
&call imagegrid
&call float
&return
***********************************************************************
&routine workspace

&if [show program] ne ARC &then quit

&if [exists %.outlocation%/Grids/%.number% -workspace] &then
&type +++Workspace Exists+++
&else createworkspace %.outlocation%/Grids/%.number%

&if [exists %.outlocation2%/%.number% -workspace] &then
&type +++Workspace Exists+++
&else createworkspace %.outlocation2%/%.number%

&return
**********************************************************************
&routine Rectify

&if [show program] ne ARC &then quit

&if [exist %.outlocation%/%.number%.tif -file] ~
  &then &sys erase %.outlocation%/%.number%.tif

&type +++Rectifying %.original%+++
rectify %.inlocation%.\%.original% %.outlocation%\%.number% # # %.clip%

&return
**********************************************************************
&routine imagegrid
```

```
&if [show program] ne ARC &then quit

&if [exist %.outlocation%/Grids/%.number%/%.number% -grid] ~
  &then kill %.outlocation%/Grids/%.number%/%.number% all

&type +++Converting %.number% to Grid+++
imagegrid %.outlocation%\%.number% %.outlocation%/Grids/%.number%/%.number%

&return
*********************************************************************
&routine float

&if [show program] ne GRID &then &do
&if [show program] ne ARC &then quit
grid
&end

&if [exist %.outlocation2%/%.number%/%.number% -grid] ~
  &then kill %.outlocation2%/%.number%/%.number% all


&type +++Converting %.number% to Float+++
/*%.outlocation2%/%.number%/%.number% =
float(%.outlocation%/Grids/%.number%/%.number%)

/*&return

&if [exist %.outlocation2%/%.number%/%.number%c1 -grid] ~
  &then kill %.outlocation2%/%.number%/%.number%c1 all
&if [exist %.outlocation2%/%.number%/%.number%c2 -grid] ~
  &then kill %.outlocation2%/%.number%/%.number%c2 all
&if [exist %.outlocation2%/%.number%/%.number%c3 -grid] ~
  &then kill %.outlocation2%/%.number%/%.number%c3 all

%.outlocation2%/%.number%/%.number%c1 =
float(%.outlocation%/Grids/%.number%/%.number%c1)
%.outlocation2%/%.number%/%.number%c2 =
float(%.outlocation%/Grids/%.number%/%.number%c2)
%.outlocation2%/%.number%/%.number%c3 =
float(%.outlocation%/Grids/%.number%/%.number%c2)

&return
*********************************************************************
```