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**A Hybrid Model For Predicting
Permafrost Occurrence And Thickness**

by

James Frederick Wright, B.A.

Department of Geography

Carleton University

Ottawa, Canada

May 23, 1995

**A thesis submitted to the Faculty of Graduate Studies in partial fulfillment of the
requirements for the degree of Master of Arts, Geography.**

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**submitted by James Frederick Wright, B.A. (Geography), in partial fulfillment of the
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A handwritten signature in cursive script, reading "M.W. Smith", written over a horizontal line.

Thesis Supervisor

Michael W. Smith

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Chair, Geography Department

Michael W. Smith

Carleton University

May 23, 1995

Abstract

At present, our ability to delineate the extent of perennially frozen ground is very limited, with maps of permafrost distribution identifying three broad zones of continuous, discontinuous and sporadic coverage. This thesis relates the output from a simple Stefan-based equation to predictions of permafrost thickness generated by a one-dimensional finite element heat conduction model. The relationships observed are integrated into a GIS-compatible, hybrid permafrost prediction model (HPPM) which has the potential to predict permafrost occurrence and thickness at regional and local scales. An evaluation of HPPM performance is undertaken through its application to the Fort Simpson and Norman Wells regions within the Mackenzie Valley, Northwest Territories. HPPM predictions of permafrost occurrence and thickness agree favourably with local borehole information and geophysical survey data along the Norman Wells pipeline right-of-way. Equilibrium permafrost responses to +1°C and +2°C climate warming scenarios were investigated at Fort Simpson by adjusting HPPM climate parameters to simulate increases in mean annual air temperatures. Modeling results suggest that nearly all permafrost in the Fort Simpson region will disappear in response to a +2°C climate warming.

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Fred, April 1995.

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CHAPTER 1

Purpose and Objectives

1.1 Introduction

Over half of the Canadian land mass is underlain by permafrost, which is defined as a temperature condition in which earth material remains below 0°C for more than a year (Williams and Smith, 1991). Where permafrost contains significant amounts of ice, any disturbance of the thermal regime may have important implications for ecological and terrain conditions, and for human activities. Disturbance may arise from the disruption or removal of the surface vegetation (which modulates the heat exchange between the atmosphere and the mineral earth) or from a persistent change in long-term atmospheric conditions (climate change). Degradation or aggradation of ice-rich permafrost potentially leads to terrain instability (ground subsidence or heave). These processes are of concern to planners and engineers active in northern regions, particularly in terms of their effects on physical structures (buildings, roads, pipelines) and land use (farming, forestry, hunting and trapping).

It is widely acknowledged that enhanced greenhouse warming will probably affect the Earth in a significant way during the next century. Current predictions from general circulation models (GCMs) suggest that in the northern polar latitudes mean annual air temperatures could increase by as much as 1°C per decade beyond the middle of the next century (although predictions of the precise locations and degree of warming still vary

significantly between models). Climatic change of such magnitude and rapidity may have serious consequences for the permafrost environment and arctic development. In order to address these issues adequately we need to determine the distribution and nature of permafrost at local and regional scales. Given the prohibitive costs associated with the precise delineation of permafrost distribution by field methods (borehole drilling, probing), an alternative method for predicting permafrost occurrence would be useful. In the context of an anticipated global warming, the approach should also have the capability to predict changes in the distribution and thickness of permafrost expected in response to changes in either atmospheric, or surface, conditions.

This thesis describes the development of a Hybrid Permafrost Prediction Model (HPPM) which utilizes available climatic data (freezing and thawing degree days) and terrain data at the regional scale (typically, map scales of 1:250,000 or 1:125,000). The model, which is implemented within a geographic information system (GIS), is designed to predict the spatial distribution of permafrost occurrence and to provide an estimate of permafrost thickness. It assumes that the atmosphere-ground thermal regime is in equilibrium. A simple equation for predicting the occurrence of permafrost (Jorgenson and Kreig, 1988) forms the theoretical basis for the HPPM. A one-dimensional discontinuous-element heat conduction model (Goodrich, 1982) was used as a means for isolating the influence of various climate and terrain parameters on permafrost thickness. Descriptive equations derived from this procedure were recombined with the Jorgenson and Kreig (J&K) equation, resulting in a series of GIS-compatible modeling equations which comprise the Hybrid Permafrost Prediction Model.

The Hybrid Model is suited to the ready investigation of multiple environmental scenarios, such as assessing the potential impacts of global climate change in northern regions. Model performance was evaluated against predictions of permafrost occurrence and thickness generated by the finite-element heat conduction model. In addition, a demonstration of its application to two geographic regions was carried out near Fort Simpson and Norman Wells, NWT.

1.2 Historical Approaches to the Prediction of Permafrost Occurrence

The spatial distribution of permafrost in North America ranges from being nearly continuous in its most northerly regions to discontinuous and sporadic in nature as the southern limits of its extent are approached. Given the vastness of these territories and the prohibitive logistical and economic realities associated with sampling these regions at appropriate scales, it is not surprising that field measurements of the distribution of permafrost are lacking for most northern regions. In view of this, there have been two general approaches to the prediction of permafrost occurrence which utilise existing environmental and terrain data.

1.2.1 Logical Models of Permafrost Occurrence

The first approach attempts to associate known occurrences of permafrost with specific conditions of environment and terrain which have been observed at permafrost sites. These associations may then be applied to areas where the distribution of permafrost is unknown. This approach does not attempt to parameterise any of the natural processes or terrain properties relevant to the genesis and maintenance of frozen ground. It relies

instead on an assumption of logic (that vegetation-permafrost associations observed in sampled permafrost sites may be viewed as a cause-effect relationship) which justifies the application of these associations to other sites exhibiting similar characteristics.

Permafrost occurrences within the southern regions of the discontinuous zone are known to be associated with terrain units having a thick insulating peat cover and with certain dense tree stands (usually black spruce) which provide summer shading and reduced winter snow cover (Brown, 1970). Dingman and Koutz (1974) investigated permafrost-vegetation relations in a 1.8 km² drainage basin in central Alaska. The presence or absence of permafrost was determined by probing with a 1-meter graduated steel rod (note that only the occurrence of shallow permafrost may be determined by this method). They found that while permafrost was generally present over much of the study area, it appeared to be absent under white spruce-birch forest stands. These forest units were observed to occur on well-drained soils. It was speculated that elevated water contents in the upper soil profile are often a consequence of the presence of permafrost, which impedes water drainage downward into the soil. This implies that many of the vegetation types observed in permafrost-bearing terrain exist *in response* to these elevated water contents, rather than being directly associated with permafrost occurrence. A potential insolation index derived from Lee's (1962, 1964) concept of equivalent latitude (utilising terrain slope and aspect) was also shown to be related to permafrost occurrence and the depth of the seasonal active layer.

A study by Rennie, Reid and Henderson (1978) described permafrost-vegetation associations for a broad range of terrain and vegetation conditions at Fort Simpson, and

included observations of permafrost occurrence in relation to topographical shading and north-facing slopes. Electromagnetic resistivity surveys, testhole drilling, and detailed air photo interpretation of terrain and vegetation were used to delineate permafrost boundaries. Their results were in general agreement with Dingman and Koutz (1974), but suggested that permafrost occurrence is variable under both black and white spruce. Cowell et al. (1978) noted that while permafrost often occurs under black spruce islands, at the southern fringe of the discontinuous zone these islands may exist in response to the underlying mineral soil topography without the presence of permafrost.

Vitt et al. (1994) provide a good description of bog landforms and their association with permafrost occurrence, as well as the implications of past climatic regimes and the genesis and succession of bog landforms in Western Canada. Aylsworth et al. (1993) investigated peatland distribution in the Fort Simpson region and determined that the presence or absence of permafrost is mirrored by the occurrence of peat bogs and fens respectively.

Correlations between various vegetation units and the occurrence of permafrost have been used as the basis for modeling the distribution of permafrost. A notable example utilizes vegetation classes derived from Thematic Mapper satellite data and ancillary map data to develop logistic discrimination functions for predicting the presence of permafrost (Morrissey et al. 1986). Random sampling (stratified according to frozen, discontinuously frozen, and unfrozen classes) of a photo-interpreted permafrost map provided data which were regressed individually against various environmental variables. Logistic discrimination functions were derived through a rigorous evaluation of regression outputs

relevant to the particular combination of environmental conditions occurring at a given pixel, and are expressed as a probability of membership in each permafrost class. Prediction accuracy (based on the proportion of fifty-eight training sites that were correctly-classified) approaching 80% was attained when modeling results were compared to the photo-interpreted permafrost maps. Peddle and Franklin (1992) used an evidential reasoning classification system (MERCURY) to attain better than 80% prediction accuracy in comparison with the results of permafrost probing at over 400 test sites.

While these modeling results are encouraging it should be noted that such approaches have a number of limitations in the context of predicting changes in permafrost distribution in response to climatic change. It is clear that a specific vegetation type or assemblage is not always an indicator of the presence or absence of permafrost. Exceptions exist that must surely reflect the influence of other terrain and climate factors that are not accounted for in a logical model. Additionally, where prediction accuracy is based on a comparison with photo-interpreted data, we must be concerned with the fact that logical or evidential classifications are derived using many of the same rules that are utilised in the process of photo interpretation. In the context of a probable global warming, logical models provide no mechanism for evaluating the change in permafrost distribution in response to a changing climate. Furthermore, we may be interested in providing an estimate of the thickness of permafrost, as well as its spatial distribution. The modeling approaches previously described have no capacity for predicting the depth to which ground at any particular site may be frozen. In order to investigate the three-dimensional distribution of permafrost expected under a number of climate scenarios it is

necessary to develop a model based upon a functional representation of the climate and terrain factors influencing the ground thermal regime.

1.2.2 Transient Numerical Models

An alternative approach to permafrost prediction involves the use of numerical models which attempt to explicitly parameterise heat-flow relations between the atmosphere and the various terrain elements in order to generate a detailed representation of the ground thermal regime. Goodrich (personal communication, 1993) provided a *one-dimensional finite-element heat conduction model* (TONE) which is executable on a desktop computer. TONE supports very detailed descriptions of the climatic regime at the interface of the atmosphere and the ground surface, and may operate at a wide variety of time scales (i.e., from a few hours or days to many thousands of years). Thermal properties of the substrate may be explicitly defined in terms of temperature-dependent thermal conductivities and heat capacities. Calculations are made in user-defined time intervals and are representative of transient conditions occurring at grid nodes. As a transient model, TONE requires the specification of boundary conditions and an initial temperature profile. Ground temperatures are calculated for each grid node at successive time steps, with temperature changes at a particular node being dependent upon the specified thermal properties of the soil unit modeled, and the temperature profile at the previous time step.

Grid thickness and resolution (fineness) may be varied according to user specifications. The model can accommodate multiple substrate layers having different thermal properties. TONE does not consider the potential influences of water migration or

ice-lens growth. Values for the geothermal heat flux (known to vary from region to region) may be user-defined. For permafrost problems, the influence of vegetation and snow cover may be generalized by applying appropriate n-factor values to the annual temperature wave (Lunardini, (1978).; n-factors are discussed in more detail later in this thesis). Alternatively, snow cover may be treated as an additional layer with its own explicit thermal properties.

A single execution of TONE on a personal computer requires several minutes to several hours, running until a pre-determined criterion for attaining equilibrium is met. Average execution time is on the order of one hour. Additional time costs are associated with preparing data input files and the analysis of output data. The direct application of this type of model to permafrost problems at regional scales would be prohibitive, due to the potential occurrence of hundreds of unique combinations of terrain conditions, each requiring a separate model run.

It is necessary, therefore, to adopt an alternative approach in order to develop an efficient model for predicting permafrost occurrence and thickness over a region, and which also has the capacity to predict permafrost responses to a changed climate.

CHAPTER 2

Developing the Modeling Approach

2.1 A Conceptual Model of the Ground Thermal Regime

At the most basic conceptual level, the occurrence of permafrost is associated with average annual *ground* temperatures which are below the freezing point of water. It is reasonable to assume that this condition exists as a consequence of average annual *air* temperatures that are also below freezing. The air temperature isotherm may therefore be considered as a basic delimiter of permafrost extent. Brown (1967) investigated the relationship between mean annual air temperature (MAAT) and permafrost occurrence. The 0°C isotherm did not appear to have a direct correspondence with permafrost occurrence. Instead, the -1.1°C and -8.3°C MAAT isotherms were used to delimit the southernmost boundaries of the discontinuous and continuous permafrost zones respectively. While useful for visualising the general distribution of frozen ground at continental scales, a strictly air temperature-based approach fails to incorporate regional and local variations in terrain characteristics known to exert a significant influence on the ground thermal regime. These include the insulating effects of vegetation and snow cover, variations in topography (elevation, slope and aspect), the mineralogy of various soil units, and soil water content (Jorgenson and Kreig, 1988).

Figure1: A conceptual model of the climate-permafrost relationship

- after Luthin & Guymon (1974)

Williams and Smith (1991) adopted a simple conceptual model of the basic elements of the ground thermal regime in which the system is partitioned into three “layers”, each of which may exhibit variability in terms of the thermal properties and processes occurring in geographic space (Figure 1). The uppermost layer represents the atmosphere above a particular site, within which the influences of solar radiation and atmospheric convection are dominant in determining air temperatures at the interface to the layer immediately below. Assuming a constant geothermal heat flux, temperatures experienced in the geological substrate (the bottom layer) should reflect the long-term

influence of those existing in the uppermost layer. The degree to which this influence is felt depends upon the heat transfer characteristics of the intervening *buffer* layer. For a vegetated site, the transmission of heat into and out of the ground is modulated according to the properties and processes associated with the particular surface cover (e.g.: conduction, evapotranspiration, albedo effects, as determined by vegetation species composition, density, and height). The influence of snow cover may also be included within the buffer layer.

The characteristics of individual layers may vary temporally as well as spatially. The temperature of the active atmosphere is potentially variable at all time scales, with cyclical patterns being evident at diurnal and annual time periods. Long-term climatic trends may also be important. Winter snow cover, seasonal growth and senescence of vegetation, and the succession of species introduce temporal variability to the properties of the buffer layer. Thermal properties (thermal conductivity, heat capacity) of the geological substrate may change in response to temporal variations in water content and to seasonal changes in the state of this water.

The model in Figure 1 has been implemented at the site-specific scale by Smith and Riseborough (1983), to investigate the range of ground temperature responses to variation in climate and site conditions. They employed a numerical microclimatic model within which the surface energy balance was described in terms of the influences of surface cover (vegetation or snow) surface roughness, albedo, slope and aspect, and soil wetness. Temperature-dependent soil thermal properties were explicitly described, and the annual climatic regime was prescribed according to mean monthly temperatures for

Whitehorse, Yukon Territory. Their study concluded that, under a warming climate, rates of permafrost degradation were influenced to a greater degree by variability in site conditions than by the distribution of warming throughout the year.

This approach, while feasible for site-specific studies (for which the variability in site conditions may be described in great detail), would be unmanageable for regional-scale applications, where many hundreds of unique combinations of site conditions may exist. Therefore, it is necessary to utilise a more generalised description of regional climate and terrain conditions, and to develop a simplified means for determining their effect on the ground thermal regime. The following sections outline the details of these generalisations, as employed in the development of regional-scale, permafrost prediction models.

2.2 Evolution of the Modeling Approach

In order to progress from the conceptual model to a workable permafrost prediction model it is necessary to parameterise the role of each layer in determining the temperature regime of the ground at depth. It is assumed for each modeling case, that the annual climatic regime characterizing the upper layer is stable and that long-term thermal equilibrium is attained between all layers.

2.2.1 Mean Annual Temperature and Freeze-Thaw Indices (Upper Layer)

Lunardini (1981, p. 133) shows that the depth to the bottom of permafrost is controlled by the surface temperature, the geothermal flux, and the thermal conductivity of the substrate. Where water is present in significant amounts, the thermal conductivity of

the substrate is higher during the freezing season than during the thaw season, due to the much higher conductivity of ice versus liquid water. Consequently, the influence of the surface temperature will penetrate to greater depths during the freezing season. This has implications for the manner in which annual air temperature data is incorporated into a predictive model. Simply using mean annual air temperatures allows no consideration of the annual range of temperature deviation about the mean (amplitude), or of more interest to us, the temperature deviation about the 0°C threshold. The concept of freeze and thaw indices provides a measure of the magnitude of this variation for the freezing and thawing seasons respectively.

Freeze and thaw indices are derived through time-integration of that portion of the annual temperature wave that falls below or above 0°C respectively, expressed in degree-days (Lunardini, 1981. p.27) For example, in the case where the temperature at the ground surface is 0°C with a sinusoidal wave amplitude of 23°C, the freeze index (DDF) is 2672 degree-days as is the thaw index (DDT). In this case, freezing conditions exist for half of the annual cycle, while a thaw condition exists for the other half. Given the higher thermal conductivity of the frozen substrate, we may expect a greater rate of heat transfer between the earth and atmosphere during the freezing season (assuming no vegetation or snow cover), leading to long-term average ground temperatures which favor the frozen state, even though the MAAT is 0°C. The depression of ground temperatures relative to the surface temperature is known as the thermal offset, described by Goodrich (1978) and confirmed by Burr and Smith (1988).

2.2.2 The Vegetated Surface Layer

If the ground surface is defined as the interface between the existing vegetative cover and the underlying soil matrix, it becomes necessary to adjust the measured or estimated air temperature and associated freeze-thaw indices to reflect the effect of the intervening vegetative layer on temperatures actually experienced at the defined surface. Lunardini (1981, pp. 559-576) has described this influence in terms of freezing and thawing surface *n-factors*. Conceptually, *n-factors* include the influence of a number of heat transfer processes occurring within the vegetated surface layer (e.g.: short and long-wave radiative heat transfer, reflection, evapotranspiration, conduction and convection). *N-factors* are derived in a similar manner to the freeze-thaw indices described above except that annual temperature waves for both the air *and* the defined surface are time-integrated separately. (Figure 2).

Figure 2: Generalised representation of a method for determining seasonal *n-factors*.

The ratios of the freezing and thawing surface indices to corresponding air indices are defined as the winter and summer n-factors respectively:

$$\text{Winter n-factor } (n_f) = \frac{\text{surface freeze index}}{\text{air freeze index}}$$

$$\text{Summer n-factor } (n_t) = \frac{\text{surface thaw index}}{\text{air thaw index}}$$

N-factor values have been determined experimentally for particular surface types; most of the n-factor values provided by Lunardini (1981, p. 563) are related to engineered surfaces such as pavement, concrete and gravel rather than to natural vegetation covers. Jorgenson and Kreig (1988) provide n-factor values for eight vegetation types encountered in the Spinach Creek Watershed near Fairbanks, Alaska; their values include the seasonal influence of snow.

N-factors are applied as simple multipliers to known or estimated air temperature indices in order to obtain values for freeze-thaw indices at the soil surface. Seasonal n-factors derived from temperature measurements at a particular geographic location are assumed to be applicable to other sites exhibiting the same surface-cover conditions. Estimation of freezing n-factors for vegetated surfaces is complicated by the presence of snow. Snow depth and density can be highly variable at both local and regional scales. Given the difficulty of separating the relative contributions of the vegetation and snow components, snow effects are generally included in winter n-factors. This implies that a

particular vegetation cover within which snow cover varies, may not be adequately represented by a single seasonal n-factor. Therefore, it is questionable whether winter n-factor values may be transposed unmodified for application to *other* regions which exhibit similar surface vegetation characteristics. An evaluation and subsequent modification of winter n-factors with respect to relative snow cover characteristics would be desirable in order to increase our confidence in them. Such an exercise is beyond the scope of this thesis, however. Alternatively, snow models which predict the distribution, depth and physical characteristics of snow cover from climate and topographical data can be used to estimate the spatial distribution of winter n-factors based on the premise that snow effects may dominate the thermal properties of the surface in winter (Goodrich, 1978). This thesis will not investigate this approach, but will favor the use of n-factors for which snow cover effects are included.

Data for the derivation of n-factors (including snow effects) for vegetation units specific to the Fort Simpson area have recently been collected by Alan Taylor of the Geological Survey of Canada (personal communication, 1994). Unfortunately, these data are based on temperature measurements for a single year (1993-94) and may not be representative of the long-term climate regime. An attempt has been made to combine these data with the n-factors provided by Jorgenson and Kreig to derive n-factor values suitable for application in the Fort Simpson Region.

2.2.3 Substrate Characteristics

The *rate of heat transfer* within the substrate depends upon the thermal conductivity of the soil unit in question. The *temperature change* experienced in response to a change in heat content is dependent on the heat capacity of the soil. When water is present in significant amounts, soil heat capacity and thermal conductivity values are dependent on whether the water is in the frozen or unfrozen state. An additional quantity of heat (heat of fusion) must be transferred in order to change the phase-state of this water, with the bulk of the phase change occurring at temperatures near 0°C. While phase-change effects are very important for short-term transient problems, for temperature regimes at long-term equilibrium, heat capacity may be ignored and only thermal conductivity need be considered (Williams and Smith, 1991).

Spatial variations in substrate thermal properties will depend on mineralogy, grain-size distribution, dry density, and water content of the various soil units within the area under study. Few empirical data regarding the distribution of these soil characteristics are available for northern regions. A number of techniques exist for experimentally *measuring* the thermal conductivity of soils, but the values so derived are specific to the particular combination of physical properties for the soil being measured, and may not be applicable to other soils of that general type. In order to use measured values of thermal conductivity for permafrost modeling, it would be necessary to obtain measurements for *all* of the soil units within a region that exhibit unique combinations of these properties.

A more practical approach for regional-scale studies involves the *estimation* of thermal conductivity from generalised information about soil physical properties. Farouki

(1981) provides a summary of the best-known methods for estimating the thermal conductivity of mineral soils. Of particular interest are the equations proposed by Kersten (1949) and Johansen (1975) which calculate thermal conductivity in terms of soil texture, moisture content and dry bulk density. Johansen's equations also account for mineralogical variations in quartz content. It is generally agreed (Farouki, 1981) that Johansen's equations provide reasonable estimates of thermal conductivity for a wide variety of soils, and with greater reliability than Kersten's equations.

2.3 Stefan's Equation for Frost and Thaw Estimates

Stefan (1891) proposed equations for approximating the maximum phase-change depth in response to a step-change in surface temperature for a homogeneous, single-layer system. The initial temperature profile is assumed to be isothermal at 0°C. If we regard freeze and thaw indices as being analogous to temperature step-changes, Stefan's equations may be used to determine the freeze and thaw depths expected for a particular annual surface temperature regime. Lunardini (1981, p.551) suggested that the ratio of Stefan's frost and thaw estimates can be used as an index of permafrost occurrence. Where the calculated freeze depth exceeds the thaw depth, the occurrence of permafrost is indicated. The Stefan equations do not account for the sensible heat required to raise ground temperatures to 0°C, nor for the conduction of sensible heat from the phase-change layer to lower layers of the soil profile (Lunardini, 1981, Nelson and Outcalt, 1983). Consequently, most researchers have been reluctant to rely on the *absolute* depths for phase-change predicted by Stefan-based equations. However the *ratio* of freeze and thaw estimates has formed the basis for some models of permafrost occurrence.

2.3.1 The Frost Index Approach for Predicting Permafrost Distribution

Nelson and Outcalt (1983) utilized Stefan's freeze and thaw depths for calculating a Frost Index Number to predict the occurrence of permafrost. Freeze and thaw indices were used to represent the seasonal change in temperature occurring in the atmosphere. Freeze and thaw depths were approximated as:

$$Z_f = \{(2 \cdot K_f \cdot S \cdot DDF) / (x_w \cdot L)\}^{1/2} \quad (1)$$

$$Z_t = \{(2 \cdot K_t \cdot S \cdot DDT) / (x_w \cdot L)\}^{1/2} \quad (2)$$

Where:

DDF = freezing degree days (air)

DDT = thawing degree days (air)

Z_f = frost depth

Z_t = thaw depth

K_f = frozen thermal conductivity of substrate

K_t = unfrozen thermal conductivity of substrate

S = scale factor for time units employed

x_w = volumetric water/ice content

L = latent heat of fusion

The Frost Index Number (F) is defined as the ratio of the frost depth to the thaw depth:

$$F = Z_f / Z_t \quad (3)$$

If water content for a given soil unit is assumed to be constant through time, the equation reduces to:

$$F = \{(K_f \cdot DDF) / (K_t \cdot DDT)\}^{1/2} \quad (4)$$

Where $F > 1$, the freeze depth is greater than the thaw depth and permafrost may be expected to occur. It is reasonable to infer that larger frost numbers are indicative of thicker permafrost. Nelson and Outcalt used frost number values of 1.0 and 1.5 to delineate the southern boundaries of the discontinuous and continuous permafrost zones for Alaska. Freeze indices were adjusted to reflect the influence of snow cover, using snow-climate relationships proposed by Lachenbruch (1959) and Bilello (1969). A good agreement with empirical data regarding the extents of these zones was obtained. However, for mapping purposes the soil substrate was assumed to be homogeneous throughout the study area, and no attempt was made to modify frost numbers to reflect local variation in vegetation cover. Although the model is capable of incorporating variations in substrate properties, it is unsuitable for predicting permafrost distribution at regional scales, at which the spatial variability of vegetation cover can be expected to exert a significant influence.

2.3.2 The Jorgenson and Kreig Model

Jorgenson and Kreig (1988) proposed a model for predicting permafrost occurrence that is conceptually and structurally similar to that described above. However, it includes parameters for describing the influence of vegetation cover (n-factors) and a potential insolation index (P) for incorporating the topographic influences of terrain slope and aspect. Their model is as follows:

$$R = ((DDT \cdot N_t \cdot P) / (DDF \cdot N_f)) / (K_f / K_t) \quad (5)$$

Where:

DDT = thawing degree days	}	<u>atmosphere</u>
DDF = freezing degree days		
N_t = summer n-factor	}	<u>buffer layer</u>
N_f = winter n-factor		
P = potential insolation index		
K_t = thawed thermal conductivity	}	<u>substrate</u>
K_f = frozen thermal conductivity		
R = permafrost index		

P is defined as the ratio of the latitude at the site to its equivalent latitude

($P = L/L_e$) and is calculated as follows:

$$L_e = \sin^{-1} (\sin s \cdot \cos h \cdot \cos L + \cos s \cdot \sin L) \quad (6)$$

Where:

s = slope of surface

h = aspect of surface

L = latitude of site

L_e = equivalent latitude of site

The Jorgenson and Kreig model is compatible with the conceptual model of the atmosphere-ground thermal regime adopted for this thesis, since all three layers of the model described earlier are represented in the determination of the permafrost index (R). Units for both the numerator and the denominator reduce to Jm^{-1} (joules per meter) which suggest that R is a ratio of the surplus of ground heat during the thaw season, to the deficit of ground heat for the freeze season, *relative to 0°C*. Values of R less than 1 imply that a net deficit exists, indicating the presence of permafrost, while values greater than 1 imply its absence. Jorgenson and Kreig applied their model to a small portion of the Spinach Creek Watershed near Fairbanks, Alaska, with an areal permafrost extent of approximately 40% at a MAAT of -3.5°C. Their predictions for the distribution of permafrost agreed closely with that mapped by photo-interpretation. Additional model runs were used to predict the distribution of permafrost occurrence expected for a number of alternative climates, in which thawing and freezing degree days were varied to reflect different MAATs. The extent of permafrost was seen to increase in response to cooler MAATs and to decrease for warmer temperatures. Permafrost persisted on north-facing slopes at MAATs of +2°C and beyond, but permafrost extent was less than 6 percent of the study area.

The Jorgenson and Kreig model facilitates the investigation of equilibrium permafrost distribution in response to changes in any or all of the three layers of the conceptual model adopted. The impact of increasing or decreasing mean annual air temperatures is modelled directly through substitution of appropriate degree-day values. Changes in the nature of the surface cover (e.g.: removal of vegetation due to forest fires or human activities, increases or decreases in average snow cover, or succession of vegetation species in response to climate

change) can be represented by specifying alternative n-factor values. The implications of climate-induced alteration of local drainage patterns may also be investigated on the basis that the thermal properties of the substrate will vary according to the amount of water present.

This model, and the others described previously, predict the presence or absence of permafrost only, without any reference to permafrost thickness. For permafrost regions, the evaluation of terrain responses to surface disturbance or possible climate change, and identification of appropriate construction techniques, require information about permafrost thickness.

This thesis will proceed under the assumption that the Jorgenson and Kreig model encompasses all of the basic elements necessary for evaluating the ground thermal regime on a site to site (grid cell) basis, with respect to the presence or absence of permafrost. Furthermore, it will be assumed that adequate knowledge of regional terrain characteristics within the study area is available to permit assignment of reasonable values for the various parameters required by the model. The remaining task, and the main goal of this thesis, is to develop a means for estimating the equilibrium thickness of permafrost (or, more precisely, the depth to its base), that would be expected under specified climate and terrain conditions. This will lead to the ability to map not only the distribution of permafrost occurrence, but also to attach an estimate of permafrost thickness to these predictions, under present and possible future climates.

CHAPTER 3

Deriving a Means for Predicting Permafrost Depth

3.1 A Hypothetical Modeling Terrain

Having identified a model for predicting the occurrence of permafrost, it would be convenient if the output of the model could be related to the thickness of permafrost expected for a particular set of input parameters. Since the value $R=1$, has been defined (and to some degree, verified) as the threshold between permafrost occurrence or absence, it seems reasonable to expect that R -values progressively less than 1 should be indicative of thicker permafrost. This is a difficult premise to test in the real world, however. In the first place, other factors that are not accounted for in our model (such as water migration and ice lens growth, or the non-homogeneity of soil profiles at depth) may confuse an evaluation of model predictions. Secondly, there exist only very limited data regarding the specific regional-scale distribution of permafrost, and even less about the associated thickness. Thirdly, the current level of confidence in the values of input parameters (such as n -factors) increases uncertainty about the predictive result that we might wish to compare to actual field measurements. Certainly one needs to test the performance of a model against real-world data. Therefore, in order to discover a systematic relationship between permafrost thickness and a value of R generated by the J&K model, a hybrid model was developed in which R values are related to predictions of permafrost thickness produced by a finite-element heat conduction model (TONE). The finite-element approach

to solving heat conduction problems is well-established and will not be discussed in this thesis. Details regarding the application of finite-element methods to conductive heat transfer problems are provided by Myers (1971) and Goodrich (1982). Finite element methods have been applied to investigations of the ground thermal regime by Goodrich (1978), and TONE has been used as a tool for investigating permafrost responses to climate change at Carleton University (Riseborough and Smith, 1993). TONE has also been applied to practical problems of ground freezing: a notable example being a study of the impacts of ground freezing on sidewalks conducted for the City of Edmonton, (Goodrich, 1993; personal communication).

TONE may be configured to accept the same input parameters as are utilised in the J&K model, thereby facilitating the co-generation of output from the two models such that for any specified set of inputs (representing some combination of climate and terrain conditions), an R-value and a prediction of permafrost thickness will be obtained. This permits us to structure inputs so that a wide range of conditions expected to occur in a natural setting may be modeled and evaluated with respect to the characteristics of the ground thermal regime. It is necessary only to model a sufficient number of conditions to explicitly define the relationships we are seeking to describe. These can then be applied to the myriad of terrain conditions that may be encountered in the real world.

The depth to the base of permafrost can be obtained directly from TONE output of zero degree isotherm depths. However, for very thick permafrost, there are some model execution problems associated with larger grid sizes. To avoid these problems, for each model run, the grid thickness (representing soil depth) was adjusted to ensure that the

point of zero annual ground temperature amplitude was within the grid. With this procedure, finer grid spacing could be obtained, and model execution times were shorter. TONE output of the annual temperature envelope were used to obtain the depth and temperature of the point of zero amplitude. Given the assumption of a uniform soil profile, the depth to the base of permafrost was obtained by interpolation, based on the geothermal gradient implied by the specified thermal conductivity and geothermal heat flux. This method might also be used to adjust model predictions to account for multiple soil layers with different thermal properties, providing that the point of zero amplitude falls within the uppermost layer.

3.2 R vs. Permafrost Thickness

In this thesis, the term *permafrost thickness* refers to the distance from the defined ground surface to the base of the permafrost, irrespective of active-layer thickness. Approximately 80 initial TONE runs were made representing a variety of air temperature and n-factor regimes. Initially, two different substrate conditions were modeled due to the time-intensive requirements of specifying temperature-dependent thermal conductivities. These conditions were representative of a silt/clay soil at 100% and 50% saturation. For each set of model inputs, an R value was calculated and a TONE prediction of permafrost thickness was obtained. The initial runs were designed to generate predictions (for a sufficiently broad range of hypothetical terrain conditions) in order to reveal a relationship between the R value and the associated permafrost thickness predicted. Figure 3 plots TONE predictions for permafrost thickness against the calculated value of R.

Figure 3: Relations between the calculated value of R and predicted permafrost thickness.

Permafrost was predicted to occur only when R values were less than 1, confirming the threshold value specified by Jorgenson and Kreig. While it can be seen that a general tendency exists for greater permafrost depths to be associated with lower values of R, the relationship shows considerable scatter. A power function curve can be fitted to the data, but for any particular value of R, a wide range of permafrost depths are possible. It is clear that, while R appears to be a good indicator of permafrost occurrence, it is not a very precise indicator of permafrost thickness. This is not surprising, since the simple ratios utilised in the J&K equation dictate that many combinations of parameter values can produce a single value of R. It is necessary, therefore, to identify the influences of separate input

parameters in order to discover the manner in which they combine to produce different thicknesses of permafrost.

3.2.1 Data Discrimination on the Basis of Thermal Conductivity

A reasonable starting point for examining the influence of the various input parameters is to separate the data on the basis of thermal conductivity. This can be done according to the soil water content. Figure 4 is a plot of TONE predictions of permafrost thickness against the R-value calculated according to the J&K model, where data have been separated according to the degree of saturation of the soil (a clay-silt at 50% and 100% saturation, 40% porosity).

Figure 4: R vs. permafrost thickness, separated according to thermal conductivity

The plot indicates that the fully saturated soil (with the higher frozen thermal conductivity) tends to produce thicker permafrost in general, but separation of the data is indistinct, even though the thermal conductivities are quite different in absolute terms. However, in terms of the J&K model, it is really the ratio of the frozen and thawed thermal conductivities that is important. Since TONE inputs were derived from an explicit description of the physical and thermal characteristics of a particular soil type, the *thermal conductivity pairs* are a reflection of the degree of saturation of that soil (Figure 5). Both frozen and unfrozen thermal conductivities rise systematically (and significantly in absolute terms) over the full range of saturation ratios, but the ratios of frozen to unfrozen conductivities are confined to a relatively narrow range. This is due to the fact that the difference between frozen and unfrozen values is limited by the pore space available for water or ice.

Figure 5: Variation of thermal conductivity with soil saturation ratio.

3.2.2 Separation According to N-factor Pairs

The failure to obtain a distinct separation of data on the basis of thermal conductivity alone suggests that any distinction may be obscured by the effect of variable n-factors within the data set. Better separation of the data may be achieved by distinguishing between seasonal n-factor pairs for a single conductivity regime. Figure 6 shows the data for the fully saturated soil only (i.e.: a single pair of thermal conductivities, K_r , K_l). In this case the data have been separated on the basis of the distinct pairs of n-factors used as model inputs (only a sample of all the pairs modelled are shown). A definite pattern emerges, with the data for each pairing displaying a systematic increase in permafrost thickness as the value for R decreases. This pattern appears to follow a power function curve and indeed responds to a log transformation of the X-axis.

Figure 6: Separation of data according to n-factor pairs

When permafrost thickness is plotted against the absolute value of $\log R$ (for $R < 1.0$), as illustrated in Figure 7), a conspicuously linear relationship emerges with a strong tendency for convergence at the origin. This provides further confirmation of the J&K-defined threshold for permafrost occurrence.

Figure 7: Relations between predicted permafrost thickness and $|\log R|$.

The linear relationship identified for particular n-factor pairs can be to be defined simply according to a *slope value* (S), which describes the rate of increase of permafrost thickness as $|\log R|$ increases. Movement along a particular slope represents a change in mean annual air temperature. Therefore, for a given terrain unit, a change in MAAT does not influence the value of S, so long as soil water content remains constant. If one were able to

specify the correct slope value for a particular set of soil and terrain conditions, permafrost thickness could be determined simply by multiplying by the calculated value of $|\log R|$.

A similar plot was made for the model soil at 50% saturation, with correspondingly reduced frozen and unfrozen thermal conductivities. Identical n-factor pairings were employed as in the fully saturated case. The same general pattern was observed, but the slopes of all lines were substantially reduced (Figure 8). Note that the maximum slope under a given soil thermal conductivity regime is associated with the 1:1 n-factor pair (i.e.: a condition for which there is no intervening surface layer between the atmosphere and the soil). This maximum slope (where $N_t = N_f = 1$), therefore, has the potential to serve as a reference for the determination of slopes for all other n-factor values.

Figure 8: Slope relations between n-factor pairs for different saturation ratios.

The absolute maximum slope for any specified soil will occur when the soil is fully saturated, and both summer and winter n-factors are equal to 1 (i.e. the soil surface is bare). This will be defined as the *standard condition* of the soil, and the slope associated with this condition is the *standard slope* (S_s). Some non-vegetated surfaces (such as asphalt) may have a summer n-factor that is greater than 1 (Lunardini, 1981), however, this analysis is restricted to n-factors associated with vegetated surfaces. The value of the standard slope was determined for the modelled soil through a series of TONE runs which specified the standard condition over a range of MAATs. The value for S_s was obtained through a linear curve fitting of the output for these runs, and was found to be 580. This value may be used to calculate the permafrost depth for a fully saturated, fine-grained soil that is devoid of surface cover or snow year-round. However, this terrain condition will exist rarely, if ever, in nature. It is necessary, therefore, to devise a means for adjusting the standard slope to reflect the influence of surface cover (n-factors other than 1) and unsaturated soil conditions. The following method for the determination of the slope (S) serves as the basis for the construction of the Hybrid Permafrost Prediction Model.

3.3 Construction of a Hybrid Permafrost Prediction Model

3.3.1 Determination of a Conductivity Index

In order to proceed with the determination of an appropriate slope value from which to calculate permafrost depth, a series of TONE runs was designed to clarify the specific nature of the change in slope (S) associated with variation in thermal conductivity. Attempts to organise the data on the basis of either the frozen or unfrozen thermal conductivity were unsuccessful. It became clear that the annual thermal conductivity *regime* must be evaluated, with both the

frozen and unfrozen values contributing to the ground thermal state. Therefore, conductivity pairs were varied to reflect the range of soil moisture conditions from very dry to fully saturated. Since the slope value (S) for a particular terrain condition (ie.: a specified set of n-factor, potential insolation index, and thermal conductivity values) was shown to be independent of the MAAT (p. 31), input temperatures were selected to produce values R that were less than 1 (ie., the presence of permafrost is indicated), while n-factor values were initially held constant. The output from this series of runs was analysed in order to derive a conductivity index (I_k) that organised the data into a form that could be described mathematically. Initially, a simple ratio of the frozen to unfrozen thermal conductivity was plotted against slope values, without success. By trial and error, the following relationship between frozen and unfrozen thermal conductivity was found to organise the slope data into a linear form:

$$I_k = K_f^2 / K_t \quad (7)$$

The analysis was repeated a number of times, with different n-factor pairs. The results for each n-factor pair were standardised to facilitate a comparison of the output for the different series of model runs (standardisation involved ratioing slope values within each series to the maximum slope value produced in that series). This was done to confirm that the conductivity index was independent of n-factor values, and thus applicable to a broad range of surface cover conditions. It is difficult to ascribe physical meaning to what is essentially a descriptive equation derived for the sake of convenience (for organising the dataset). It does,

however, suggest that frozen thermal conductivity values are more important than unfrozen values in determining a slope value. The results (for two n-factor pairs only) are shown in Figure 9.

Figure 9: Slope modifier (F_k) as determined by a thermal conductivity index (I_k).

Linear fitting of the data in Figure 9 produced an equation which determines a value (F_k) as follows:

$$F_k = 0.2752 (I_k) + 0.0875 \quad (8)$$

F_k is a fractional modifier which, when applied to the standard slope (S_s), identifies the appropriate slope value for the conductivity pair specified. A value of $F_k=1$ will be produced

for a fully saturated soil. Thus, if the model soil was unsaturated but bare (both n-factors equal to 1), then the appropriate slope value would be:

$$S = S_s \cdot F_k \quad (9)$$

3.3.2 Determination of an N-factor Index

Most natural surfaces will not be bare, but will be vegetated throughout all or much of the year, and in northern regions will have snow cover for a significant portion of the winter season. The modulating effect of this surface cover on heat exchange between the atmosphere and the soil must be represented by n-factor values other than 1. It is necessary, therefore, to devise a means for determining the appropriate slope value for any specified pair of n-factors.

Several series of TONE runs were designed in a similar fashion to those described in the previous section, in order to isolate the effects of n-factor variations independent of the thermal conductivity conditions. In this case, an n-factor index (I_n) was defined as:

$$I_n = ((1 - N_t) + (1 - \log N_f^2)) / (N_t + N_f^2) \quad (10)$$

The form of this relationship was arrived at through trial and error, beginning with a simple ratio of n-factors. Progressively more complicated indices were tried, resulting in the present form which successfully organised the series output data in a systematic way. Terms in the numerator are subtracted from unity in order to relate the index to the reference point at which n-factors are equal to 1, while the log transformation was applied to allow the resulting plot to be fitted with a power function curve. This index was plotted against the slopes

calculated from TONE outputs. No direct relationship with predictions of permafrost thickness was observed. Two separate series (for 100% and 50% soil saturation) were run, to ensure that any relationships identified would describe changes in slope resulting from n-factor variations, independent of the thermal conductivity. As before, the calculated slopes were standardised to a maximum of 1 in order to directly compare the results from the two scenarios. The results are plotted in Figure 10.

Figure 10: Slope modifier (F_n) as determined by an n-factor index (I_n).

Curve-fitting of the data provided an equation for calculating a fractional modifier (F_n) which may be used to adjust the standard slope (S_s) according to any specified combination of n-factors:

$$F_n = I_n^{-0.473737} \cdot 0.77532 \quad (11)$$

Therefore, if the model soil were fully saturated, but had a seasonal ground cover such that winter and/or summer n-factors were not equal to 1, then the appropriate slope value would be:

$$S = S_s \cdot F_n \quad (12)$$

3.3.3 Determining S for a Specified Terrain Condition

Recall that the plots of I_k and I_n vs. their respective standardised slope values indicate that the fractional slope modifiers F_k and F_n may be applied independently of the values of other model parameters. This means that we may combine the slope modifiers into a single equation to derive the correct slope to use in calculating the expected permafrost depth for the modelled soil, under any specified conditions of terrain. The desired slope value is simply the product of the standard slope (S_s) and the two fractional slope modifiers F_k and F_n such that:

$$S = S_s \cdot F_k \cdot F_n \quad (13)$$

where:

S = desired slope specific to soil and terrain conditions

S_s = standard slope for fully saturated bare soil

F_k = slope modifier based on seasonal thermal conductivities

F_n = slope modifier based on seasonal n-factors

Since this slope represents the rate of increase in the depth to the bottom of permafrost for a unit increase in the absolute value of $\log R$, the completed hybrid model predicts permafrost depth (D) as:

$$D = S \cdot |\log R|, \text{ (for } R < 1) \quad (14)$$

Or
$$D = (S_s \cdot F_k \cdot F_n) \cdot |\log R| \text{ (} R < 1) \quad (15)$$

3.3.4 Relationships for Other Soil Types

Before the HPPM may be applied to an actual geographic area it is necessary to extend our modelling capability to include other major soil units expected in a regional environment. Standard slopes were derived through additional series of TONE runs for a coarse-grained (sandy) soil consisting of 40% quartz and for an organic soil unit consisting of 2 meters of peat overlying a silt/clay base. The sandy soil was modelled through the full range of water contents from dry to fully saturated. Because most surficial geology maps identify organic soil units as being either bog or fen (both of which are very wet), only the saturated condition was modelled for these soils, and thus an additional equation for deriving a value for F_k specific to organic soils was not derived. The final set of relationships are as follows:

Fine-grained soils (silts & clays):

$$S_s = 580$$

$$F_k = 0.2752 (I_k) + 0.0875$$

Coarse-grained (sandy) soils:

$$S_s = 670$$

$$F_k = 0.2241 (I_k) + 0.0429$$

Organic units (bogs and fens):

$$S_s = 771$$

$$F_k = 1.0$$

All terrain units:

$$F_n = I_n^{-0.473737} \cdot 0.77532$$

3.4 Technical Performance of the HPPM

The technical performance of the HPPM was evaluated with respect to the predictions of the finite-element heat conduction model (TONE). This approach is rationalised on the basis that, in the context of a regional-scale mapping project, the goal is to obtain a prediction comparable to that of a finite-element model, but with vastly simplified computational requirements (in order to make cell by cell calculations over the study area feasible within a GIS). The degree to which the HPPM may be satisfactorily applied to an actual geographic region is evaluated later in this thesis.

Testing was done using data related to the silt-clay soil profile condition. No separate evaluation of performance with respect to the other soil types was undertaken, due to the effort required to prepare and execute additional TONE runs. The evaluation involved the 20 runs that were used in defining the mathematical relationships comprising the HPPM, plus 50 additional verification runs whose parameters were chosen in a more-or-less random fashion.

Figure 11 shows the comparison of TONE outputs to HPPM predictions of permafrost thickness for these 70 distinct terrain conditions. Predictions of permafrost thickness ranged from a few meters to nearly 300 meters.

Figure 11: Comparison of HPPM predictions to TONE outputs for permafrost thickness.

Linear regression of TONE estimates of permafrost thickness against HPPM predictions indicate a standard error across the whole range of predictions of 7.44 meters, with an r^2 of 0.99. However, Figure 11 suggests that there is some autocorrelation in the residuals, with absolute errors being less for predictions of thin permafrost vs. very thick permafrost. For predictions less than 50 meters, the standard error is only 4.12 meters ($r^2 = 0.93$), while for those between 50 and 300 meters the standard error is 9.39 meters with an r^2 of 0.98. The standard error falls to 2.0 for predictions less than 30 meters, with an r^2 of 0.97. Note that no

separate evaluation of the goodness of fit has been carried out on equations 8 and 11, but that the combined influences of their fit characteristic are inherent in the HPPM predictions just analysed.

The above analysis indicates that while the standard error associated with predictions of permafrost less than 30 meters thick is small in absolute terms (2 meters), there will be a significant degree of uncertainty associated with predictions of very thin permafrost. For predictions of permafrost more than a few meters thick, however, Hybrid Model performance appears to be quite satisfactory in terms of its ability to reproduce the outputs of a finite-element heat conduction model. This suggests that, given realistic values for the various model input parameters, HPPM predictions should reasonably reflect the geographic distribution of permafrost, assuming heat conduction is the dominant thermal transfer process. The following chapter describes the application of the HPPM to an investigation of permafrost distribution in the Fort Simpson region of the Northwest Territories.

CHAPTER 4

Applying the HPPM to a Geographic Region

4.1 Introduction

In order to predict the likely distribution of permafrost over a geographic region, the HPPM was implemented within the SPANS® geographic information system. This involved the acquisition of readily available maps describing the distribution of vegetation cover types and surficial soil units. The information from these maps served as the basis for the determination of thermal conductivities and appropriate n-factor values for each grid cell across the study area. Separate map layers depicting soil texture, soil bulk density, and saturation ratio were generated within Spans® GIS. These map layers were maintained as a repository for spatially referenced parameter values to be used in HPPM calculations. It was not necessary to actually generate maps of thermal conductivity, because these calculations have been integrated into the HPPM equations. However, thermal conductivity ratios (K_f/K_t) are presented in Map 3 (Appendix).

Regional degree-day indices were calculated using long-term climate data gathered at Fort Simpson Airport. A digital elevation model (interpolated from 1:50,000 topographic maps) was used to derive a potential insolation index, which modifies regional degree-day indices according to local variations in topography. Man-made features such as the Fort Simpson townsite and the local airport were designated as offsite (ie.: excluded from the analysis), as were significant water bodies such as lakes and rivers.

Within the GIS, vector map data was resolved to a 30 meter grid. At this resolution, millions of calculations are typically required to predict permafrost distribution at the regional scale. Therefore, the modeling equations implemented must be computationally efficient to permit a relatively rapid execution of the model. The series of equations derived in the Chapter 3 are suited to implementation within the SPANS® GIS modeling language. The following section describes in detail the conversion of climate and terrain data to appropriate values for the various model thermal parameters.

4.2 Study Area: Regional Terrain Characteristics

The HPPM was applied to a region approximately 56 km by 54 km encompassing the confluence of the Mackenzie and Liard Rivers, and including the townsite of Fort Simpson and the local airport. Topography is generally subdued throughout much of the region, with broad lowlands extending south of the Mackenzie River and on both sides of the Liard. These rivers tend to be incised about 5-15 meters, particularly on the northern and eastern shores. A gradually sloping plateau is apparent to the northeast of the Mackenzie, while at the western boundary of the study area, a range of hills rise several hundred meters above the lowland plain.

Regional surficial geology is characterised by extensive glaciolacustrine deposits in the lowlands south of the Mackenzie River and west of the Liard (Map 1). A considerable portion of these lowlands is overlain by organic veneers associated with bogs and fenland. These veneers are typically 1-3 meters thick but may reach several meters thick in some locations (Aylsworth, et al., 1993). To the north of the Mackenzie River a broad till plain dominates, with local organic units being less extensive than those to the south. On either

side of the Liard, aeolian sand deposits (overlying the glaciolacustrine sediments) create an undulating dune topography with intervening depressions. These depressions are characterised by poor drainage associated with organic accumulations which impede the flow of surface water downward into the soil. The margins of an extensive fenland (the Great Fen) are apparent towards the southwest corner of the study area. Locally, alluvial deposits and slide debris are associated with stream channels and river courses. High ground to the west consists of colluvial and till deposits.

Regional vegetation characteristics reflect the generally poor drainage associated with the subdued topography (Map 2). According to the Environmental Social Program map series (ESP#101, 95H, 1973), nearly 40 percent of the study area is designated as either bog or fen peatland. A further 15 percent is dominated by black spruce, which tolerate conditions of excessive moisture. Upland (white) spruce account for an additional 25 percent of the area, preferring somewhat drier conditions. The remaining 20 percent of the region is dominated by upland pine and deciduous species found in well-drained environments.

Climate normals for Fort Simpson indicate a long-term mean annual temperature of -4°C (23°C annual amplitude), with average annual rainfall of 355 mm, and annual snowfall averages of 151 cm (MacInnes et al., 1989). Little information is available concerning the regional distribution of permafrost, and data provided by various sources is often in conflict. Areal coverage as low as 10 percent has been suggested (Rennie et al., 1978). Ditch log observations of permafrost for sections of the Norman Wells pipeline traversing the Fort Simpson region suggest a coverage of between 16 and 31 percent

(MacInnes, 1989). Even less information is available regarding permafrost thickness. Rutter et al. (1973) report permafrost depths exceeding 8 meters under peat plateaus, and borehole logs for the region have recorded ground ice to at least the maximum borehole depth of 11 meters for some terrain units. Judge (1973, 1975) suggests that permafrost thickness in the southern sections of the Norman Wells Pipeline route is generally less than 20 meters.

4.3 Deriving Values for Model Parameters from Available Maps

Confidence has been established in the HPPM, in terms of its ability to predict permafrost occurrence and thickness based on a heat conduction approach to thermal problems. In order to usefully apply the model to a geographic area, however, we must derive reasonable values for model input parameters, from whatever data is currently available. In the context of a regional-scale mapping project, it is not feasible to intensively sample the region in order to obtain the precise distribution of vegetation units, or field measurements of soil moisture conditions and seasonal thermal conductivities. At regional scales, the most complete sources of data about terrain characteristics are likely to be published maps of surficial geology, topography and vegetation cover. In some cases suitably classified remotely-sensed data may be available to substitute for vegetation maps. In any case, these do not explicitly provide the data required. There are no n-factor maps or thermal conductivity maps which can be directly applied to a regional terrain analysis. It is necessary, therefore, to adopt some method for translating the nominal classifications of the various terrain units described on existing maps, into reasonable model parameter values.

4.3.1 Climate Parameters

Thawing and freezing degree day indices are used to represent the entire annual climatic regime. Even with this level of simplicity, there are still some difficulties associated with obtaining appropriate or reasonable values. A weather station located at Fort Simpson Airport provides a source of monthly temperature data that may be converted into the required degree-day indices. However, these indices are specific to the airport, and it is by no means certain that temperatures recorded there are representative of the study area as a whole. Local factors such as proximity to water bodies, differences in elevation, exposure to wind, etc. may modify the microclimate experienced at particular sites. For this study, however, it was assumed that the data from the Fort Simpson weather station are representative of the region in general, and were modified only on the basis of local slope and aspect according to the potential insolation factor (P).

Table 1 summarizes the annual temperature regime for Fort Simpson for current conditions and under the 2 climate-warming scenarios modeled. The annual temperature wave has been generalised as a sine wave with a period of 365 days and an amplitude of 23°C. Warming scenarios are represented by an incremental increase in the MAAT of 1°C and 2°C. Degree-day indices have been calculated for each scenario.

Table 1: Summary of the annual air temperature regime at Fort Simpson

Scenario	MAAT	Amplitude	DDF	DDT
Current	-4° C	23° C	3443	1983
1° C warming	-3° C	23° C	3242	2146
2° C warming	-2° C	23° C	3047	2317

A digital elevation model was constructed from 1:50,000 topographic maps of the region, from which additional maps depicting local slope and aspect were derived. These were used to calculate the potential insolation factor (P). A map was produced depicting the spatial variation in P across the study area, to be applied as a modifier to summer degree-day indices on a cell by cell basis across the study area (equation (6), Ch. 2). This facilitated the systematic differentiation of local heating or cooling effects due to variations in topography. In the Fort Simpson region, these effects are very localised, occurring mostly on slopes associated with river banks and other drainage channels.

4.3.2 Thermal Properties of the Substrate

The availability of long-term weather data for Fort Simpson allows a high level of confidence in the degree-day values used as model inputs across the study area. There is less certainty regarding the assignment of soil characteristics used to estimate seasonal thermal conductivities, but this has been carried out in a rigorous fashion using the best data available at the regional scale.

The model requires that frozen and unfrozen thermal conductivities be specified for each terrain unit being modeled. Given the lack of site-specific measurements of thermal conductivity it is necessary to estimate values based on the terrain-related information available. Johansen's (1975) equations for determining thermal conductivity were utilised. This method calculates frozen and unfrozen thermal conductivities based on specifications of soil texture, dry bulk density, quartz content, the saturation ratio and an estimation of the unfrozen water content in the frozen state. Regional-scale maps of surficial geology and vegetation cover were used as surrogate indicators of soil physical

properties and soil water content. Dry bulk densities were assigned to individual soil units based on a review of information from a number of sources (Lunardini, 1981., Spangler and Handy, 1982., Jorgenson and Kreig, 1988., Williams and Smith, 1991.).

Table 2: Physical Properties of Surficial Soil Units

Surficial Soil Unit Description	Dry Bulk Density (Kg/m³)	Texture Class
Alluvial terrace	1600	Coarse
Alluvial plain	1600	Coarse
Colluvial complex	1200	Fine
Aeolian deposits	1400	Coarse
Glaciolacustrine plain	1800	Fine
Glaciolacustrine beaches	1800	Coarse
Glaciofluvial outwash	1100	Coarse
Ice contact deposits	1100	Coarse
Glacial till	1900	Fine
Organic	300	Organic

Estimating soil water contents presented a particular challenge because they may be expected to be highly variable within a given soil unit due to local variations in surface runoff characteristics, topography, water table configuration, etc. It did not seem reasonable, therefore to utilise estimations of water contents that may accompany descriptions of surficial deposits. Jorgenson and Kreig (1988) used vegetation type as an indicator of soil moisture levels based on the premise that certain species thrive under (or tolerate) a limited range of soil moisture conditions. Furthermore, it seems reasonable to assume that vegetation species associated with the occurrence of permafrost exist *in response* to the elevated water contents resulting from restricted drainage through a

frozen soil layer. The water content associated with each vegetation type was assigned according to the preference or tolerance levels implied in the J&K study. This scheme is outlined in Table 3. The vegetation classification is adapted from the Environmental Social Program map series (ESP#101) published in 1972. Water contents are expressed as a saturation ratio rather than in gravimetric terms, so that they can be more readily associated with the conductivity conditions discussed in this thesis.

Table 3: Thermal parameters associated with various vegetation units

ESP Vegetation Type	Saturation Ratio	Summer n-factor	Winter n-factor
Upland Hardwoods	.50	.95	.33
Upland Pine	.40	.95	.35
Upland Spruce Dominant	.65	.80	.33
Upland Spruce-Feathermoss (S)	.75	.80	.33
Upland Spruce (S)	.70	.83	.41
Upland Spruce-Feathermoss (SH)	.70	.80	.33
Upland Shrub	.60	.93	.21
Black Spruce-Lichen	.85	.41	.20
Black Spruce-Sphagnum	.90	.41	.20
Sphagnum Bog	.95	.51	.21
Sedge Fen	1.00	.66	.12
Pioneer Steep Slope Mixtures	.35	.73	.36

Note: (S) refers to a spruce dominated forest; (SH) to a spruce-hardwood mixture

Parameters for the physical characteristics presumed for the various soil units are then used as inputs to Johansen's equations, providing an estimation of both frozen and unfrozen thermal conductivities for each terrain unit.

4.3.3 Determining N-factors

The assignment of n-factor values is much more problematic than for thermal conductivities, given the lack of data specific to natural vegetation units. For this reason it was necessary to take an approach in which the performance of the HPPM was considered to be “anchored” to the climate and thermal conductivity components of the model. Published n-factor data for vegetated surfaces in northern regions are limited to those values suggested by Jorgenson and Kreig (1988), from the Spinach creek watershed in Alaska, and by Lunardini (1981). Additional data specific to the Fort Simpson region were provided by Alan Taylor of the Geological Survey of Canada (personal communication, 1994), but these are derived from a single year of record and usually from only one or two sampling sites in any particular vegetation type. Significant discrepancies are apparent between n-factors from the different sources. In particular, the summer n-factor values provided by Taylor were much lower than those from either Lunardini (1981) or Jorgenson and Kreig (1988). Winter n-factors agreed reasonably well, and discrepancies between these were assumed to be related to differences in snow cover for the different source regions. Summer n-factors, therefore, were assigned initially according to an evaluation of the data from all sources, but with the Jorgenson and Kreig (1988) data having a dominant influence, since their values have been applied successfully in a permafrost study. Following an initial application of the model to the Fort Simpson study area, additional adjustments were made to some n-factors (i.e.: increased or decreased slightly) to ensure that HPPM predictions were consistent with currently available data concerning regional permafrost conditions. Borehole data from the Norman Wells Pipeline

corridor (IPL, 1982) and bog and fen borehole data provided by Rutter et al. (1973) were used in this "calibration" procedure. Unfortunately only 2 or 3 boreholes for each vegetation type were suitable for this purpose. These n-factor values were subsequently applied to similar vegetation types occurring within the study area.

Table 4 compares n-factor values assigned as HPPM inputs to those proposed by Jorgenson and Kreig. It is anticipated that in future, more reliable n-factor data will become available for modeling applications. Winter and summer n-factor maps were produced to serve as additional spatially-referenced parameter sources for the execution of the HPPM.

Table 4: Comparison of HPPM and Jorgenson & Kreig n-factors

Vegetation		HPPM		J & K	
Type	Area %	Nt	Nf	Nt	Nf
Pine dominant	6	.95	.35	-	-
Dominantly deciduous	13	.95	.33	.95	.30
Upland shrub	0.5	.93	.21	.85	.30
Pioneer steep slope	0.5	.73	.36	-	-
Upland spruce dominant	1.5	.80	.33	-	-
Upland spruce-feathermoss (SH)	19	.80	.33	.85	.35
Upland spruce-feathermoss (S)	9	.83	.41	.80	.35
Black spruce-sphagnum	12.5	.41	.20	-	-
Black spruce-lichen	1.5	.41	.20	.50	.30
Bog	10.5	.52	.21	-	-
Fen	26	.66	.12	-	-

4.4 Execution of the HPPM within Spans® GIS

Figure 12: Flow chart of HPPM execution.

The Spans® Geographic Information System is a quadtree-based (compressed raster) GIS which includes a sophisticated modeling language to facilitate the cell by cell execution of complex mathematical functions. Individual map layers represent a source of spatially-referenced values for equation variables. The HPPM exists as a modeling

equation within Spans®. Model output may be set to produce maps of thermal conductivity, R-values, permafrost depth, etc., or any of these outputs may be queried on screen with reference to a base map. Figure 12 describes the implementation of the HPPM within a GIS. The model was run for current climate conditions and for two regional warming scenarios (1°C and 2°C above the normal MAAT).

Maps 4, 5, & 6 present HPPM predictions of permafrost occurrence based on a reclassification of Jorgenson and Kreig (1988) R-values. An unfrozen class and two frozen classes are separated by a marginal class in which R-values fall within .05 of the permafrost occurrence threshold (at $R=1$). For areas classed as marginal, very thin, warm permafrost (permafrost at temperatures near 0°C) may or may not be present. In general, within the two frozen classes, it is expected that colder, thicker permafrost will occur in Frozen2 ($R < .80$) relative to that occurring in Frozen1. Maps 7, 8, & 9 predict the potential depths to the base of the permafrost. These depths are based on an assumption of a uniform soil profile extending to the depth of prediction.

CHAPTER 5

Discussion and Conclusions

5.1 Evaluating the Performance of the HPPM

The HPPM was applied to the Fort Simpson region in order to obtain predictions of equilibrium permafrost distribution and thickness under the three climate scenarios outlined in section 4.4. Since the calibration of n-factors described in section 4.3.3 was based on data from the Fort Simpson area (in the southern permafrost zone), we may expect HPPM predictions to reasonably reflect current permafrost conditions across this region (provided that conduction is the dominant heat transfer process). These predictions are evaluated in the following section. In order to gain a greater level of confidence in the HPPM, it was applied to an additional geographic region in the vicinity of Norman Wells (located approximately 400 kilometers north of Fort Simpson), for current climate conditions only. Permafrost distribution at Norman Wells is known to be much more extensive than at Fort Simpson, with significantly greater permafrost thickness. A separate evaluation of HPPM performance at Norman Wells is presented.

5.1.1 Predictions for the Current Distribution of Permafrost at Fort Simpson

Maps 4 & 7 illustrate the HPPM predictions of the current distribution of permafrost (-4 MAAT) and the potential depths expected for the Fort Simpson area.

These predictions are based on the assumption that the ground thermal regime is in equilibrium with the current climatic regime.

The HPPM predicts that approximately 27 percent of the study area is underlain by permafrost (Table 5). Only 2 percent of this is classed as Frozen 2 (having values of R less than .80). Another 8.5 percent is classed as marginal ($.95 < R < 1.05$ implying the possibility of warm (mean temperatures near 0°C), thin permafrost, or its absence. Sixty-five percent of the area is classed as unfrozen. Note that this class includes rivers and lakes that were assumed to be unfrozen and not specifically modeled within the HPPM.

Table 5: Predicted permafrost occurrence at Fort Simpson (percent of study area)

Class	R-value	MAAT		
		-4°C	-3°C	-2°C
Frozen 2	$< .80$	2.09	.04	.01
Frozen 1	$.80 - .95$	24.74	2.56	.05
Marginal	$.95 - 1.05$	8.53	11.78	2.04
Unfrozen	> 1.05	64.64	85.61	97.90

These predictions compare favourably with observations of permafrost occurrence along the Norman Wells pipeline right-of-way, based on the interpretation of a continuous geophysical survey conducted by Interprovincial Pipelines Ltd. (IPL, 1982, Kay et al., 1983). Between kilometerposts 380.4 and 528.8, 31.57 percent of the terrain traversed by the right-of-way was classed as frozen and 68.43 percent unfrozen. Between km 528.8 and km 695.9 the terrain traversed is only 16.05 percent frozen. Approximately 34 km and 40 km respectively are actually within the study area. On the basis of this information

we might expect the amount of frozen terrain within the Fort Simpson region to reflect the either of these values, or to approach their average (about 24 percent). Geophysical data for these subsections indicate that 20 % of the right-of-way within the study area is frozen (the approximate location of the right-of-way is shown on Map 4). However, HPPM predictions for the northern subsection imply a permafrost extent of about 34 percent, compared to about 8 percent in the southeastern section. Some of this discrepancy may be related to the high level of generalisation inherent in the ESP vegetation classifications. Results might be improved by utilizing vegetation data gathered at larger scales, or through the use of suitably-classified satellite data.

Table 6: Permafrost occurrence by vegetation type (percent of class)

Vegetation Unit	Frozen2	Frozen1	Marginal	Unfrozen
Fen				100
Pine dominant				100
Dominantly deciduous				100
Upland shrub				100
Pioneer steep slope		4.6	24.2	71.2
Upland spruce dominant		0.9	43.5	55.6
Upland spruce-feathermoss (SH)		17.6	0.9	81.5
Upland spruce-feathermoss (S)	0.8	10.5	88.7	
Black spruce-sphagnum	9.1	90.9		
Black spruce-lichen	74.1	25.9		
Peat bog	98.8	1.2		

Note: (S) refers to a spruce dominated forest; (SH) to a spruce-hardwood mixture

Vegetation-permafrost associations based on the field observations of permafrost occurrence were outlined in Chapter 1. Areal cross-tabulation of vegetation type with HPPM predictions of permafrost occurrence (Table 6) appears to confirm these associations. Fens, upland shrub species, pine and deciduous forests are unfrozen. The occurrence of permafrost under upland spruce is variable, while black spruce forests and peat bogs are uniformly frozen.

As a further check on the HPPM predictions, borehole data from the Norman Wells Pipeline corridor were examined for information about permafrost depths along the transect as it crosses the Fort Simpson region (IPL, 1982). A subset of 28 boreholes in various terrain units within the Fort Simpson study area was examined. Much of this data was of limited use because most boreholes were less than 10 meters deep. In addition, many of the boreholes were located on previously disturbed sites, such as existing right of ways. While some indication of the local terrain slope was included, there was no indication of the local surface aspect, rendering the slope information unusable. The small number of boreholes representative of specific terrain units does not permit a rigorous statistical analysis of HPPM predictions for Fort Simpson. Furthermore, boreholes essentially provide point data, and thus it is difficult to know to what extent they represent conditions over a 30m grid cell. There may be site-specific factors which are not resolved at the map scales of the model input data. However, they do suggest that, in the Fort Simpson area, black spruce forests tend to be frozen beyond the 10 meter borehole limit. White (upland) spruce forests tend to be either unfrozen, or frozen to depths less than 10 meters (depending on soil characteristics). The ground beneath pine cover was

usually unfrozen while under deciduous cover permafrost was almost always absent. Additional borehole data for organic terrain units in the Fort Simpson region (Rutter et al., 1973) confirm that peat bogs tend to be frozen to depths of 6-8 meters or more. While data suggest that fens are generally unfrozen within the top 4-6 meters, few data are available on ground thermal characteristics at greater depths. This information is in general agreement with the HPPM predictions of permafrost thickness presented in Table 7.

Table 7: Permafrost thickness by vegetation type

Vegetation Unit	Area	Thickness (m)					
		(Percent of Vegetation Class)					
	%	Unf.	1-5	6-10	11-15	16-20	>20
Fen	26	100					
Pine dominant	6	100					
Dominantly deciduous	13	100					
Upland shrub	0.2	100					
Pioneer steep slope	0.5	86	11				
Upland spruce dominant	1.6	98	1	1			
Upland spruce-feathermoss (SH)	19	83	0.2	1.3	16	0.18	
Upland spruce-feathermoss (S)	9	0.7	88	0.4	9.8	0.14	0.8
Black spruce-sphagnum	12.4			16.4	74.3	8.8	0.26
Black spruce-lichen	1.4		0.23	25.7		1.8	72.2
Peat bog	10.6	1.1		97.4	1.3		

A relatively rare terrain unit consisting of closed white spruce-feathermoss on a sandy aeolian soil provided an interesting opportunity to evaluate model performance. This unit occurs in a single contiguous area near Fort Simpson Airport. More than 70 percent of upland spruce forests occur on fine-grained glacial tills and glaciolacustrine plains. Less than 10 percent occur on aeolian sands. In the summer of 1994 a 20 meter borehole was drilled within this unit by the Geological Survey of Canada with the

assistance of this researcher. Observations of the rates of boring progress suggested that permafrost was present to at least 12 meters depth. Table 6 indicates that a large majority of these forests are either permafrost-free or fall in the marginal category. However, the HPPM predicted that this particular terrain unit would be in the Frozen1 category, with a permafrost thickness of 12 meters. While this prediction may be somewhat fortuitous, it does illustrate the model's capacity to predict permafrost distribution by incorporating a wide range of climate and terrain factors into a quantitative analysis technique.

Although a limited amount of corroborative data was available for the Fort Simpson region, the HPPM appears to have the potential for describing the essential nature of permafrost distribution at a regional scale. If it is accepted that the HPPM predictions adequately reflect the actual distribution of permafrost within the region, the HPPM may then be used to examine the impact of different climate scenarios, by changing the degree-day indices in accordance with different mean annual air temperatures. In this way, equilibrium permafrost distributions expected under alternative (changed) climates may be investigated.

5.1.2 HPPM Predictions for Alternative Climate Scenarios

Maps 5 and 6 illustrate the distribution of permafrost expected under two regional warming scenarios (MAAT increases of +1°C and +2°C respectively). These predictions assume that all other terrain characteristics (i.e.: species composition, soil water content, snow cover, etc.) remain constant throughout the warming. According to Table 8 it is clear that permafrost in the Fort Simpson region is very sensitive to increasing MAATs (climate warming). The areal extent of permafrost is substantially reduced in response to a

1°C warming, while nearly all permafrost could be expected to disappear in response to a 2°C warming.

Table 8: Permafrost predictions for 3 climate scenarios (percent areal coverage)

Depth Range	Current	1°C Warming	2°C Warming
Unfrozen	65.6	88.0	99.1
1m - 5m	7.7	9.8	.86
6m - 10m	12.2	.07	.02
11m - 15m	12.5	1.96	.01
16m - 20m	.08	.04	.02
21m - 30m	2.0	.04	.01
> 30m	.06	.01	-

Since the HPPM is limited to equilibrium conditions, it provides no estimate of the time required to effect the changes in permafrost distribution and thickness predicted in response to a given change in climate. Riseborough and Smith (1993) used TONE to model the impact of climate warming at a single peat bog site in the Fort Simpson area. Theirs was a transient analysis, for which a relatively intricate representation of a warming climate was modeled (using a Monte Carlo sampling technique to generate inter-annual variability). If it is assumed that peat bogs maintain permafrost longer than most other terrain units (Vitt and Halsey, 1994), then the results from Riseborough and Smith suggest that there is a 50 percent probability that all permafrost in the Fort Simpson region will disappear within 45 years, and a 100 percent probability that this will occur within 63 years.

In terms of evaluating terrain responses to climate warming, it is certainly useful to have the capability to predict the distribution and thickness of permafrost at the regional scale. However, in order to effectively predict where significant ground subsidence is likely to occur (a major importance for the stability of built structures) it would be necessary to incorporate information regarding the distribution of ground ice in the region. Such an endeavor is beyond the scope of this study.

5.1.3 Application of the HPPM to the Norman Wells Region

The HPPM was initially calibrated for application to the Fort Simpson region, using available information about local permafrost thickness associated with various terrain units (Chapter 4). In order to further validate the model, it was applied to an area of similar size at Norman Wells, some 400 km north of Fort Simpson. It is reasonable to expect that the HPPM should be capable of predicting the nature of permafrost distribution in regions exhibiting similar terrain types, but with different annual temperature regimes.

An investigation of the climate normals (1951-1980) indicates that Fort Simpson and Norman Wells have similar climatic regimes, except that the MAAT at Norman Wells is about 2°C colder (MacInnes et al, 1989). Both experience an annual temperature range (on a monthly mean basis) of about 45° C. Annual rainfall totals are 328 mm and 355 mm for Norman Wells and Fort Simpson respectively, with annual snowfall totaling 147 cm and 151 cm. The monthly distribution of precipitation is also similar.

Both regions exhibit similar vegetation and soil types. However, the Norman Wells region is dominated by a broad expanse of black spruce forest underlain by

glaciolacustrine silt deposits. Organic terrain units such as bogs and fens make up a very small proportion of the region (see Map 10), compared with their dominance at Fort Simpson. Deciduous forests area also very rare, and pine trees are virtually absent.

Where similar vegetation units occur, n-factor and soil moisture values used for the Fort Simpson study were utilised in the second area. The degree day indices were changed to reflect the lower MAAT. Table 9 summarizes the HPPM predictions for the occurrence of permafrost at Norman Wells. Maps 11 & 12 show the predicted distribution and thickness of permafrost for Norman Wells under the current climate regime.

Table 9: Permafrost thickness within each vegetation class (Norman Wells)

Vegetation Class	Area	Percent of Vegetation Class						
		Unf.	1-10m	10-20m	20-30m	30-50m	50-80m	>80m
Fen	<1	95	<1	1	4			
Burn area	2.4	<1	<1	86	1.5	11		
Dominantly deciduous	3	90	<1	<1	5.5	3	<1	
Upland shrub	<1	98	1	<1	<1			
Pioneer steep slope	5.5	30.5	65.5	4	<1	1.3	<1	
Upld. spr.-feathermoss	8	24	60	8	3	5		
Riparian spruce	2				20	56	40	2
Black spruce-sphagnum	57	<1		2	61	31	5	
Black spruce-lichen	8	1		2	57	38	2	
Bedrock	7	Offsite						
Water	5	Assumed frozen						
		Unf.	1-10m	10-20m	20-30m	30-50m	50-80m	>80m
Areal extent of depth class (%)		19.2	8.5	4.1	41	23.5	3.6	.04

Approximately 81 percent of the Norman Wells region is predicted to be underlain by permafrost. Nineteen percent of the study area is unfrozen. This compares very favourably with ditch log observations of permafrost occurrence along the Norman Wells pipeline right-of-way (MacInnes et al., 1989), for which frozen terrain was encountered over 83.7 percent of Construction Spread 1 (0 - 149.5 km). Bare, exposed bedrock slopes were considered to be offsite and were not included in the areal estimations above. Lakes and rivers were assumed to be unfrozen. If these water bodies are excluded from consideration, then the occurrence of permafrost increases to about 90 percent. Studies by Judge (1973 ; 1975) indicate that permafrost thickness in the northern section of the pipeline route is generally less than 50 meters and not more than 80 meters. Table 9 indicates that most of the permafrost at Norman Wells is predicted to be less than 50 meters thick, with the bulk of this being between 20 and 50 meters, and less than 1 percent being thicker than 80 meters.

Judge (1973) provides information about permafrost depths from four boreholes at Norman Wells, two of which are located in the vicinity of the townsite, and one which is located just west of the Mackenzie River opposite the townsite. The former indicate permafrost thicknesses of 37 meters and 27 meters, while at the latter location permafrost may be between 45 and 60 meters. HPPM predictions in the vicinity of the townsite are uniform (due to the nature of the map data used to derive model inputs) at 31 meters. Predictions for the west side of the river are in the 30-40 meter range, with locations on north-facing slopes having between 50-60 meters. In general terms, HPPM predictions compare favorably with these site-specific borehole data. A fourth borehole is located in

the upland region approximately 100 km east of Norman Wells and suggests permafrost extends to a depth of 115 meters. The maximum HPPM prediction for the Norman Wells region was 109 meters, occurring in the uplands north of the townsite. It should be noted that the HPPM was applied to the Norman Wells region with climate parameters that are biased towards lowland conditions representative of the river valley. Adjustments which might reflect upland climates were not included in this modeling exercise.

It is apparent that the HPPM is able to adequately reproduce the statistical distribution of permafrost coverage for an alternative geographic location. Permafrost depths predicted also compare favorably with information available for the Norman Wells region. However, care should be taken to consider the implications of variations in climate (especially local snow cover) and terrain conditions when transporting the model to other geographic regions.

5.2 Geographic Uncertainties and HPPM Performance

The predictions of the HPPM must be evaluated in the context of a number of uncertainties that are inherent both in the model and in the data used as model input. The discrepancies between HPPM predictions of permafrost depth and those predicted by the finite-element heat conduction model were addressed in Chapter 4. In the case of the fine-grained soil (silt-clay at $1,500 \text{ kg/m}^3$ dbd), HPPM depth predictions are, on average, within 6 percent of TONE predictions. However, there are potentially more significant sources of uncertainty that arise from the application of the model to an actual geographic region. Uncertainties inherent in the model itself, (including those associated with the

finite-element model, TONE) could be analysed by conducting a sensitivity analysis involving the six major input parameters.

Uncertainties related to the database must be analysed in terms of the level of confidence assigned to the values of these parameters, together with an evaluation of the positioning accuracy with which they are applied in geographic space. Given, the current lack of availability of reliable n-factor and thermal conductivity measurements for northern vegetation and surficial units, and the high level of generalisation inherent in region-scale maps, such an analysis would be of little value. HPPM predictions in this thesis should be interpreted in terms of their usefulness for describing the regional characteristics of permafrost distribution and thickness, rather than as predictions of permafrost conditions at any particular site. While a quantitative analysis of HPPM performance will not be undertaken in this thesis, a qualitative evaluation of the major sources of uncertainty inherent in HPPM predictions is presented in the following sections.

5.2.1 Uncertainties Inherent in the HPPM

Uncertainties arise from the need to apply the HPPM to surficial units with characteristics that may be considerably different than those specifically described in the generation of the hybrid model. For example, the HPPM was applied to all fine-grained soils within the study area, and in many cases their physical properties will vary significantly from those described for the model soil. For a given saturation ratio, lower bulk densities tend to favor the formation of permafrost, because of the increase in the proportion of the relatively high-conductivity mineral component. Thermal conductivity adjustments were made to reflect the bulk densities assigned to the various surficial units,

according to Johansen's (1975) equations. These adjustments shift HPPM predictions in the appropriate direction, though it is impossible to evaluate the magnitude of the shift without regenerating the HPPM equations (particularly equation (8)) using the new soil properties. Shift magnitudes based on these adjustments do appear to be reasonable, however. Thermal conductivities for coarse grained soils with bulk densities other than 1500 kg m^{-3} were adjusted in a similar fashion.

In the case of organic soil, the HPPM was restricted to a single condition consisting of 2 meters of saturated peat overlying a saturated silt-clay base. While this is unlikely to be the case across the whole region, it appears to be a reasonable description of the major organic areas (bogs and fens) identified on regional surficial geology maps (Lavkulich, 1971, Aylsworth et al, 1993). Non-organic soil units having thin organic veneers, or very thick organic deposits, are not specifically modeled in the analysis. The thermal influences of thin organic covers are represented implicitly in the n-factors associated with particular vegetation conditions such as black spruce forests, upland spruce-feathermoss, etc. It is likely that there are organic terrain units within the study area that deviate significantly in character from those represented in the HPPM. Consequently there will be some uncertainty associated with HPPM predictions for these situations.

HPPM predictions are based on the assumption that the annual temperature variation can be adequately represented as a sine wave of a particular amplitude and a period of 365 days (Lunardini, 1981. p.551). This appears to be a reasonable assumption for Fort Simpson (Figure 15). If the model were to be applied to a region where the

annual temperature wave deviated significantly from a sinusoidal pattern, and/or had a substantially different annual amplitude, model predictions can be expected to be skewed to some degree. Investigations using TONE indicate that high annual amplitudes (given a fixed mean) favor the occurrence of colder, thicker permafrost. The seasonal conductivity differential (higher in winter) permits a net loss of ground heat in response to equal increases in winter and summer surface temperature maxima and minima respectively.

Figure 13: Sine-wave representation of annual temperature data for Fort Simpson.

The HPPM is an equilibrium model, and potential deviations of climate from the long-term normals cannot be accounted for directly. Riseborough and Smith (1993) have shown that a period of several consecutive years in which the ground experiences

abnormally cool temperatures can increase permafrost thickness as winter heat loss from the ground is increased substantially under the condition of high frozen thermal conductivity. This permafrost is relatively slow to degrade when climate conditions ameliorate or return to normal because of the relatively low summer conductivity. The ground thermal regime is in disequilibrium, and indeed this casts doubt on whether equilibrium is ever "achieved" in nature. This in turn leads to the question of a temporal lag between the ground thermal regime and the climate regime. Where aggradation or degradation of permafrost occurs in response to climate change, perturbations in surface temperatures may take a very long time to penetrate into the ground at depth. Therefore, the current permafrost distribution in a region may to some extent be a reflection of past climatic conditions, rather than being in equilibrium with the present climate.

Another modeling limitation involves the use of seasonal (summer and winter) *n*-factors, each of which is applied uniformly throughout the respective season, depending on whether air temperatures are above or below 0°C. In reality, the modulating effects of surface cover on the annual temperature wave are usually variable throughout the seasons, either as vegetation growth increases, peaks, and declines through the summer season, or as snow accumulates and densifies in winter, and eventually melts. The *n*-factors used in the HPPM are considered to be seasonal averages, although this is not a necessary simplification.

Further uncertainties arise from the practical limitations in model scope, in terms of phenomena such as the presence of excess ice and the thermal influence of ground water flow, which are not included as model elements.

5.2.2 Uncertainties Related to the Database

Of concern in all geographic analysis involving the combination of various thematic overlays are issues related to the accuracy of geographic registration of individual data layers, the mapping scales of the various source maps, classification accuracy, and the implications of discrete boundaries separating different map classes. Primary map data for this study were provided by the Geological Survey of Canada in georeferenced, digital format, with the exception of the digital elevation model which was derived from manually-digitised elevation contour proofs at 1:50,000 scale. It is assumed that these digital overlays are accurately georeferenced, one to the other. It would be very difficult to make appropriate corrections if this were not the case. Unlike maps and images of developed areas, those for northern regions contain very few identifiable landmarks which could serve as control points correcting map registration. Margins of water bodies are unreliable as control points due to the variability in water levels from season to season, and year to year.

The reliability of model predictions depends on how accurately the various input parameters and model algorithms represent the physical properties and processes related to a particular set of terrain conditions. This represents the most challenging aspect of HPPM application at regional scales.

For example, we do not know to what extent n-factors measured at a particular site are applicable to similar vegetation units within the region. If we assume an estimate of 10 percent variability in seasonal n-factors between sites with similar surface cover, then model predictions may be bounded with respect to this potential variability. At Fort

Simpson, the HPPM predicts 14 meters of permafrost for black spruce-sphagnum moss, overlying a fine-grained soil at 1800 kg m^{-3} . In this case, $N_t = .41$, $N_f = .20$, $K_f = 2.28$ and $K_t = 1.62$, with R calculated as 0.84. A 10 percent decrease in N_t coupled with an similar increase in N_f will increase the HPPM prediction to 30.2 meters, while increasing N_t and reducing N_f by 10 percent produces no permafrost. Clearly the HPPM is very sensitive to this range of uncertainty in n-factor values.

A similar sensitivity may be shown for thermal conductivity values, if one assumes that frozen and unfrozen values are independent of each other. However, this is not the case. Figure 5 indicates that, for a given soil, a increase or decrease in K_f is accompanied by a change in K_t , *in the same direction*. Therefore, conductivity ratios, are restricted to a narrower natural range than are n-factor ratios. Thus, a 10 percent uncertainty in thermal conductivity values has a smaller impact on R -values (and predictions of permafrost thickness) than does a 10 percent uncertainty in n-factor values.

If these potential errors are combined for all variables, they may become quite large. However, the HPPM predicts that nearly 90 percent of permafrost at Fort Simpson is less than 15 meters thick, and does not exceed about 24 meters. This implies that our estimates of parameter values are reasonable for this region. Furthermore, if black spruce forests exhibited a within class natural variability such that their insulating properties (as represented by n-factors) varied by 10 percent, one would expect to observe significant areas of permafrost up to 30 meters or more in thickness. As noted earlier in this chapter, an upper limit of 20 meters for permafrost thickness in the Fort Simpson region has been suggested by Judge (1973; 1975), which agrees well with HPPM predictions in general. In

addition, modeling results obtained using the same parameter assignments in the Norman Wells area are in good agreement with observations of permafrost characteristics in that region. These results should increase our level of confidence in our ability to derive reasonable parameter values for HPPM implementation at regional scales.

Clearly, great care must be taken in assigning values for thermal parameters when applying the HPPM to a geographic area. Using available information regarding permafrost distribution and thickness for model calibration can aid in achieving satisfactory modeling results.

Assuming that it is possible to derive reasonable values for model parameters, the terrain conditions these represent must actually occur at the geographic location of interest. It is difficult to know at what geographic locations this requirement is not being met, given the level of generalisation inherent in the regional-scale base maps used in this study. For example, a contiguous area classified as white spruce forest on a 1:125,000 mapsheet may contain significant areas of deciduous cover that might be distinguished on a 1:50,000 map. An HPPM prediction for this area would necessarily reflect the contiguous nature of the input data, but would be in error with respect to information available at a larger scale.

For any given map scale, there is likely to be considerable within-class variation. Classification schemes for most natural systems are generalisations of a potentially unlimited number of combinations of elements. These classifications are often defined on the basis of some dominant element or subset of elements which are considered to be significant in terms of their relevance to a particular line of investigation. For example,

areas classified as white spruce may contain significant numbers of deciduous species. Where the proportion of deciduous trees exceeds some threshold, the forest would be assigned another classification within the scheme (e.g. mixed forest). Since we cannot be sure about the precise species makeup within the class "white spruce", there is an inherent uncertainty associated with "correctly" classified terrain units. In extreme cases a particular terrain unit may simply be incorrectly classified, which can lead to gross errors in model prediction. Errors of this sort may be very difficult to identify, and are likely to go unnoticed.

The discrete boundaries characteristic of thematic maps have additional implications for the spatial precision with which model parameter values may be assigned. It is generally understood that such boundaries do not necessarily represent an abrupt change in terrain properties, but there is more probably a transition from one class to another, over some distance of which we are uncertain. The certainty of the class at a particular grid location, therefore, depends to some extent on its distance from a boundary.

This study was undertaken using readily available, regional-scale map data. Consequently there is a high degree of spatial generalisation inherent in HPPM predictions here. A considerable improvement in spatial resolution might be obtained by utilising classified satellite imagery for the determination of parameter values related to vegetation cover (i.e.: n-factors, soil moisture). However, it is much more difficult to improve the spatial differentiation and classification accuracy of substrate characteristics.

5.3 Suggestions for Further Research

HPPM modeling results must be interpreted in the context of the limitations and uncertainties outlined above. While HPPM predictions appear to reasonably reflect the general characteristics of permafrost distribution and thickness for the regions modeled, they should not be considered as representing site-specific conditions. Additional work should be undertaken with the goal of presenting predictions in a probabilistic form, which may better reflect HPPM capacity for predicting permafrost distribution and thickness at regional-scales.

Perhaps the area of greatest concern with respect to the level of confidence in HPPM predictions is that related to the current lack of reliable, long-term n-factor data. The collection of additional n-factor data specific to northern terrain units, and the incorporation of snow model data in the determination of winter n-factors should improve model performance in regional and local applications. Indeed, the HPPM may be particularly well suited for local area studies in which major elements of the terrain can be intensively investigated prior to model application. This would ensure that values assigned to the various model parameters more precisely reflect the spatial distribution of local terrain characteristics.

The consolidation of existing information regarding permafrost distribution and thickness throughout the Mackenzie Valley would facilitate a more thorough evaluation of HPPM predictions, and could lead to refinements of the procedures employed in calibrating the model.

The HPPM provides a basis for evaluating the potential impact of climate change on northern landscapes, under various climate scenarios. Investigations could be extended to yield useful information about possible physical responses of the landscape, and could provide a means for predicting the probable locations and magnitudes of change. This could be accomplished through the consideration of the consequences of changes in various surficial geologic units to a new thermal regime, such as ground subsidence and slope instability (due to a loss of soil strength as ice-bonding is reduced). The creation of an expert system (a rules-based approach which can incorporate many different kinds of information in the decision-making process) may be the most practical approach for this type of endeavour, given the difficulty of quantifying additional spatial variables, such as changes in drainage patterns and the potential succession of vegetation species.

5.4 Conclusion

The Hybrid Permafrost Prediction Model affords the opportunity to apply a rigorous methodology to the investigation of permafrost occurrence at regional scales. In addition, an estimate of permafrost thickness is associated with the predictions. Model predictions were shown to be in general agreement with available information concerning the present distribution and thickness of permafrost within the Fort Simpson study area. The HPPM, having been calibrated for Fort Simpson on the basis of local borehole data, was able to reproduce the general characteristics of permafrost distribution for another geographic region further north (Norman Wells). This success is aided by the similarity of the annual precipitation regime for the two regions, particularly in terms of total annual snow cover, which can have a dominating influence on ground temperatures.

If a reasonable level of confidence is presumed for HPPM predictions, the investigation of regional permafrost responses to various scenarios of climate change becomes simply a matter of changing degree-day indices (and perhaps winter n-factors to reflect changes in snow cover) to represent the new climatic regime in subsequent model runs.

The HPPM has several advantages over traditional methods for predicting the regional distribution of permafrost. Models based on the correlation of permafrost occurrence with mean annual air temperatures fail to account for the thermal influences of various soil conditions and vegetation types, whereas the HPPM includes these factors as integral modeling elements. Models which are based on logical associations between permafrost occurrence and specific combinations of terrain components (e.g.: vegetation cover, soil type) are insensitive to regional and local variations in the climate regime, and are incapable of predicting permafrost responses to climate change.

The Hybrid Permafrost Prediction Model exhibits a promising potential for investigation of ground thermal characteristics in a wide variety of environmental settings, and provides a basis for evaluating terrain responses to alternative climate scenarios.

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PM-1 3¼"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

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