Prediction of Ground Temperature for Southern Portion of Prairie Provinces

Entzu Hsieh, Alexandre Tchekhovski
AMEC Foster & Wheeler, Calgary, Alberta, Canada
Greg Sasaki
Enbridge Pipelines Inc., Edmonton, Alberta, Canada

ABSTRACT
Prediction of the mean annual and seasonal ground temperatures at 1.5 m depth were carried out for the southern portion of the Prairie Provinces. The study area is characterized with various soil types, differing climate zones and agricultural lands with different planting and harvesting dates. One-dimensional geothermal analyses were conducted to predict the ground temperatures at shallow depth. Various sets of boundary conditions including air temperature, ground vegetation, and snow thickness were considered in the model. Sensitivity analyses were conducted to evaluate the impact of soil heat capacity, thermal conductivity, and climate parameters on predicted ground temperature.

RÉSUMÉ
La prédiction des températures moyenne annuelle et saisonnière du sol à une profondeur de 1.5 m a été effectuée sur la portion sud des provinces des prairies. La zone d'étude est caractérisée par différents types de sols, de climat et de terres agricoles avec différents types de plantation et de dates de récoltes. Des analyses géothermiques à une dimension ont été effectuées afin de prédire la température du sol à faible profondeur. Différents ensembles de conditions limites, incluant la température de l'air, la végétation en surface, ainsi que l'épaisseur du couvert de neige ont été considérés dans le modèle. Des analyses de sensibilité ont été effectuées afin d'évaluer l'impact de la capacité thermique du sol, de sa conductivité thermique, ainsi que de différents paramètres climatiques sur la prédiction de la température du sol.

1 INTRODUCTION

The southern portion of the Prairie Provinces is experiencing rapid development in a relatively dense network of various linear structures such as pipelines, power lines and roads. Ground temperature is one of the key required parameters for designing pipeline structures. The northern boundary of the study area crosses the provinces at approximately the latitude of Edmonton, AB, while the southern boundary of the study area corresponds to the Canada-USA border. The western boundary is approximately the longitude of Edmonton, AB, and the eastern boundary follows the Manitoba-Ontario border.

The area investigated is characterized with various soil types, climate zones, and agricultural lands with different planting and harvesting dates. Based on identified soil characteristics, as well as climate and vegetation conditions, the southern portion of the Prairie Provinces was subdivided into various geotechnical districts. The mean annual and seasonal ground temperatures for winter, spring, summer, and fall at 1.5 m depth were predicted for each of the identified geotechnical districts. The approaches for this study include the following five tasks:

- Identification of climatic zones;
- Identification of soil types in each zone;
- Identification of types of agriculture;
- Determination of soil thermal properties;
- Ground temperature prediction using numerical modeling;
- Discussion of predicted ground temperatures.

2 TERRAIN CHARACTERIZATION

2.1 Climate

Data published by Environment Canada in Climate Normals for 1971 to 2000 for weather stations located in the southern portion of the Prairie Provinces were analyzed. In total, data from 24 weather stations was used to establish the climate characterization for the study area. Table 1 shows the mean summer, winter and annual air temperatures for 14 of the selected Canadian weather stations.

In general, in the study area, the air temperatures increase from the northwest to the southeast. The mean annual temperature generally increases from about 2.5°C in Edmonton, AB to about 3.7°C near the Manitoba-USA border (Plum Coulee, MN weather station). The mean summer (June to August) temperature increases from 15°C in Edmonton, AB to about 19.0°C in Plum Coulee, MN. The mean winter (December to February) temperature decreases from -11.6°C in Camrose, AB to -15.3°C in Winnipeg, MN.

Table 1. Summer Average, Winter Average and Mean Annual Air Temperature (°C)

Weather Station	Summer Average	Winter Average	Mean Annual
Edmonton, AB	15.0	-11.8	2.4
Camrose, AB	15.6	-11.6	2.7
Viking, AB	16.0	-11.9	2.8
Kerrobert, SK	16.6	-14.0	2.3
Outlook, SK	17.6	-12.6	3.4
Saskatoon, SK	17.2	-14.8	2.2
Regina, SK	17.7	-13.8	2.8
Yorkton, SK	16.7	-15.5	1.6
Kipling, SK	16.7	-14.2	2.0
Maryfield, SK	17.4	-13.6	2.8
Souris, MN	17.6	-14.2	2.5
Glenboro, MN	18.0	-14.6	2.8
Plum Coulee, MN	19.0	-13.7	3.7
Winnipeg, MN	18.3	-15.3	2.6

The snow depth on the ground was calculated from the snowfall data, based on the assumption that initial snowfall density is 0.1 g/cm³ and the average density of snow on the ground is 0.3 g/cm^3 from November to February, and is 0.35 g/cm^3 for March. The higher snow density in March is due to considerably warmer air temperatures at the end of the snow season. On this basis, the snow thickness at the end of the each month for which there was snow cover was calculated using the following formula:

$$H_i = 0.1 \sum_{i=1}^{5} \frac{F_i}{\rho_i} \qquad [1]$$

Where:

n = 1 (for November) to 5 (for March)

H_i = Snow thickness on ground, cm;

F_i = Snowfall thickness, cm;

ρ_i = Snow Density, g/cm³

Table 2 below shows the calculated mean monthly depth of snow on the ground.

Table 2. Calculated Mean Monthly Snow on Ground (mm)

Weather Station	Nov.	Dec.	Jan.	Feb.	Mar.
Edmonton, AB	60	120	205	255	310
Camrose, AB	55	120	210	265	330
Viking, AB	55	110	165	195	230
Kerrobert, SK	35	80	120	150	190
Outlook, SK	25	90	135	170	205
Saskatoon, SK	45	105	170	205	245
Regina, SK	45	115	180	230	280
Kipling, SK	50	130	200	255	315
Maryfield, SK	60	135	215	270	335
Souris, MN	30	100	175	235	290
Glenboro, MN	50	105	170	225	275
Plum Coulee, MN	65	135	205	260	140
Winnipeg, MN	70	135	215	260	310

2.2 Climate Change Trend

In addition to analysis of Climate Normal data, the mean monthly air temperatures for Edmonton, Regina and Maryfield between 1971 and 2012 were reviewed. Figure 1 presents the mean and 5-year running mean air temperatures for winter (December to February), spring (March to May), summer (June to August), and fall (September to November) for Regina, SK.

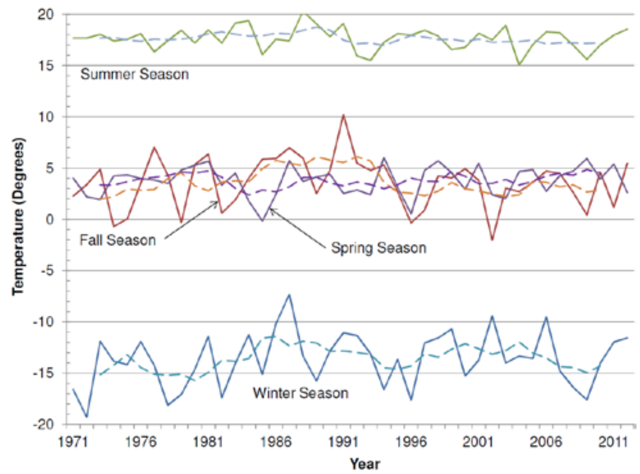

Figure 1: Mean and 5 Year Running Summer, Fall, Winter, and Spring Air Temperatures for Regina Weather Station

It can be seen from the figure that the maximum air temperature fluctuations are up to approximately 10 degrees for the winter seasons, while fluctuations for the summer seasons are less, at up to approximately 4 degrees. Fluctuations for the 5-year running temperatures are less, but still in a range of 4 degrees for the winter season, and approximately 2 degrees for the summer season. In spite of the significant fluctuations of air temperatures year to year, there is no noticeable cooling or warming trend between 1971 and 2012. Similar results were also observed for the Edmonton and Maryfield weather stations. On this basis, the Climate Normals data (1971 to 2000) were used to predict soil temperatures for the southern portion of the Prairie Provinces.

2.3 Surficial Geology

The southern portion of the Prairie Provinces falls into the outer margin of the Laurentide Ice Sheet which covered much of Canada in the past. The types of deposited soils reflect repeated deposition related to multiple glacial advance and retreat events.

The main types of soil deposits identified within the study area were moraine, glaciofluvial, fluvial, glaciolacustrine, and lacustrine. In addition to the main soil deposition types, outwash and eolian deposits were identified within the provinces of Saskatchewan and Manitoba.

The boundaries of the identified soil types within the geotechnical districts are not well defined, and are determined approximately, likely with accuracy of several km.

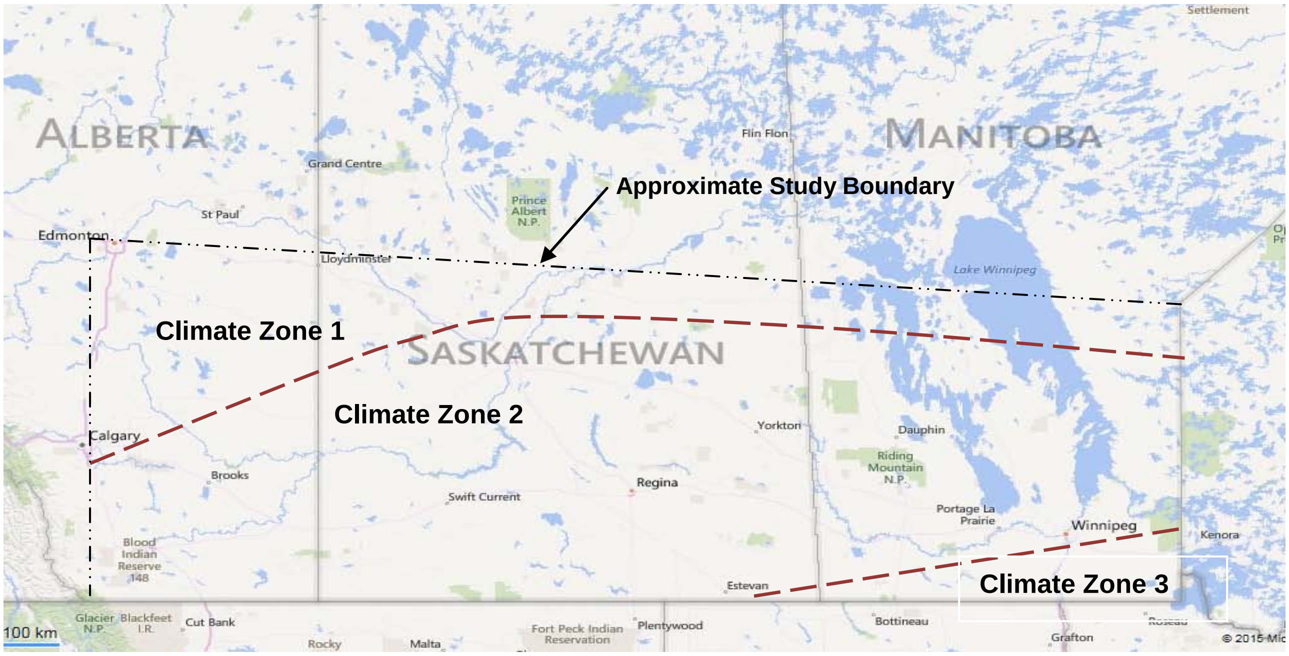

Figure 2: Climate Zones within the Investigated Area

2.4 Vegetation

The southern portion of the Prairies Provinces includes parkland vegetation which can be described as a transition between moist boreal forest and prairie grassland. Boreal forest vegetation consists of aspen woodlands, wetlands, fescue grasslands and riparian areas with moss, lichen, and grass as ground cover.

Prairie grassland vegetation is dominated by spear grass, wheat grass, blue gamma grass, needle and thread grass, green needle grass and sagebrush.

3 CLIMATE ZONES

Three climate zones were identified within the investigated area. The basis for identification of the climate zones were mean annual air temperature and thawing indexes. The freezing index was also calculated, but was not considered for identification of the climate zones due to the presence of the snow cover which often has a greater influence on the soil temperature, compared with the winter freezing index.

The approximate extent of each identified zone is shown in Figure 2. Table 3 provides the mean monthly air temperature, mean annual air temperature and freezing and thawing indexes for the identified climate zones. Table 4 provides the mean monthly snow thicknesses on the ground for the identified climate zones.

3.1 Climate Zone 1

Climate Zone 1 is located approximately south from Edmonton, AB, and north of Kerrobert and Saskatoon, SK. The average summer air temperatures in this zone range from 14.8°C to 16.8°C and winter air temperatures are in a range from -11.1°C to -14°C. The mean annual air temperature is 2.5°C. The mean monthly snow depth increases from 50 mm in November to 260 mm in March.

3.2 Climate Zone 2

The south boundary of Climate Zone 2 is located approximately south of Kerrobert and Saskatoon, SK and north of Glenboro, MN. The average summer air temperatures in this zone range from 16.4°C to 18.7°C and the winter air temperatures range from -12°C to -15.9°C with an average annual air temperature of 2.9°C. The mean monthly snow depth in this zone increases from approximately 45 mm in November to 280 mm in March.

3.3 Climate Zone 3

Climate Zone 3 is located in the southeast corner of the study area bounded by the Canada-USA border. The mean annual air temperature in this zone is approximately 4°C. This zone is characterized by the warmest summer air temperatures, near 19°C. The winter monthly air temperatures are approximately -14°C. Mean monthly snow depth in this zone increases from approximately 70 mm in November to 330 mm in March.

4 PHYSICAL PROPERTIES OF INDENTIFED SOILS

Various sources of information were used to collect data on bulk density and moisture contents of the soils. Limited data on soil composition was found in published surficial geology maps and published monographs. The majority of the data on physical parameters of the identified soils were obtained from AMEC's regional offices in Canada as results of previous geotechnical field investigations within the study area. The collected data are summarized in Table 5. It can be seen in the table that the identified soils are characterized by a wide range of moisture contents and bulk densities.

Table 3. Mean Monthly, Mean Annual Air Temperatures (°C), Thawing and Freezing Indexes

Climate Zone	1	2	3
January	-14.0	-15.9	-14.7
February	-11.1	-12.0	-11.4
March	-4.6	-5.1	-4.1
April	4.5	4.4	5.1
May	10.8	11.8	12.4
June	14.8	16.4	17.5
July	16.8	18.7	19.9
August	15.9	17.9	19.0
September	10.7	11.9	13.4
October	4.5	5.0	6.0
November	-5.8	-5.2	-3.3
December	-11.9	-13.4	-11.7
Annual	2.5	2.9	4.0
Thawing Index	2,388	2,636	2,856
Freezing Index	1,430	1,558	1,364

Table 4. Mean Monthly Snow Thickness (mm)

Climate Zone	Nov.	Dec.	Jan.	Feb.	Mar.
1	50	110	175	215	265
2	45	110	175	225	275
3	65	145	220	280	330

Table 5. Physical Properties of Identified Soil

Soil Types	Moisture Content (%)	Bulk Density (kN/m^3)
1. Moraine Silty Clay and Silt	10 to 45	17.0 to 21.0
2. Outwash Sandy Silt, Sand and Gravel	10 to 20	18.5 to 20.0
3. Lacustrine Sand, Silt and Clay	15 to 30	17.0 to 20.0
4. Glaciofluvial and Fluvial Sand and Silt	15 to 32	18.0 to 20.5
5. Eolian Sand	5 to 10	19.5 to 20.5

5 PREDICTION OF SOIL TEMPERATURE

The geothermal modeling program SIMTEMP, 1D version, (AMEC Foster & Wheeler proprietary program) was used to predict the soil temperature. The simulator uses the finite element method to compute a numerical solution for heat transfer. Physical/mathematical algorithms used in the SIMTEMP model have been published (Chekhovskyi and Zenova, 1989), and the simulation process has been verified against well-known analytical solutions of the heat transfer problem, and has been compared with numerical solutions produced by other commercial/non-commercial geothermal software. AMEC has successfully used the SIMTEMP program for a variety of geothermal applications over a period of approximately 20 years. For the current application, the model mesh was 30 m deep with nodes 0.1 m apart to a depth of 3 m, and then the spacing between nodes was increased to 0.5 m. For all analyses, the model was run for a period of 10 years starting from October 1.

5.1 Upper and Lower Boundary Conditions of Model

The upper boundary conditions consisted of the mean monthly air temperatures applied on the snow surface from November through March, and on the bare ground surface or ground vegetation surface from April through October.

Due to a minimum radiation balance in months with snow on the ground, it was assumed in the model that the snow surface temperature is equal to the air temperature. For months with no snow, an n-factor methodology was used to predict the ground/vegetation surface temperature. Two different n-factors were applied to the mean monthly air temperatures to calculate the bare ground or ground vegetation surface temperature. An n-factor of 1.3 was used in April, May, August, September, and October, while an n-factor of 1.2 was used in June and July.

A heat flux of 0.02°C/m corresponding to Earth's average geothermal gradient was applied at the bottom of the model mesh.

5.2 Thermal Resistance of Snow Cover and Ground Vegetation

Table 4 summarizes the mean monthly snow depths applied in the geothermal model. The snow densities applied in the model were as described in Section 2.1.

The snow thermal resistance (m^2°K/W) was calculated using Equation 2 (Tchekhovski and Tchernyadiev, 1984).

$$R_{snow} = \frac{H_{snow}\left(14 + 0.5abs\left(T_{sur} + T_{ground}\right)\right)}{39.44(\rho - 0.06)} \quad [2]$$

The ground surface temperature under snow was calculated in the model by using Equation 3, which was modified from Equation 2 to include thermal conductivity (Orlando and Ladanyi, 2004).

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$$\frac{39.44(\rho - 0.06)}{H_{snow}\left(14 + 0.5abs\left(T_{sur} + T_{ground}\right)\right)}\left(T_{sur} - T_{ground}\right) = \frac{k\left(T_{ground} - T_{soil}\right)}{h} \quad [3]$$

where:

H_{snow} – snow thickness, m;
T_{sur} – snow surface temperature, °C;
T_{ground} – ground surface temperature under snow, °C;
ρ – snow density, g/cm^3;
T_{soil} – soil temperature at some distance from the ground surface,°C;
h – distance from ground surface to T_{soil} depth, m;

k – soil thermal conductivity, W/m/°C.

The thermal resistance of ground vegetation (R_{veg}) for agricultural lands was assumed to be in the order of 0.1 m^2 °C/W (months June and July). This assessment is based on our experience with similar surface cover on previous projects.

The ground surface temperature under the vegetation cover was calculated in the model by Equation 4.

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$$\frac{1}{R_{veg}}\left(T_{veg}-T_{groundsuf}\right)=\frac{k\left(T_{groundsuf}-T_{soil}\right)}{h} \qquad [4]$$

where:
T_{veg} – vegetation surface temperature, °C;
$T_{groundsuf}$ – ground surface temperature under vegetation, °C.

5.3 Initial Temperature Conditions

The initial soil temperature throughout the model mesh was assumed to be equal to the surface temperature in October. It was considered that a more precise assessment of initial temperatures was not required, since the model was run for 10 years and the soil temperatures would achieve an equilibrium state relative to the input boundary conditions.

5.4 Thermal Soil Properties

5.4.1 Volumetric Latent Heat

The volumetric latent heat at temperature t (L_t) was calculated from the relationship:
$L_t = r_d\ L\ (w – w_u)$

Where r_d is the dry unit weight of soil
L is latent heat of fusion of water to ice
w is moisture content
w_u is unfrozen moisture content at temperature t

5.4.2 Thermal Conductivities

The thermal conductivity and heat capacity of soils under frozen and unfrozen state were selected with reference to published data (Russian SNiP, 1990) based on inferred moisture and soil density. The thermal parameters were also calculated with the use of Johansen's method (1975) and an empirical formula (Johnston, et al. 1981).

Table 6 presents the average thermal parameters corresponding to unfrozen and frozen (in brackets) conditions for the main soil groups using both approaches. The model was run using both the published, and the calculated thermal conductivity and heat capacity values for the purpose of comparing the two approaches.

Table 6. Thermal Properties for Main Groups of Soils

Soil Types	Thermal Conductivity (W/m/°k)		Heat Capacity (MJ/m^3/°k)	
	Pub.	Cal.	Pub.	Cal.
1. Moraine Silty Clay and Silt	1.38 (1.53)	1.60 (1.83)	2.50 (2.00)	2.50 (1.97)
2. Outwash Sandy Silt, Sand and Gravel	1.88 (2.00)	1.67 (1.82)	2.77 (2.15)	2.30 (1.79)
3. Lacustrine Silt and Clay	1.43 (1.58)	1.63 (1.90)	2.53 (2.20)	2.59 (1.99)
4. Glaciofluvial and Fluvial Gravel, Sand and Silt	1.78 (2.00)	1.68 (1.87)	2.60 (2.10)	2.34 (1.80)
5. Eolian Sand	2.10 (2.15)	1.75 (1.80)	2.30 (2.05)	1.89 (1.61)

6 RESULTS AND DISCUSSION

6.1 Discrepancies between Soil Thermal Conductivities and Heat Capacity

The average difference between the thermal conductivities for unfrozen soils based on published and calculated data is about ±14 percent. The maximum difference of about 20 percent was obtained for eolian sand (published thermal conductivity 2.10 W/m/°C; calculated thermal conductivity 1.75 W/m/°C).

The average difference between the heat capacity of unfrozen soil based on published and calculated data is about ±11 percent. The maximum difference of about 22 percent was also obtained for eolian sand (published heat capacity 2.30 MJ/m^3/°C; calculated heat capacity 1.89 MJ/m^3/°C).

The average difference between the thermal conductivities for frozen soils based on published and calculated data is about ±15 percent. The maximum difference of 20 percent was obtained for lacustrine silt and clay (published thermal conductivity 1.58 W/m/°C; calculated thermal conductivity 1.90 W/m/°C).

The average difference between the heat capacity of frozen soil based on published and calculated data is about ±14 percent. The maximum difference of about 27 percent was obtained for eolian sand (published heat capacity 2.05 MJ/m^3/°C; calculated heat capacity 1.61 MJ/m^3/°C).

6.2 Effect of Thermal Conductivity and Heat Capacity Discrepancies on Predicted Soil Temperature

The mean annual soil temperatures and seasonal soil temperatures at a depth of 1.5 m for the identified climate zones and soil types were predicted by geothermal modeling. As an example of the results, Figures 3 and 4 present the soil temperatures for fluvial silt and clay and eolian sand, respectively, in climate zone 2 for the different seasons of the year using calculated thermal properties.

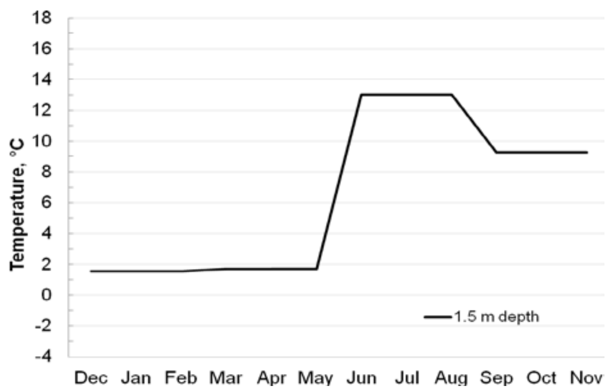

Figure 3: Predicted Ground Temperature in Climate Zone 2 for Lacustrine and Fluvial Silt and Clay

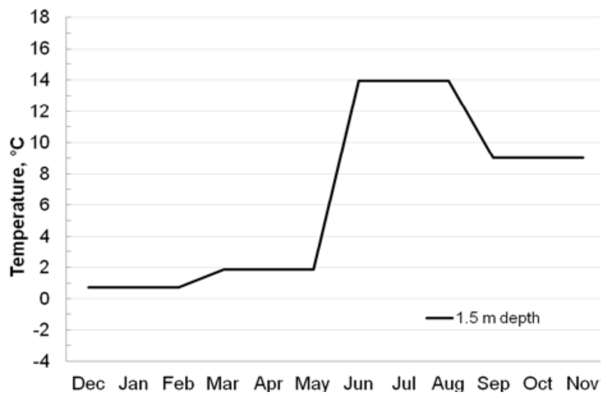

Figure 4: Predicted Ground Temperature in Climate Zone 2 for Eolian Sand

The results of the modeling indicate that only relatively minor differences in the predicted temperatures occur as a result of applying either published or calculated thermal properties of the soils in the model. For instance, comparison of the predicted temperatures in climate zone 2 for the eolian sand demonstrates that the difference of the soil temperatures in summer months is approximately 0.5°C, in spite of a considerable difference in the published and calculated unfrozen thermal conductivities (1.75 W/m/°C for published and 2.1 W/m/°C for calculated). The difference in the predicted soil temperatures for the winter months for eolian sand in climate zone 2 is only approximately 0.1 °C, whereas the difference in the frozen thermal conductivities is 0.35 W/m/°C (1.8 W/m/°C for published and 2.15 W/m/°C for calculated). The minor effect of such changes of the thermal conductivities on the ground temperature is due to the fact that the soil temperatures at the shallow depth mainly depend on the upper boundary conditions, including air temperatures, ground vegetation, and snow thickness.

Similar differences in predicted soil temperatures, using the two approaches to assessing soil thermal conductivities was found for soils of various origin and composition. Table 7 shows the average difference between calculated values of the soil temperature at 1.5 m depth using either published or calculated input values for various soil types in climate zone 2 during each of the seasons of the year. In general, application of the published or calculated thermal conductivities and heat capacities results in an average difference of the predicted soil temperatures of less than one degree Centigrade.

Table 7. Difference Between of Soil Temperatures at 1.5 m Depth for Four Seasons in Climate Zone 2

Soil Types in Zone 2	Winter (°C)	Spring (°C)	Summer (°C)	Fall (°C)
Moraine Silty Clay and Silt	0.25	0.2	0.3	0.1
Outwash Sandy Silt, Sand and Gravel	0.3	0.35	0.35	0.15
Lacustrine Silt and Clay	0.5	0.3	0.5	0.1
Glaciofluvial and Fluvial Sand and Silt	0.2	0.4	0.3	0.2
Eolian Sand	0.1	0.8	0.5	0.1

Table 8 summarizes the predicted mean annual and seasonal ground temperatures at 1.5 m depth for identified climate zones within the southern portion of the Prairie Provinces.

Table 8. Predicted Annual and Seasonal Ground Temperatures at 1.5 m Depth in Study Area

Climate Zone	Annual (°C)	Winter (°C)	Spring (°C)	Summer (°C)	Fall (°C)
1	5.5 to 5.8	1.0 to 1.5	1.5 to 1.8	10.9 to 11.7	8.2 to 8.3
2	6.2 to 6.7	1.2 to 2.1	1.8 to 2.3	12.5 to 14.0	9.1 to 9.5
3	7.5 to 7.8	1.9 to 2.5	2.7 to 3.2	14.2 to 15.4	10.5 to 10.8

6.3 Ongoing Field Measurements

A field investigation and laboratory program would provide a more specific soil profile and properties within the study area. However, as mentioned above, variations in thermal conductivity and heat capacity, as well as soil origin and composition have insignificant impact on the ground temperature at shallow depth. The influence of the upper boundary conditions, including radiation balance, evaporation and condensation, turbulent heat transfer, and thermal influence of ground vegetation and snow cover are considered to be the key factors which determine the ground temperature regime at shallow depth.

For the current study, information was not available on either thermal properties of the ground vegetation, or on the temperature of the ground/vegetation surface. For this reason, an n-factor method was adopted to calculate the ground/vegetation surface temperature based on air temperatures obtained from Climate Normals. Such an approach may not accurately reflect the actual boundary conditions. For detailed investigation of the ground vegetation thermal properties and potential impact on ground temperature, a test site in the community of Hardisty, AB was selected to further evaluate the parameters which determine the upper boundary conditions of the geothermal model.

A total of five thermistor cables were installed in November 2014 to measure field temperatures. Two thermistor cables with a bead spacing of 0.3 m were installed below the ground surface to measure ground temperature to a depth of 3 m. For comparison purpose, one cable was installed in ground with natural vegetation cover, and the other cable was installed in a stripped area. Two other thermistor cables with a bead spacing of 25 mm were installed above the ground surface to measure temperatures in the snow/vegetation cover up to a height of 0.5 m. Another cable was installed above the ground surface for air temperature measurement at various heights above the ground surface in an open area. In addition, a sensor was installed at about 2 m above the ground surface to measure air temperature in a shaded area. All individual sensors were connected to a data logger for automatic information collection at a specified time interval.

The information obtained will be used to calculate site specific boundary conditions, resulting in more accurate soil temperature predictions than were achieved by application of the n-factor method. Field temperature measurements will be continued to the end of 2015.

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DISCLAIMER

This paper contains the work of the authors only, and is not intended to represent the position of Enbridge Pipelines Inc.

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