Potential changes in permafrost distribution in the Fort Simpson and Norman Wells regions

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Abstract: Modelling that predicts permafrost distribution and thickness in equilibrium with a given mean annual air temperature is applied to the Norman Wells and Fort Simpson regions. The model predicts the likelihood of permafrost, based on values of thermal conductivity for the various surficial materials in each study area and a factor which describes the insulating property of ground-surface vegetation and snow cover. Estimates of permafrost thickness are obtained for various combinations of terrain characteristics. Using maps of vegetation and surficial geology, these combinations can be compiled for each study area and used to map both permafrost thickness and extent, using a geographic information system. This technique predicts that, under an increase in mean annual air temperature of 2°C, permafrost extent decreases slightly and thickness decreases markedly for the Norman Wells area. For the same temperature increase at Fort Simpson, permafrost almost completely disappears.

Résumé : On a appliqué un modèle prévoyant un équilibre entre la répartition et l'épaisseur du pergélisol et la température annuelle moyenne de l'air à des secteurs de 40 km^2 situés près de Norman Wells et de Fort Simpson. Le modèle calcule la vraisemblance d'un pergélisol, en se fondant sur la conductivité thermique des différents matériaux superficiels dont est composé chaque secteur à l'étude ainsi que sur un facteur décrivant les propriétés d'isolation de la végétation et du manteau nival. On obtient des estimations de l'épaisseur du pergélisol dans des terrains affichant des combinaisons de caractéristiques variées. En utilisant les cartes de la végétation et des dépôts superficiels, on peut compiler ces combinaisons et cartographier l'épaisseur et l'étendue du pergélisol dans chaque secteur à l'étude au moyen d'un système d'information géographique. Cette technique permet de prévoir que, si la température annuelle moyenne de l'air devait augmenter de 2 °C, l'étendue du pergélisol diminuerait légèrement et son épaisseur fléchirait encore plus dans la région de Norman Wells. Pour une augmentation semblable de la température à Fort Simpson, le pergélisol disparaîtrait presque complètement.

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Contents

Author Index

INTRODUCTION

Modelling the response of climate to increased atmospheric CO_2 concentrations indicates that global temperatures will continue to warm gradually. This paper describes the predicted impact of climate warming upon the occurrence and thickness of permafrost at Fort Simpson and Norman Wells, Northwest Territories. The modelling follows a technique developed by Jorgenson and Kreig (1988), which incorporates key environmental factors for predicting the occurrence of permafrost. The Jorgenson and Kreig (J&K) model has been expanded to derive a 'Hybrid Permafrost Prediction Model' (HPPM) that estimates permafrost thickness as well as distribution. It has been applied to the Fort Simpson and Norman Wells areas (Wright, 1995). The model is implemented within a Geographical Information System (GIS) to predict the equilibrium distribution of permafrost at the two study sites under present climatic conditions and under increases in mean annual air temperature of 1°C and 2°C.

Fort Simpson study area

The Fort Simpson study area surrounds the confluence of the Mackenzie and Liard rivers in the Northwest Territories (Fig. 1). It is situated within the zone of discontinuous permafrost and thus provides a good test location for evaluating the ability of permafrost models to differentiate between frozen and unfrozen ground. The surficial geology is characterized by extensive glaciolacustrine deposits in the lowlands south of the Mackenzie River and west of the Liard River (Fig. 2). A considerable portion of these lowlands is overlain by organic veneers associated with bogs and fens. North of the Mackenzie River a broad till plain is present. On either side of the Liard River, eolian sands create an undulating dune topography, with organic deposits filling interdune depressions. An extensive fenland covers much of the southeast corner of the study area. Regional vegetation characteristics reflect the generally poor drainage associated with the subdued topography (Fig. 3), with black spruce forests, bogs, and fenland dominating the lowlands. White spruce forests occupy moderately well drained sites, whereas upland pine and deciduous species are found in well drained environments. Thirty-year climate normals (1961–1990) for Fort Simpson indicate a mean annual air temperature of -4°C, with an annual variation in mean monthly temperature of 23°C.

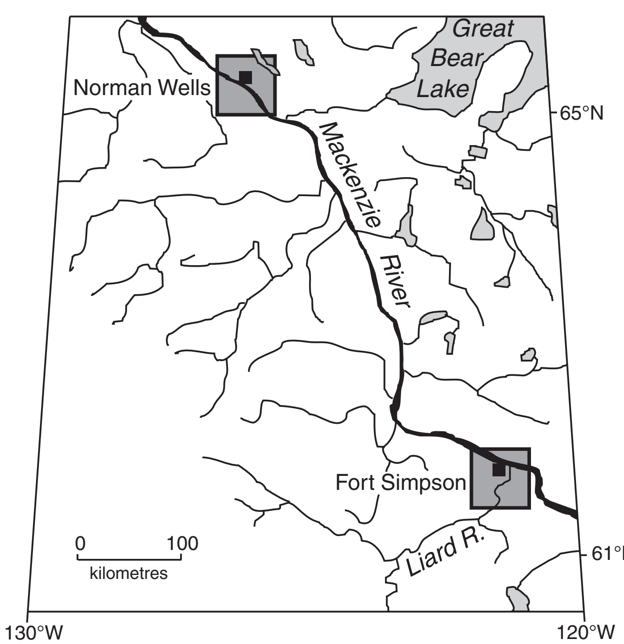


Figure 1. Locations map for the Fort Simpson and Norman Wells study areas.

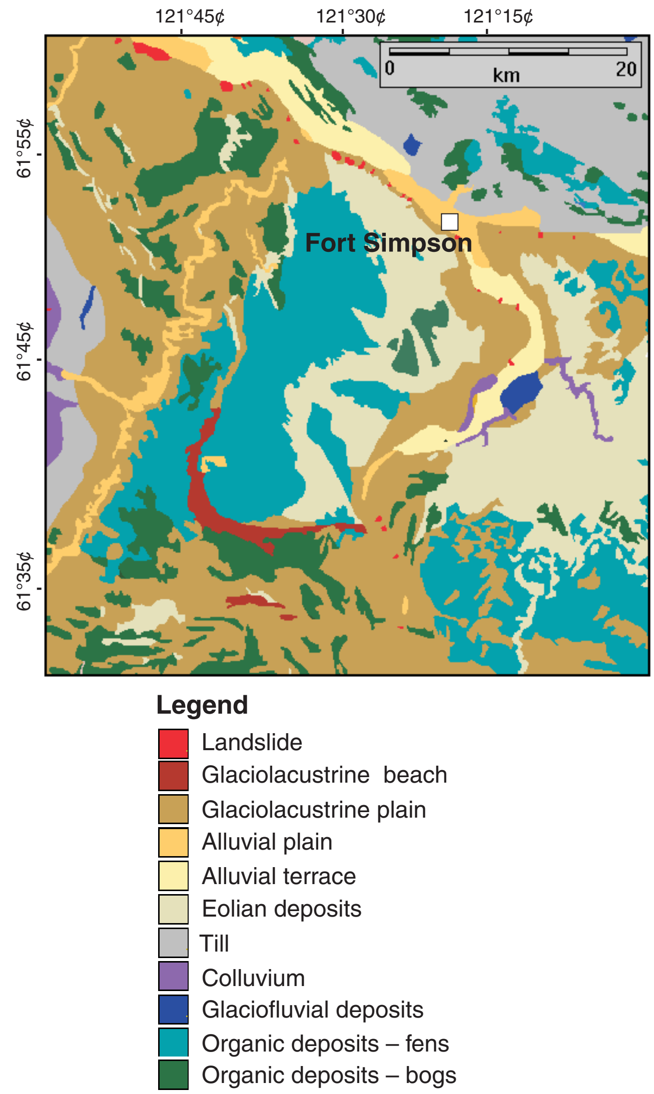


Figure 2. Surficial geology of the Fort Simpson study area.

Norman Wells study area

A second study area of similar size is located at Norman Wells, approximately 400 km north of Fort Simpson. The Norman Wells area is characterized by widespread permafrost. This affords an opportunity to evaluate Hybrid Permafrost Prediction Model performance in a location that

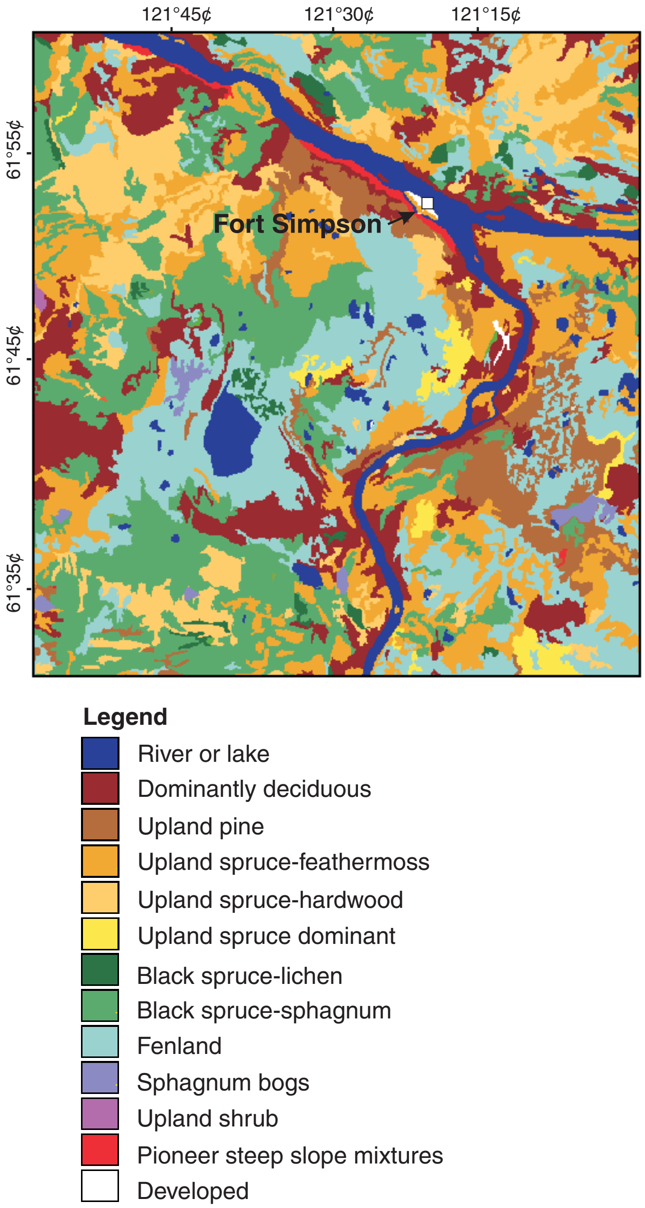


Figure 3. *Vegetation in the Fort Simpson study area.*

experiences a significantly cooler climate than that at Fort Simpson. Vegetation and soil types are similar, but the Norman Wells region is dominated by a broad expanse of black spruce forest underlain by glaciolacustrine silt deposits. Organic units such as bogs and fens make up a very small proportion of the study area, compared with their relative dominance at Fort Simpson (Fig. 4). Deciduous forests are also rare, and pine trees are virtually absent. The Franklin Range of mountains parallels the Mackenzie River to the north. Most of this range has been excluded from this analysis, as has a section of the Mackenzie Mountains in the southwest corner of the study area. Climate normals for Norman Wells indicate a mean annual air temperature of approximately -6°C and an annual amplitude of 23°C. Both the Fort Simpson and Norman Wells study areas are traversed by sections of the Norman Wells pipeline right-of-way (MacInnes et al., 1989).

AN INDEX OF PERMAFROST OCCURRENCE

Jorgenson and Kreig (1988) devised a model for predicting the occurrence of permafrost based on simple relations for estimating thawing and freezing depths under constant surface temperature. The ground thermal state (frozen or unfrozen) is assumed to be dependent on the relative duration and magnitude of air temperature above and below 0°C (expressed in degree-days), seasonal ground thermal

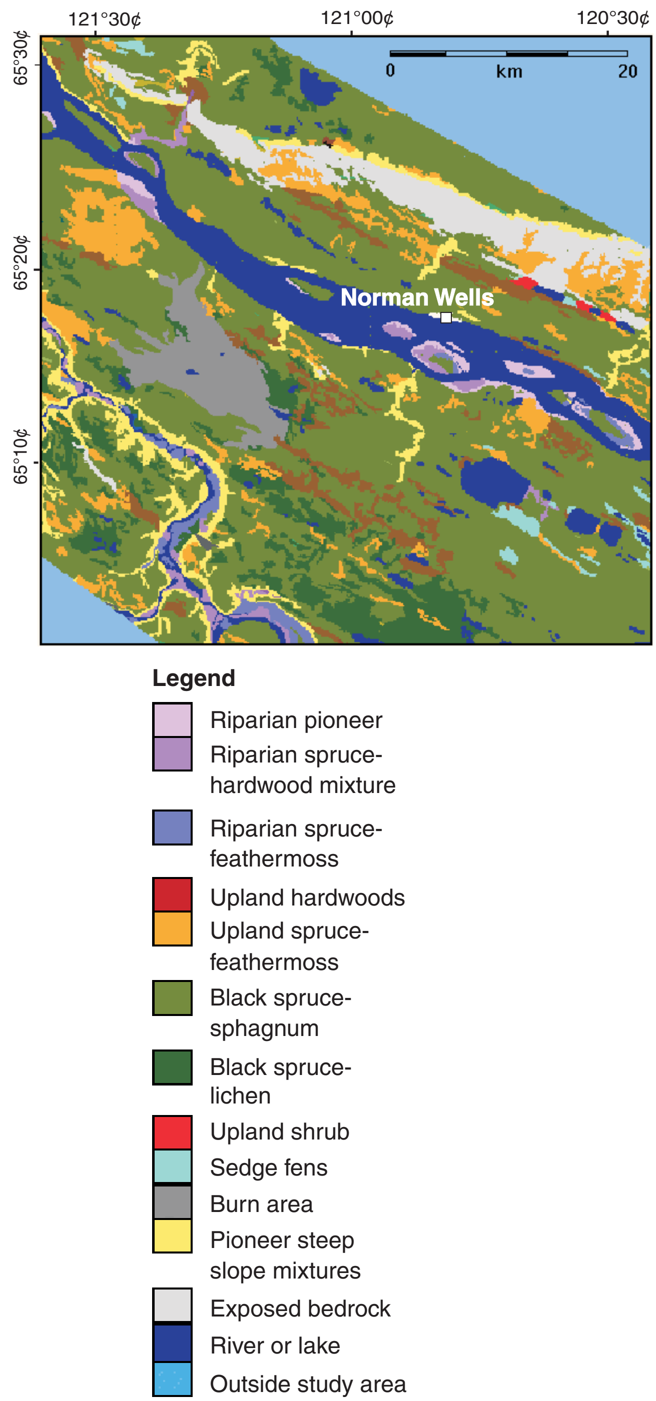


Figure 4. *Vegetation in the Norman Wells study area.*

conductivity (frozen and unfrozen), and heat transfer between the air and the ground, through intervening vegetation and snow cover. A permafrost index (R) is related to the climate and terrain factors as follows:

$$R = P \bullet \frac{DDT}{DDF} \bullet \frac{n_t}{n_f} \bullet \frac{Kt}{Kf}$$

where:

P = potential insolation index
DDT = thawing degree days
DDF = freezing degree days
$\mathbf{n_t}$= summer n-factor
$\mathbf{n_f}$= winter n-factor
Kt= unfrozen thermal conductivity
Kf= frozen thermal conductivity

Values for R that are less than 1 imply that the depth of winter ground freezing exceeds the depth of summer thaw, and thus permafrost is likely to occur. The smaller the value of R (for R < 1), the greater the likelihood that permafrost is present.

The ease with which changes in atmospheric temperatures may be transferred through vegetation or snow cover (i.e. across the 'buffer' layer) to the ground surface may be expressed as a seasonal 'n-factor' (Lunardini, 1978, 1981; *see also* Taylor, 2000). An n-factor of 1 indicates no resistance to heat transfer, while an n-factor of 0 suggests a perfect insulator. The n-factors therefore convert the air degree-day totals to estimates of degree-day values actually occurring at the ground surface. A 'potential insolation index' (P) accounts for extra heating on south-facing slopes and reduced heating on north-facing slopes due to, respectively, increased or decreased exposure to the sun during the summer season; P is defined as the ratio of the site latitude to the equivalent latitude calculated according to Lee (1962, 1964).

A METHOD FOR ESTIMATING PERMAFROST THICKNESS

According to Jorgenson and Kreig (1988), the value R=1 is defined as the threshold of permafrost occurrence. It seems reasonable to expect that values of R progressively less than 1 should be indicative of thicker permafrost. A hybrid model was developed in which values of R generated by the Jorgenson and Kreig equation are related to predictions of permafrost thickness produced by a finite-element heat conduction model called TONE (L.E. Goodrich, pers. comm., 1993). The finite-element approach to solving heat conduction problems is well established (Myers, 1971; Goodrich, 1982), and TONE has been used as a tool for investigating permafrost responses to climate change (Riseborough and Smith, 1993); however, finite-element models are complex, involving labourious calculations, and are not compatible with geographic information systems. Because TONE can utilize the same data on climate and site conditions as the Jorgenson and Kreig model, a prediction of permafrost thickness under conditions of thermal equilibrium and an associated value of R may be obtained for any specified set of model inputs. In order to develop a GIS-compatible model capable of predicting permafrost thickness, outputs from the Jorgenson and Kreig and TONE models were correlated to derive the Hybrid Permafrost Prediction Model, which produces estimates of equilibrium permafrost thickness comparable to TONE predictions, using much simpler calculations. Input values were chosen so as to represent a wide range of hypothetical climate and terrain conditions expected to occur in natural settings.

Jorgenson and Kreig's R versus TONE predictions of permafrost thickness

In this paper, the term 'permafrost thickness' refers to the distance from the ground surface to the base of the permafrost, irrespective of active-layer thickness, under conditions of a periodic steady state. Model runs were designed to generate predictions for a broad range of hypothetical terrain conditions to reveal a relation between TONE predictions of permafrost thickness and the associated values of R. Figure 5 plots TONE predictions for permafrost thickness against the calculated value of R for these hypothetical terrain conditions.

Permafrost was predicted to occur only when R values were less than 1, confirming the threshold value specified by Jorgenson and Kreig (1988). It is clear that, while the R index appears to be a good indicator of permafrost occurrence, it is not a very precise indicator of permafrost thickness. It is necessary, therefore, to identify the separate influences of the various input parameters to describe the manner in which they combine to produce thicker or thinner permafrost.

Isolating the influence of model parameters

When TONE predictions of permafrost thickness were plotted against the negative log of R, a definite pattern emerged, with the data for each terrain condition (i.e. a particular set of n-factor and thermal conductivity values) displaying a linear

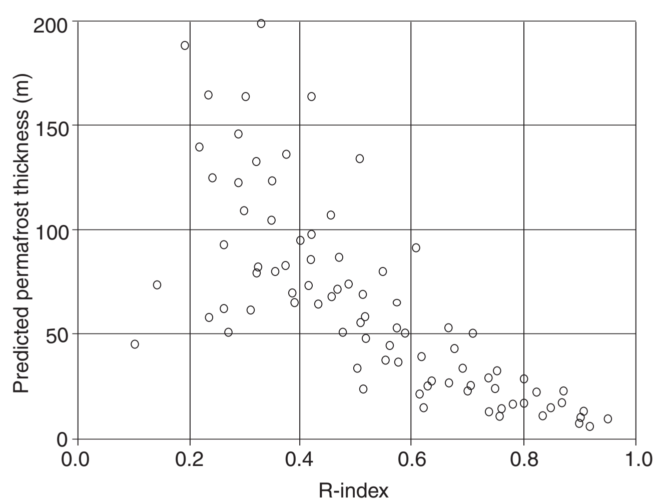


Figure 5. *Relations between the calculated value of R and permafrost thickness. Note that permafrost occurs only where R<1, but that R is a poor indicator of permafrost thickness.*

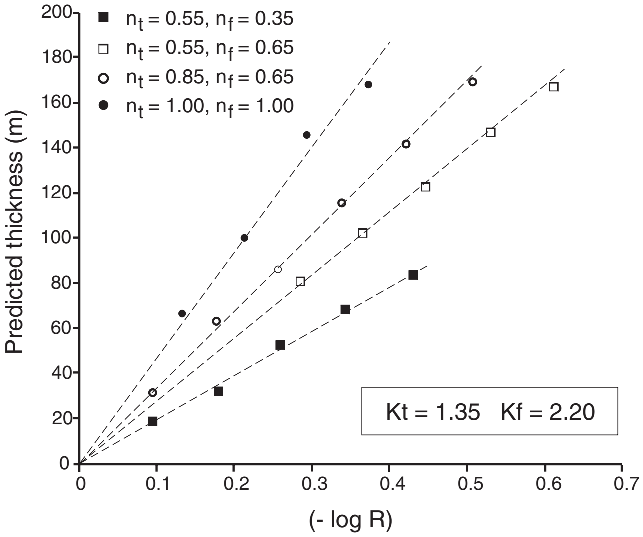


Figure 6. *Relations between R and TONE predictions of permafrost thickness. Note that all n-factor combinations produce slopes less than that at n_t=n_f=1.0, regardless of which n-factor is larger.*

increase in TONE predictions for permafrost thickness as the value for -logR increases. Figure 6 displays data for four different n-factor pairs, given a single pair of seasonal thermal conductivity values. Since these data converge at the graph origin (0,0) the relations between permafrost thickness and -logR may be described for each terrain condition simply in terms of the slope (S) of the appropriate line. Data points along an individual line represent different mean annual temperature conditions at a particular hypothetical site (i.e. a single specified set of seasonal n-factor and thermal conductivity values). Since movement along a particular line represents a change in mean annual air temperature only, it follows that a change in mean annual air temperature does not influence the value of S. This implies that if an appropriate slope value (S) is determined for any specified set of terrain parameters (n_t, n_f, Kt, Kf), then the associated TONE prediction of permafrost thickness may be obtained directly, without the need for additional TONE runs.

Technical performance of the Hybrid Permafrost Prediction Model

The technical performance of the Hybrid Permafrost Prediction Model was evaluated with respect to its ability to reproduce the predictions of permafrost thickness generated by the finite-element heat conduction model (TONE). The evaluation involved 20 runs used in defining the mathematical relations comprising the Hybrid Permafrost Prediction Model, plus 50 additional verification runs whose parameters were chosen in a more-or-less random fashion. Figure 7 shows the comparison of TONE outputs to Hybrid Permafrost Prediction Model predictions of permafrost thickness for these 70 distinct terrain conditions. Predictions of permafrost thickness ranged from a few metres to nearly 300 m.

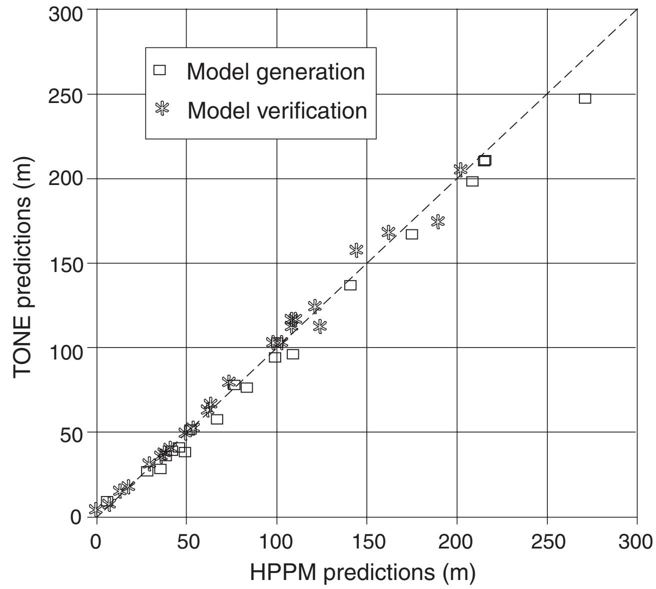


Figure 7. *Comparison of Hybrid Permafrost Prediction Model (HPPM) predictions of permafrost thickness to those generated by a finite-element heat conduction model (TONE).*

Linear regression of TONE estimates of permafrost thickness against Hybrid Permafrost Prediction Model predictions indicate a standard error across the whole range of predictions of 7.4 m, with an r^2 of 0.99. For predictions less than 50 m, the standard error is only 4.1 m (r^2 = 0.93), while for those between 50 m and 300 m the standard error is 9.4 m with an r^2 of 0.98. The standard error falls to 2.0 m for predictions less than 30 m, with an r^2 of 0.97. This analysis indicates that although the standard error associated with predictions of permafrost less that 30 m thick is small in absolute terms (2 m), this error is significant for predictions of very thin permafrost. For predictions of permafrost more than a few metres thick, however, the Hybrid Permafrost Prediction Model satisfactorily reproduces the predictions of permafrost thickness generated by the finite-element heat conduction model.

APPLYING THE HYBRID PERMAFROST PREDICTION MODEL TO PERMAFROST MAPPING AT REGIONAL SCALES

Conventional permafrost mapping techniques rely on air-photo interpretation methods that associate various terrain characteristics (particularly vegetation cover) with the occurrence of permafrost. These methods are of limited utility for predicting permafrost thickness, or for predicting permafrost response to a changing climate. Assuming that it is possible to assign appropriate values to the various model parameters, the Hybrid Permafrost Prediction Model provides a rigorous method for predicting permafrost occurrence and thickness in a manner that is sensitive to changes in any of the model inputs. This presents an opportunity to investigate current and possible future distributions of permafrost regionally, by using existing maps as primary data sources from which model parameters may be derived. Since Hybrid Permafrost Prediction Model equations are GIS-compatible, multiple scenarios may be modelled quickly and efficiently.

Deriving model parameter values from existing maps

Because each of the terms in the Hybrid Permafrost Prediction Model equations can be evaluated for individual sites, maps of permafrost occurrence and thickness can be produced. Existing maps of surficial geology, vegetation, and organic cover, and Digital Elevation Models (DEMs) constructed from NTS contour maps for each study area serve as primary data sources. All data were resolved to a 30 m x 30 m grid-cell format suitable for analysis within a raster-based GIS, such that each 30 m grid cell was assigned a complete set of model parameter values.

Maps of surficial geology and organic cover provided a basis for defining soil physical properties such as mineralogy, texture, and dry bulk density (e.g. Fig. 2, for Fort Simpson). Vegetation cover (e.g. Fig. 3, for Fort Simpson) was regarded as a surrogate indicator of soil water content (Jorgenson and Kreig, 1988), based on the assumption that particular vegetation communities thrive within a certain range of soil moisture conditions. Consequently, a particular species or assemblage of species will tend to dominate a given site in response to local soil moisture conditions. Parameters representing soil physical properties and water contents were used as input to Johansen's (*in* Farouki, 1981) empirical equations for calculating unfrozen and frozen thermal conductivities. Seasonal n-factor values were assigned to each vegetation unit based on information provided by Jorgenson and Kreig (1988) and Lunardini (1981).

The current climate in each area was assumed to be represented by temperature records kept at the Atmospheric Environment Service weather stations at Fort Simpson and Norman Wells. These data were converted to thawing and freezing degree-day indices based on monthly means of 30 year air temperature normals. In order to derive a value for P at each grid cell location, equivalent latitudes for individual sites were calculated on the basis of local terrain slope and aspect information derived from Digital Elevation Models of each region.

Implementing the Hybrid Permafrost Prediction Model within a GIS

Implementation of the Hybrid Permafrost Prediction Model within a geographic information system is summarized in Figure 8. Maps of predicted permafrost occurrence for present climate conditions and two warming scenarios (Fig. 9a, b, c, 11a, b, c) were produced through a simple classification of R-values generated by the Jorgenson and Kreig (1988) equation. R-values greater than 1.05 are assumed to indicate unfrozen ground. A marginal class (R-values between 0.95 and 1.05) implies that ground may be unfrozen or contain

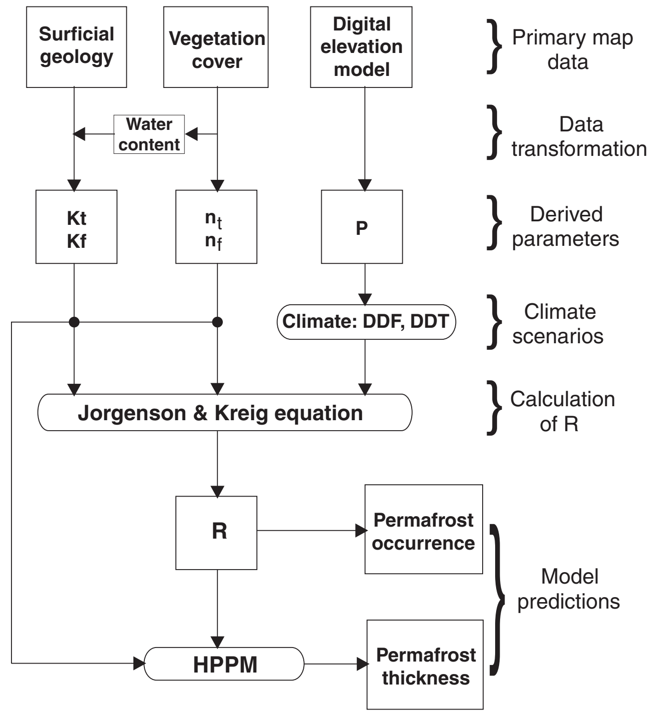


Figure 8. Flow diagram for Hybrid Permafrost Prediction Model (HPPM) implementation. DDT = thawing degree days; DDF = freezing degree days.

warm, thin permafrost. R-values between 0.85 and 0.95 (frozen 1) suggests permafrost occurrence, though much of this will likely disappear in response to climate warming. Permafrost classed as frozen 2 (R-values less than 0.85) will probably persist under predicted climate warming scenarios. Maps of permafrost thickness (Fig. 10a, b, c, 12a, b, c) are produced by applying the Hybrid Permafrost Prediction Model equations (Wright, 1995) to the value of R derived for each grid cell.

RESULTS AND DISCUSSION

Predictions of the aerial extent of permafrost occurrence at Fort Simpson and Norman Wells agree favourably with observations of permafrost occurrence based on interpretations of a continuous geophysical survey along the Norman Wells pipeline right-of-way conducted by Interprovincial Pipelines Ltd. (Interprovincial Pipe Lines (NW) Ltd., 1982; Kay et. al., 1983). These indicate that within the Fort Simpson study area, approximately 20% of the right-of-way is frozen. The Hybrid Permafrost Prediction Model predicts that 27% of the study area is frozen (Fig. 9a), with the marginal class accounting for another 8%. Borehole data along the pipeline corridor (Interprovincial Pipe Lines (NW) Ltd., 1982) suggest that black spruce forests in the Fort Simpson region tend to be situated on ground frozen to depths greater than 10 m, while ground underlying white spruce forest may be unfrozen, or frozen to depths less than 8 m, depending on soil characteristics. The ground beneath pine forests was usually unfrozen while under deciduous cover permafrost was almost always absent. Additional borehole data for organic terrain units at Fort Simpson (Rutter et al., 1973) confirm that peat bogs tend to be frozen to depths of 6–8 m or more, and that fens are generally unfrozen within the top 4–6 m. Few data are available regarding thermal characteristics of fens at greater depths. These borehole data are in general agreement with Hybrid Permafrost Prediction Model predictions of permafrost thickness at Fort Simpson under current climate conditions (Fig. 10a).

At Norman Wells, mean annual air temperatures are about 2°C lower than at Fort Simpson. The Hybrid Permafrost Prediction Model predicts that approximately 81% of the region will be underlain by permafrost (Fig. 11a; exposed bedrock was excluded from the analysis). Geophysical surveys indicate that frozen terrain was encountered over 83.7% of the pipeline right-of-way (Interprovincial Pipe Lines (NW) Ltd., 1982). Studies by Judge (1973, 1975) indicate that permafrost thickness in the Norman Wells region is

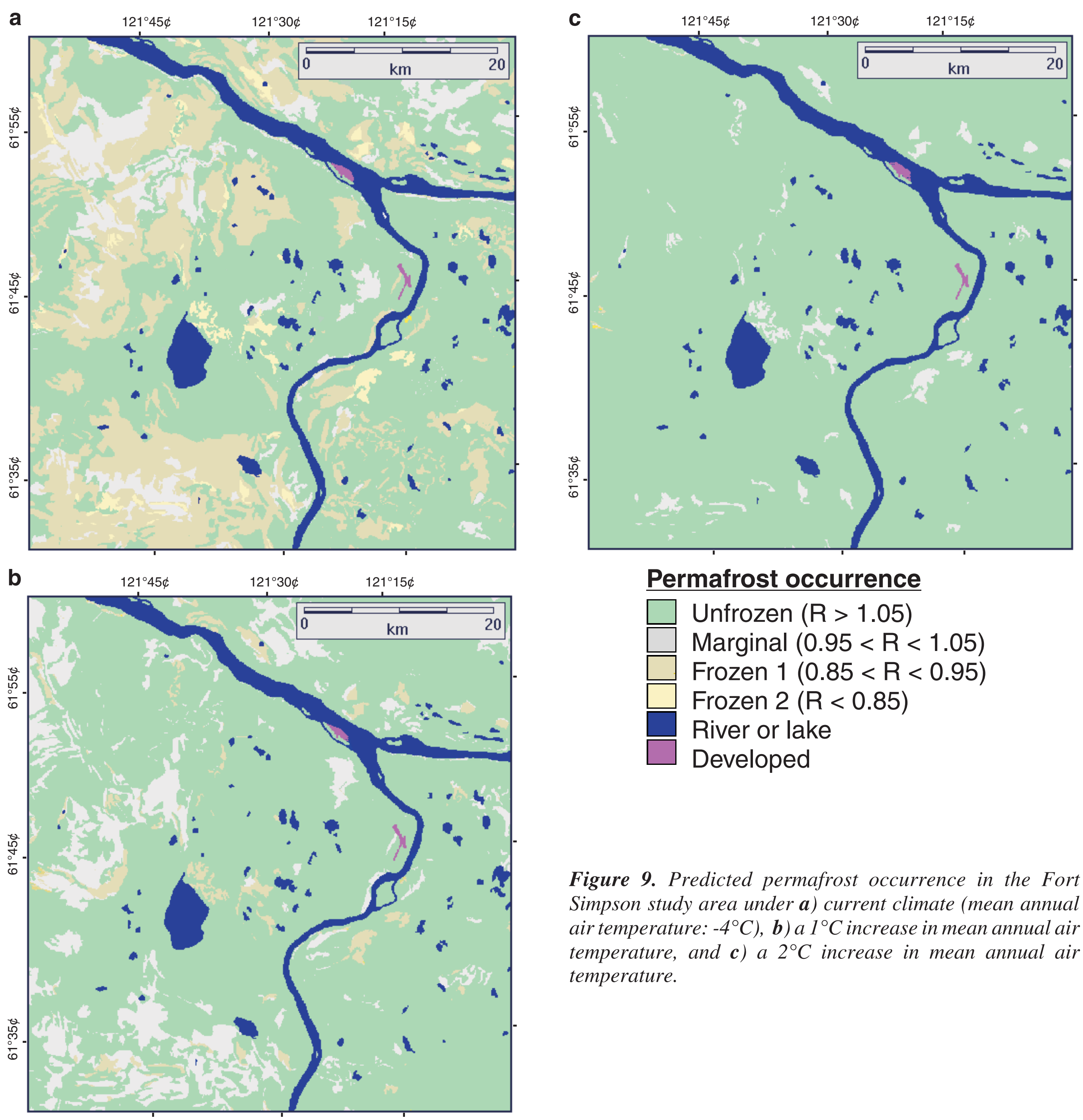


Figure 9. *Predicted permafrost occurrence in the Fort Simpson study area under **a**) current climate (mean annual air temperature: -4°C), **b**) a 1°C increase in mean annual air temperature, and **c**) a 2°C increase in mean annual air temperature.*

generally less than 50 m and not more than 80 m. The Hybrid Permafrost Prediction Model predicts that 15% of permafrost occurring at Norman Wells is less than 20 m thick, 80% is between 20 m and 50 m, and only 5% is thicker than 50 m (Fig. 12a).

While Hybrid Permafrost Prediction Model predictions are in good agreement with geophysical and borehole data, it should be stressed that these comparisons relate to statistical evaluations of the aerial extent of permafrost along the pipeline right-of-way only, and to a small number of thickness measurements at specific borehole sites. Across most of each study area, few data are available regarding the actual occurrence and thickness of permafrost (for a more detailed evaluation of model performance, *see* Wright (1995)). Furthermore, given the relatively coarse spatial resolution of map data available at small scales, Hybrid Permafrost Prediction Model predictions provide a generalized description of permafrost characteristics within the study areas. Ground thermal conditions at any particular site must be evaluated in terms of the probability or likelihood of permafrost occurrence.

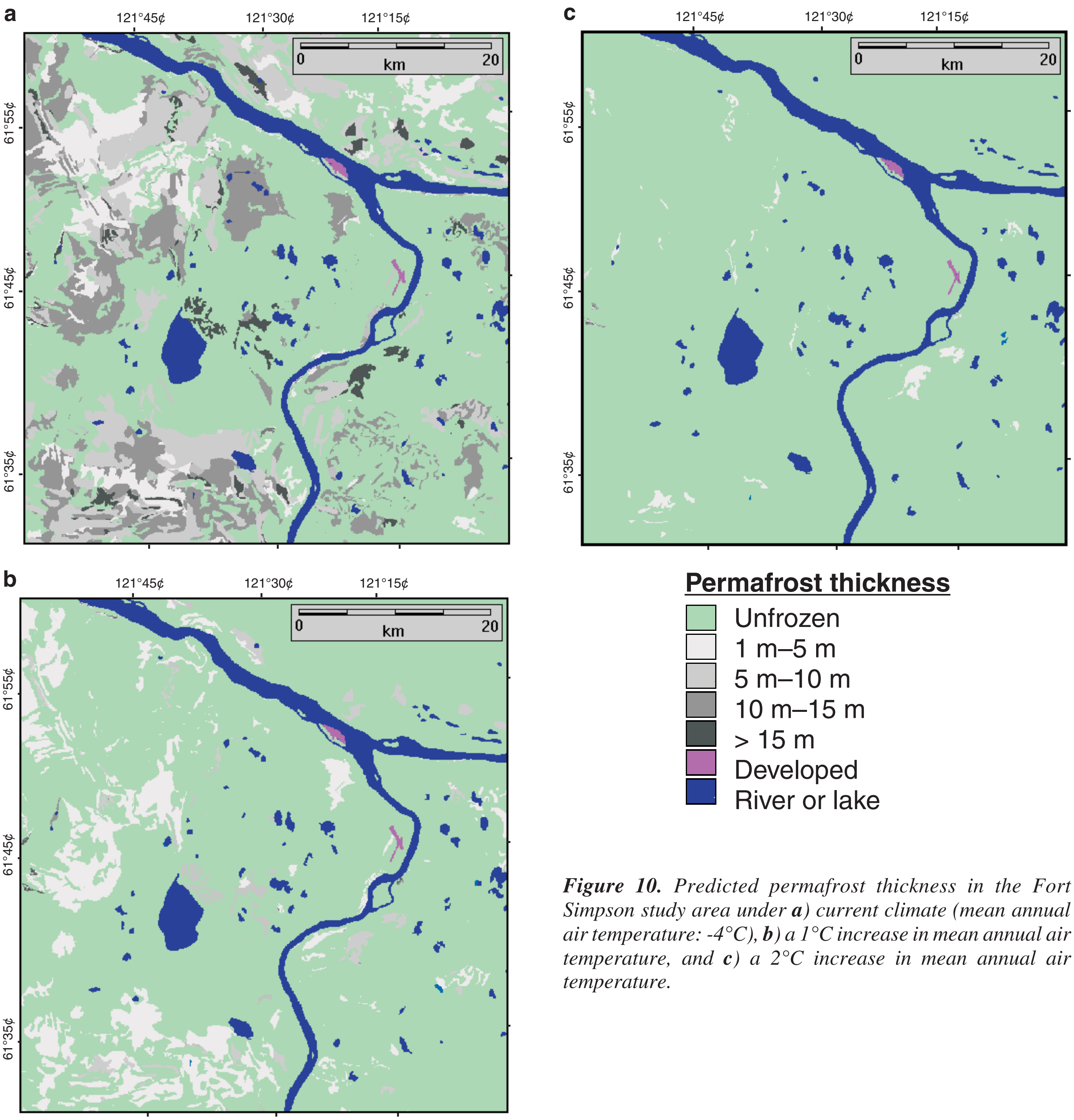


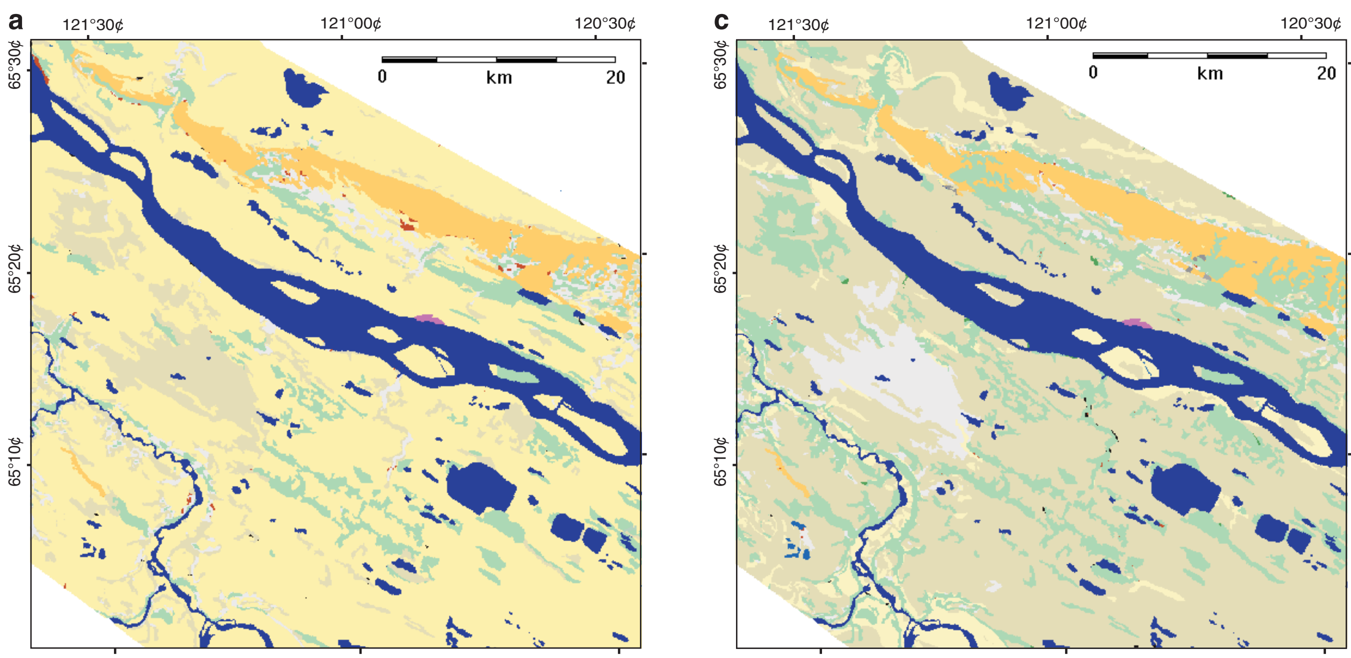
***Figure 10.** Predicted permafrost thickness in the Fort Simpson study area under **a**) current climate (mean annual air temperature: -4°C), **b**) a 1°C increase in mean annual air temperature, and **c**) a 2°C increase in mean annual air temperature.*

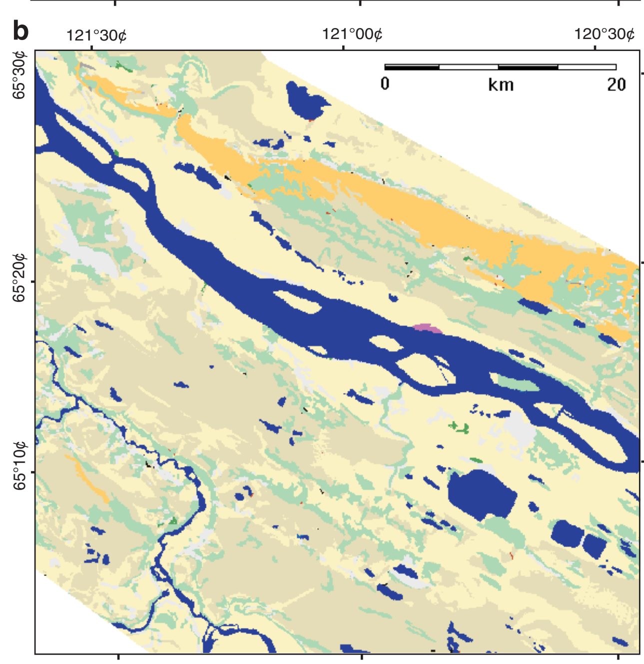
Contents

Author Index

If these predictions are accepted as reasonable representations of permafrost distribution under current climate conditions, the Hybrid Permafrost Prediction Model may be used to investigate various climate warming scenarios by rerunning the model using degree-day inputs which reflect the alternate temperature regimes (in this case, for 1°C and 2°C increases in the mean annual air temperature). Figures 9b, 9c, 10b, and 10c show Hybrid Permafrost Prediction Model predictions of permafrost occurrence and thickness at Fort Simpson under these two warming scenarios. Under a 1°C warming, the aerial extent and thickness of permafrost is substantially reduced, whereas permafrost is predicted to nearly disappear in the 2°C warming scenario. By contrast, at Norman Wells permafrost persists under both warming scenarios, but Hybrid Permafrost Prediction Model predictions suggest that its equilibrium thickness would be reduced considerably (Fig. 11b, c, 12b, c).

The Hybrid Permafrost Prediction Model exhibits a promising potential as a tool for investigating the regional characteristics of permafrost under current climate conditions. Because the model has been derived from physical relations between parameters representing the various climate and terrain elements considered to be most important in the genesis and maintenance of frozen ground, it may be applied to investigations of permafrost in different regions, or under alternative climate scenarios. This Hybrid Permafrost Prediction Model includes all the possibilities of static models





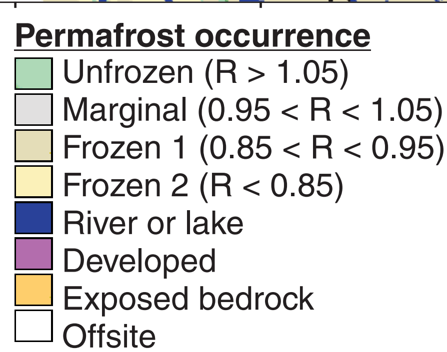


Figure 11. *Predicted permafrost occurrence in the Norman Wells study area under **a**) current climate (mean annual air temperature: -6°C), **b**) a 1°C increase in mean annual air temperature, and **c**) a 2°C increase in mean annual air temperature.*

that simply associate local vegetation and/or terrain characteristics with the presence or absence of permafrost. In addition, it allows for the prediction of permafrost thickness and the investigation of permafrost responses to various scenarios of climate change; however, successful application of the Hybrid Permafrost Prediction Model depends on the degree to which available climate and terrain data can be transformed into reasonable values for model parameters. Further work in this regard should be undertaken before the Hybrid Permafrost Prediction Model can be applied with confidence to regional-scale permafrost studies.

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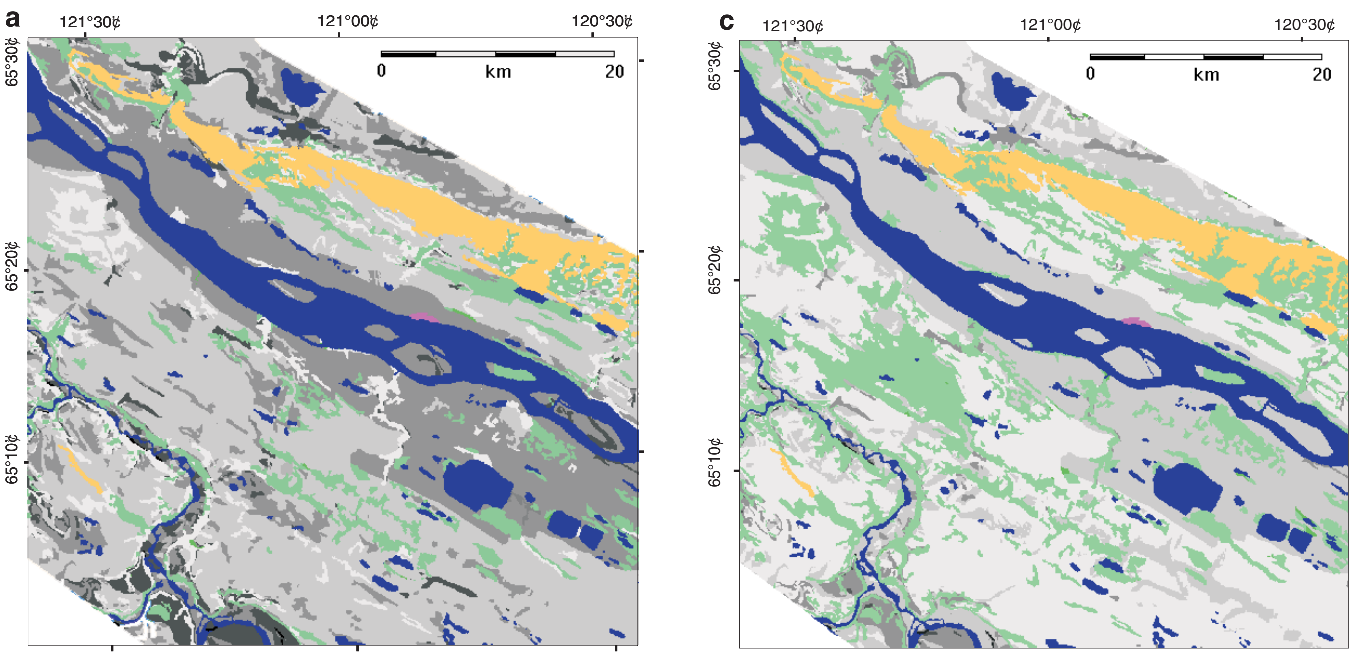

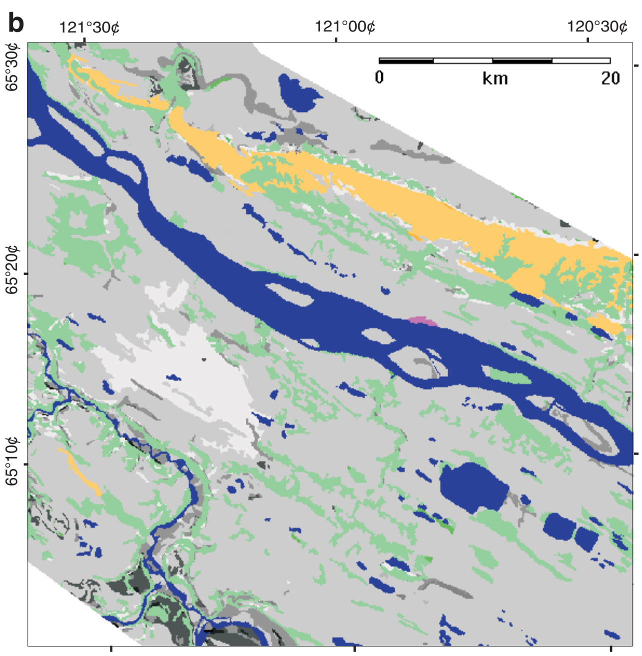

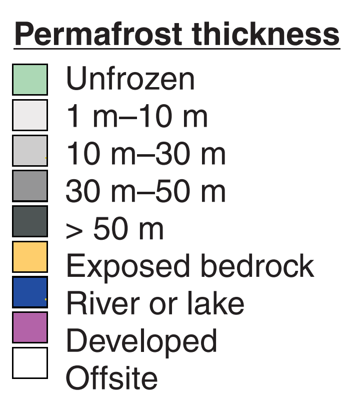

Figure 12. *Predicted permafrost thickness in the Norman Wells study area under* ***a****) current climate (mean annual air temperature: -6°C),* ***b****) a 1°C increase in mean annual air temperature, and* ***c****) a 2°C increase in mean annual air temperature.*

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