The Effect of Water Flow and Water Temperature on Thermal Regime Around Culverts Built on Permafrost

Loriane Périer*, Guy Doré[2], Chris Burn[3]

[1] : Master's student, Laval University, Center Northern Studies (CEN), 1035 av. De la médecine, Québec, Québec, Canada G1A 0A6 ; e-mail : loriane.perier.1@ualaval.ca; phone number : +1 418 561 6884.
[2] Professor, Laval University, CEN, 1035 av. De la médecine, Québec, Québec, Canada G1A 0A6
[3] Professor, Carleton University, Ottawa, Ontario, Canada K1S 5B6

ABSTRACT

This paper is based on data collected on field at Beaver Creek in Yukon, Canada. The temperature and flow of water through the culvert were measured at hourly intervals on site.
The objectives are to document thermal regime as a function of water flow and water temperature and to quantify the effects of these parameters on the thermal regime of permafrost. A 2D thermal model on TEMP/W was developed and calibrated using field observations. A mathematical model was also established between water temperatures inside the culvert, water temperatures at the entrance of the culvert, and water flow. Water temperatures at the entrance of the culvert and inside the culvert have a linear relationship, while water temperatures at the entrance and water flow are associated by a logarithmic relationship. While converting flow values to logarithmic values, a multiple linear regression was used to determine the relationship between these three parameters. From this relationship, changes in the flow rate and water temperatures at the entrance of the culvert were made to obtain the water temperature in the culvert. These new temperatures were then inserted in the TEMP/W model and the effects of these changes were observed. The following observations emerged: the variation of plus or minus 10% of the water flow has no impact on the thermal regime underneath the culvert; the variation of plus or minus 10% of the water temperature at the entrance of the culvert has a slight influence on the thermal regime; increasing the temperature causes a slight warming, while decreasing the temperature causes a slight cooling. Finally, the last simulation was conducted without insulation. The importance of insulating the culvert was evident. Indeed, the thaw depth was 30 cm with insulation, and 120 cm without insulation.
Keywords: culvert; thermal regime; flow water; water temperature; modeling; permafrost.

1. Introduction

Permafrost is defined as soil in which temperatures are at or below 0°C for at least two consecutive years (Van Everdingen, 2005). Global warming and infrastructure construction are problems in northern areas and causes the permafrost to thaw. In this case, thermal regime is an important factor to take into account to reduce negative impacts on the frozen soil. Several stabilization problems were observed close to culverts on the Alaska Highway in Yukon, Canada. In fact, allowing the free circulation of air and water through the conduit creates a high disturbance to thermal regime. In sensitive permafrost areas, settlements may occur causing culvert distortion, joint damages and water circulation under the culvert. Two culverts were instrumented on Alaska Highway and thermal monitoring of one of them to be presented in this paper. A thermal model design TEMP/W and a mathematical model, based on observations made on the field, completed thermal monitoring and allowed the evaluation of the influence of several design parameters on the thermal regime. Knowledge about the influence of temperature and water flow on thermal regime is limited but it is envisaged that the depth of thawing permafrost is always higher under culverts because the air and water flowing through the pipe transfer heat to the ground.

2. Test sites

A culvert was instrumented during early May 2013 in an existing culvert located on the Alaska Highway test site, south of Beaver Creek. The road is on warm and discontinuous permafrost which implies that it is considered as potentially unstable when its annual temperature is higher than -2 °C. The soil is very sensitive to temperature variations and permafrost may melt causing settlement, landslides or other damages affecting the safety of road users and the environment. Subgrade is subject to loss of bearing capacity and is susceptible to creep under loads imposed by the backfill. The section of the road studied has several parts with different mitigation systems as shown in **Figure 1**. All parts are equipped with system mitigations (M-Lepage, 2012), except where the culvert is located (Section 6 in gray).

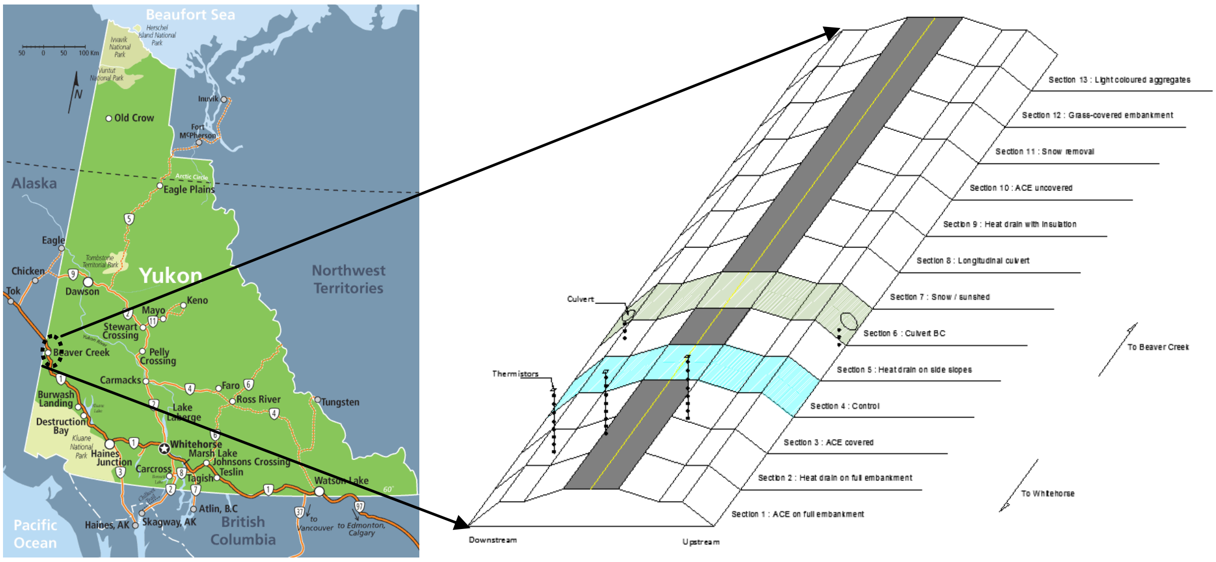

Figure 1 : Localization and description of test site

3. Instrumentation and method

During the instrumentation (early May 2013), difficulties were encountered in inserting probes into the soil to measure soil temperatures. As shown in **Figure 2**, three probes were placed: two underneath (upstream and downstream) and one on the side of the culvert, upstream. Each probe contained three thermistors which measured the soil's surface temperature at 15 cm and at 30 cm. In addition, air temperature circulating in the culvert was measured upstream. Temperatures were recorded every hour from May 24th to October 4th, 2013. A short circuit occurred upstream during the first week and deleted the recorded air and soil temperatures of the side in the culvert. Probes under the culvert upstream and downstream provided data throughout the period shown. All thermistors are connected at two data loggers (Hobo U30); one is placed at the inlet and the other at the outlet.

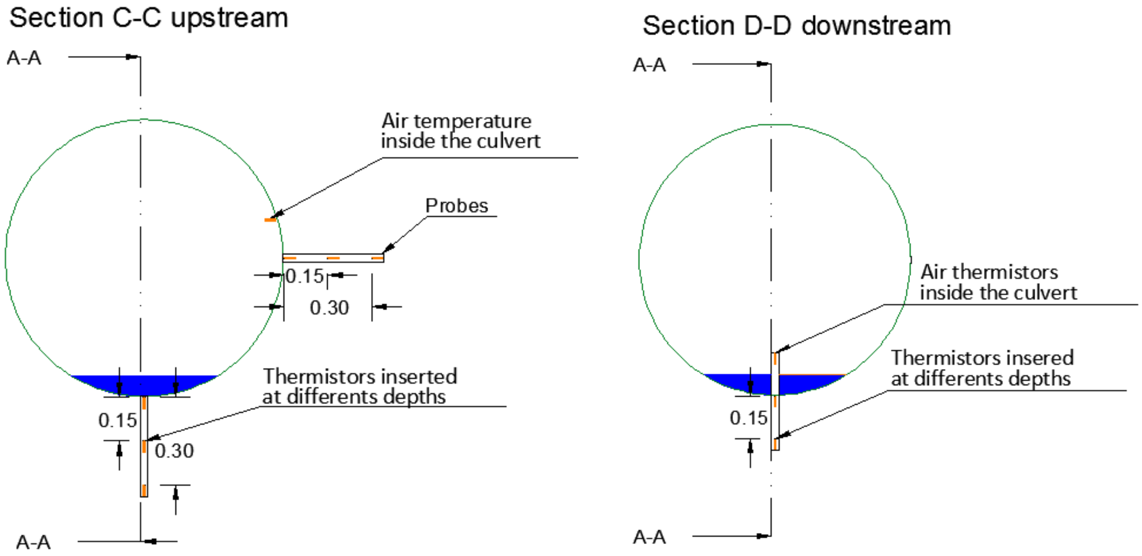

Figure 2 : Installation of instrumentation upstream and downstream

As shown in **Figure 3,** a V-weir was installed at inlet to have and control the water level passing through, and the V. Pressiometer (hobo U20) was installed in piezometer upstream V-weir to measure water pressure every hour. Due to the difference between air and water pressure, it was possible to have the water level and then to deduct flow rate with **equation 1**. The flow measurement system was successfully placed. However, it was damaged during the summer thus affecting some of the data collected. Water flowed under the weir in mid-July 2013. The installation of the weir on the active layer, partially frozen before thawing, seemed to explain the problem. Still, the data of the temperature and flow were recorded every hour from May 24 to July 11, 2013. In addition, one thermistor was installed on V-weir to measure water temperature entering in the culvert.

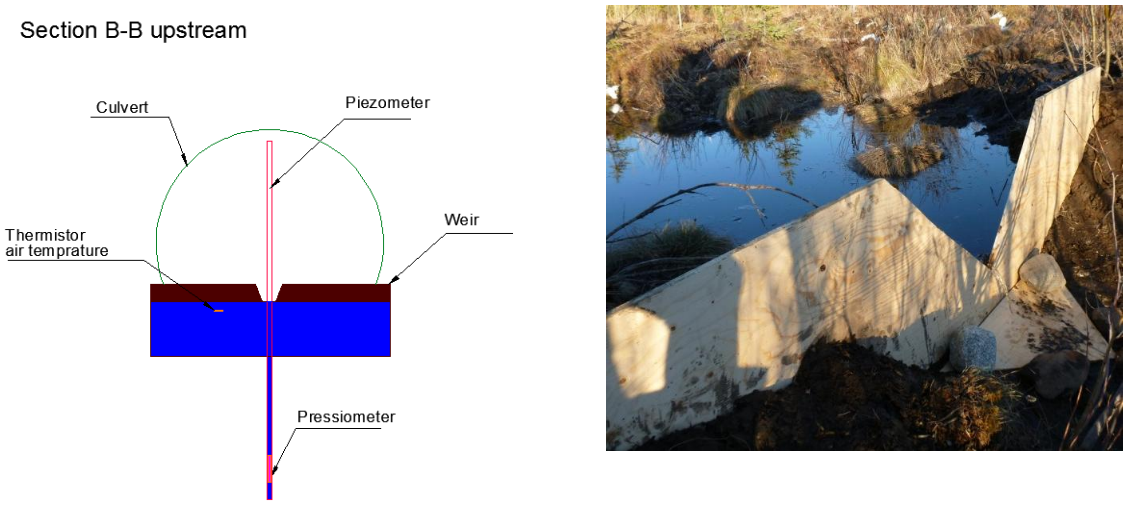

Figure 3 : Flow measurement system

The final instrumentation is presented in **Figure 4**.

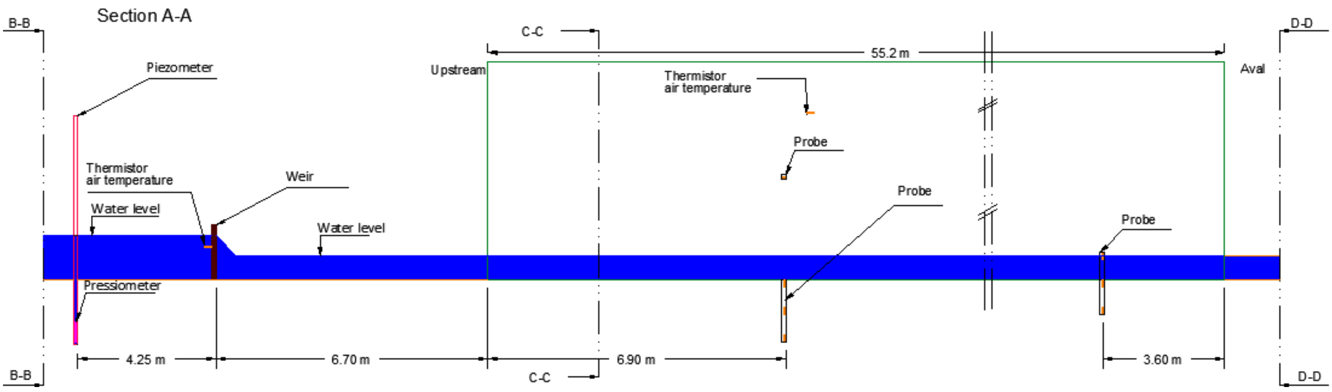

Figure 4 : Final instrumentation

The water pressure data, recorded by a Hobo U20 data logger, was coupled with changes in air pressure recorded at the same time with a barometer connected to a Hobo U30 data logger. Earlier, the water level was read on weir with a marked scale. When the variation of the water level remained constant for several hours, the flow was considered stable. At that point, the time and the measurement of the water level were taken as a reference and were coupled with the water pressure registered by the U20 at the same time. By entering this information into the software HOBOware Pro, the variation of the water level was automatically calculated every hour. The flow rate can be calculated using the relationship between water level and flow rate defined by **equation 1** (*Achour, B., Bouziane, T., Nebbar, K., 2003*).

$$\frac{8}{15} \times 0.578 \times \tan(\frac{\alpha}{2}) \times \sqrt{(2 \times g \times h^5)} \qquad (1)$$

Where α isV-weir angle, g is the gravitational acceleration and h is the water level passing in the V-weir.

4. Modeling on TEMP/W

The first step was to develop a 2D thermal model without culvert on TEMP/W using data collected on the site and using available literature. The natural soil on site consisted mainly of silt and was topped with one meter of peat and 4.5 meters of fill. The thermal properties of the soil were not measured on the field; they were estimated from available literature (Côté, J. and Konrad, J.M, 2005) (De Gandpré, I. 2012). **Erreur ! Source du renvoi introuvable.** presents the estimated values.

Table 1 : Thermal properties

Type of soil	*Depth (m)*	*Frozen thermal conductivity, λf* (kJ/j/m.°C)	*Unfrozen thermal conductivity,* λu (kJ/j/m.°C)	*Frozen thermal capacity, Cf (kJ/m³.°C)*	*Unfrozen thermal capacity, Cu (kJ/m³·°C)*	*Volumetric water content,* θu (m³/m³)
Dry fill	0,5	163,00	154,55	1860,29	2000,91	0,08
Wet fill	3,7	125,00	72,55	3434,00	2212,00	0,59
Peat	1,0	88,24	33,86	1836,50	4000,52	0,81
Silt	9,8	104,31	65,52	2700,03	4311,33	0,66

To have a good approach, it is necessary to know the soil stratigraphy and initial thermal regime. The data of the soil temperatures is available at the section control (in blue in **Erreur ! Source du renvoi introuvable.**) close to the culvert. In this section, thermistors are present at different depths in the slope of the embankment (M - Lepage, J., 2012). The temperatures were recorded every four hours, every day for a year. A daily average was calculated from the last full year of recording (2011), which is representative of the four years of data available.

Data allows drawing initial thermal regime of soil without culvert, represented by the blue and black solid line in **Figure 5.**

Boundary conditions were imposed in the model. Since air temperatures measured by the weather station present on the site (Yukon Highways and public works equipment) did not take into account the snow cover, runoff water or wind, it was decided to impose surface temperatures corresponding to the thermistor located at 30 cm below the surface of the embankment (4.2 m above the natural ground). Steady state is based on an average temperature curve that is represented by the orange line in **Figure 5**. In the model, temperatures were imposed at the base and at the surface of each soil layer to reproduce this curve. A transient state was created for the duration of 365 days to simulate the change in surface temperatures made in the year 2011. The variations corresponded to the monthly average of temperatures recorded at 30 cm depth below the surface of the embankment. The minimum and maximum values recorded were included in the change.

Finally, field modeling without a culvert on TEMP/W allowed drawing the dash curve represented in blue and black in **Figure 5.**

The second step was to introduce the culvert and insulation to the initial model. To simplify the model, the culvert was represented by a semi-circle as the temperatures right and left of the culvert were considered symmetrical and the conditions were considered adiabatic. The boundary conditions that were used for the initial model were the same except for the ones inside the culvert. This allowed drawing a point curve represented in blue and black in **Figure 5.**

As shown in **Figure 5,** the results given by the model matched well with the field observations. The blue and dark lines represent minimum and maximum soil temperatures at different depths. We observed that the culvert had a warming effect on the ground during summer, and a cooling effect during winter.

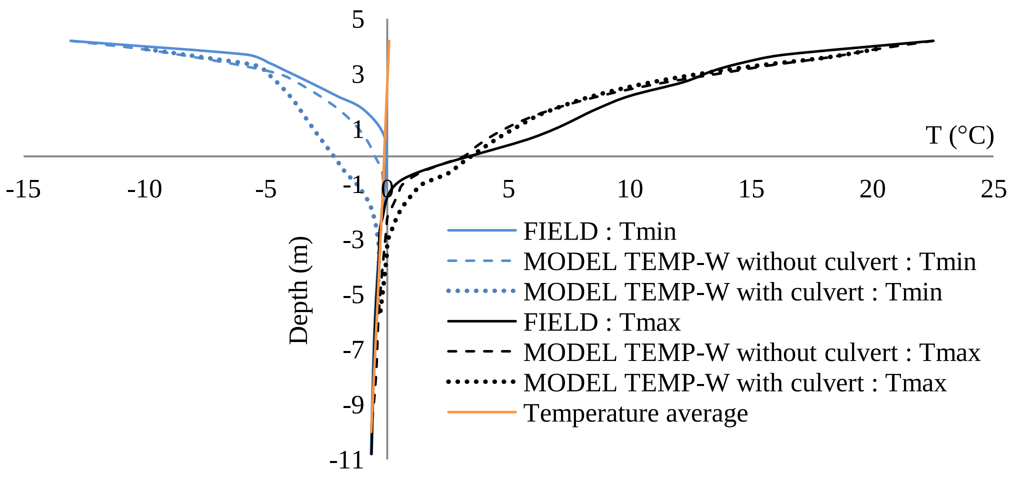

Figure 5 : Thermal regime without and with a culvert on field and on Temp-W

Inside the culvert, the main boundary condition added was water temperature (T_w), which was represented by points at the bottom of the culvert. The imposed water temperatures corresponded to the values reported by the thermistor installed on the surface at the bottom of the culvert. Variations of water temperatures for a year were imposed in a transient state. They corresponded to the recorded temperatures between May and July. For the other months, approximated temperatures were imposed by considering zero temperatures for winter months from January to March and October to December. Finally, by combining all the information, the model calibration TEMP/W allowed drawing the thermal regime under the culvert upstream and downstream shown in **Figure 6 and Figure 7**.

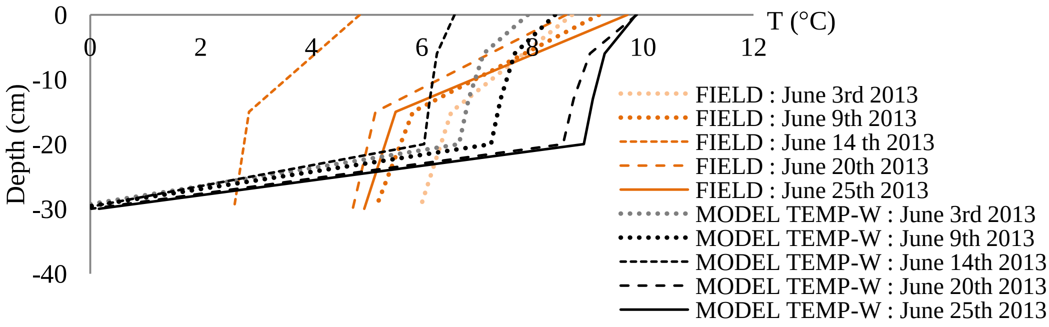

Figure 6 : Upstream June 2013, thermal regime under culvert

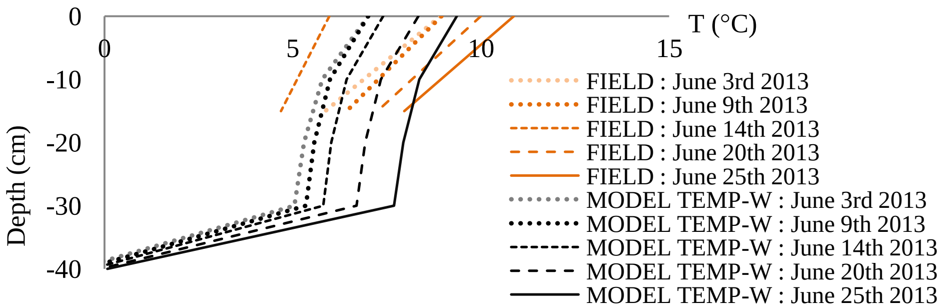

Figure 7 : Downstream June 2013, thermal regime under culvert

In **Figure 6 and Figure 7**, oranges lines represent temperatures measured on the field, and black lines represent temperatures obtained from the TEMP/W model. Downstream, the field temperatures available did not exceed 15 cm, while the upstream temperatures went up to 30 cm. June was only represented to give an example of the results. Only a few of the daily average temperatures have been shown so as not to overload the figure.

Surface temperatures were similar upstream and downstream with slight downstream cooling. The water had a tendency to cool when passing through the culvert since air temperatures and surrounding ground were colder and absorbed some of the heat from the water.

The effect of the insulation layer was not visible on the field data. Upstream, it is believed that the effect is hidden by water infiltration due to the holes made during probes installation. Downstream, the data temperature was not deep enough to be able to see the presence of the insulation.

5. Mathematical models

Statistical relationships are useful to establish a link between water temperatures in the culvert (T_{wp}), water flow (Q) and water temperatures at the entrance of the culvert (T_{wd}). After development of the relationship, it will be possible to vary the flow rate and water temperatures at the entrance of the culvert in the relationship obtained, thereby to provide a water temperature in the culvert to be applied to the model TEMP/W. Thus, it is possible to observe the effects of varying parameters on the thermal regime of the soil under the culvert.

The first step was to develop a relationship between water temperatures measured by the thermistor placed on the surface at the bottom of the culvert (T_{wp}) and water temperatures measured at the weir (T_{wd}). A weekly average of temperatures was made. A linear regression confirmed the relationship between T_{wp} and T_{wd} with a determination coefficient (R^2) equal to 0,69. **Figure 8** shows the relation.

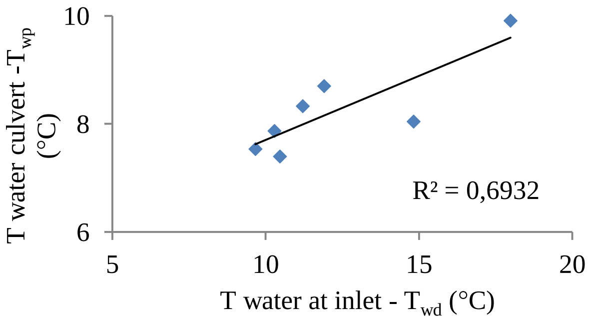

Figure 8 : Correlation between T_{wp} and T_{wd}

Following the same logic as described above, the second step consisted in finding a relation between T_{wp} and flow (Q). A weekly average of temperatures and of water flow was made. **Figure 9** shows a logarithmic relationship between T_{wp} and Q parameters. The determination coefficient (R^2) is equal to 0.56; this value is low. However, considering occasional rain events that do vary flow drastically for a short period, points of exceptional events can be extracted from the curve to obtain a stronger correlation coefficient.

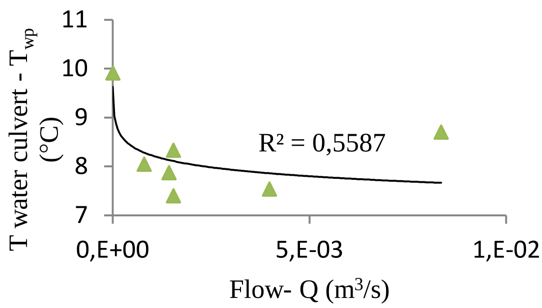

Figure 9 : Correlation between T_{wp} and Q

Flow values were transformed into logarithmic values in order to have a linear relationship between T_{wp} and Q and to do a multiple linear regression between three parameters: T_{wp}, T_{wd} and Q. This relationship has two dependant variables, T_{wd} and Q, two coefficients, X_1 and X_2, and a constant. The coefficient of multiple determinations is equal to 0,82. In addition, it is supported by 48 observations, reflecting a fairly robust correlation. T_{wp} is directly proportional to T_{wd} and logQ and is expressed by **equation 2**:

$$T_{wp} = 0.314\,T_{wd} + 0.05\log Q + 4.595 \qquad (2)$$

Where T_{wp} is water temperature in culvert in °C, T_{wd} is water temperature before entering in the culvert in °C, and Q is flow rate in m^3/s. **Figure 10** shows the validation of the empirical model.

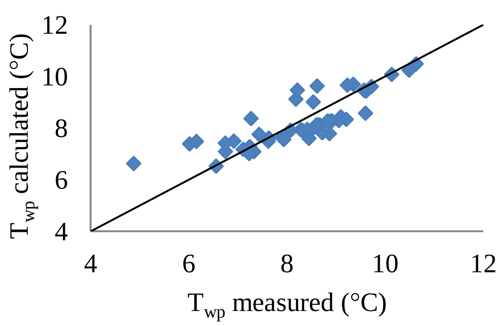

Figure 10 : Model's validation

6. Results

From **equation 2**, a change in the flow rate was imposed to obtain water temperatures in the culvert (T_{wp}). The new temperatures T_{wp} were inserted in TEMP/W model and the effects of these changes were observed. The flow rate decreased to 10 % and increased to 10 % from the values recorded on the field. **Table 2** shows these results.

Table 2 : Decrease and increase flow

Day	Q (cm^3/s) Field	T_{wp}(°C) Field	- 10% Q (cm^3/s)	T_{wp} (°C) Calculated	+ 10% Q (cm^3/s)	T_{wp} (°C) Calculated
May 27th	3183,93	7,22	2865,54	7,22	3502,33	7,23
June 3rd	3076,01	7,89	2768,41	7,88	3383,61	7,89
June 9th	2970,32	8,43	2673,28	8,42	3267,35	8,43
June 14th	3294,09	6,64	2964,68	6,64	3623,50	6,65
June 20th	3076,01	9,91	2768,41	9,91	3383,61	9,91
June 25th	3183,93	9,89	2865,54	9,88	3502,33	9,89
June 29th	3076,01	7,54	2768,41	7,54	3383,61	7,54
July 4th	3076,01	8,31	2768,41	8,31	3383,61	8,31
July 11th	2970,32	7,09	2673,28	7,09	3267,35	7,10

Values were inserted in TEMP/W and the results are presented on **Figure 11**. The following observations emerged: the variation of plus or minus 10% of water flow had no impact on the thermal regime underneath the culvert.

Water temperatures at inlet decreased to 10% and increased to 10%. By inserting these new values in relation 2, new T_{wp} values were calculated and are shown in **Erreur ! Source du renvoi introuvable.**.

Table 3: Decrease and increase Twd

Day	Twd (°C) Field	T_{wp}(°C) Field	- 10% T_{wd}(°C)	T_{wp}(°C)	+ 10% T_{wp}(°C)	T_{wp} (°C)
May 27th	8,80	7,22	7,92	6,95	9,68	7,50
June 3rd	7,89	7,89	9,82	7,54	12,00	8,23
June 9th	12,64	8,43	11,38	8,03	13,91	8,82
June 14th	6,96	6,64	6,26	6,43	7,66	6,86
June 20th	17,37	9,91	15,63	9,36	19,11	10,45
June 25th	17,30	9,89	15,57	9,34	19,03	10,43
June 29th	9,83	7,54	8,84	7,23	10,81	7,85
July 4th	12,29	8,31	11,06	7,93	13,51	8,70
July 11th	8,40	7,09	7,56	6,83	9,24	7,36

The variation of plus or minus 10% of T_{wd} had a slight influence on the thermal regime of the soil under the culvert. The values were inserted in TEMP/W, and the results are presented in **Figure 11**.
Increasing T_{wd} caused a slight warming and decreasing T_{wd} caused a slight cooling.

Finally the last simulation with TEMP/W was conducted without insulation. The importance of insulating the culvert is significant. As presented in **Figure 11**, the thaw depth is about 30cm with insulation, and about 120cm without insulation.

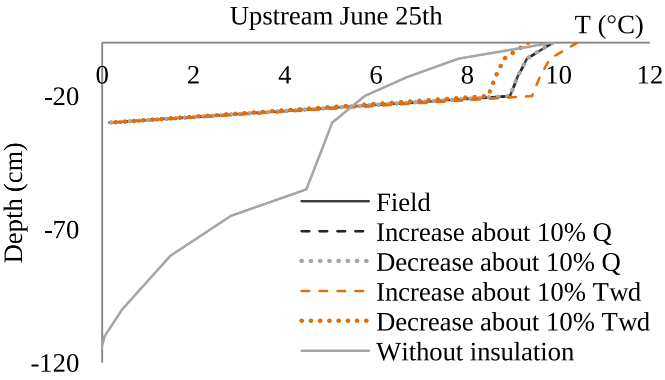

Figure 11 : All simulations

7. Discussion and Conclusions

A culvert on Alaska Highway in Yukon, Canada, was instrumented. Temperatures for the soil under the culvert upstream and downstream, for the flow, and for the water at the entrance and inside of the culvert were measured. A 2D model of TEMP/W was successfully completed. The model was calibrated from field observations available from 2011 for the model without a culvert and from May 24, 2013 to July 11, 2013 for the model with a culvert. By integrating the culvert in the ground on the TEMP/W model, the soil temperatures tended to warm during summer and cool during winter. A mathematical model was established between the water temperatures in the culvert (T_{wp}), the water temperatures at the entrance (T_{wd}), and the water flow (Q). This model showed a strong correlation. From this linear relation, a change in the flow rate and T_{wd} was made and new values of T_{wp} were calculated. The new temperatures were returned to the TEMP/W model and the following observations emerged from those variations:

- The variation of plus or minus 10 % of the flow has no impact on the thermal regime under the insulated culvert.
- The variation of plus or minus 10 % of the water temperature at the entrance of the culvert has a slight influence on the thermal regime.
- Increasing the temperature causes a slight warming, and decreasing the temperature causes a slight cooling.

Finally, a last simulation without insulation was made. The importance of isolating the culvert was clearly visible; the thaw depth with insulation is about 30 cm and about 120 cm without insulation.

Acknowledgements

The authors would like to thank the reviewers for their suggestions, and Transport Canada for their financial support. Thanks to Yukon and Public Works for their support, logistics and assistance during the instrumentation at Beaver Creek Culvert as well as for the information provided regarding the rules of construction for culverts in Yukon. Finally, the authors thank the research team and Arquluk students who were a great help for instrumentation and for the successful completion of this project.

REFERENCES

M-Lepage, J., 2012 *Thermal performance of the Permafrost Protection Techniques at Beaver Creek Experimental Road Site, Yukon, Canada*, 10th International Conference on Permafrost, Russie.

De Grandpré, I., 2011. Impact de l'écoulement souterrain sur la dégradation du pergélisol, mémoire de maitrise, Université de Montréal, p.102.

McGregor R., Doré G., Hayley D., Wilkins G., Hoeve E., Grozic E., Roujanski V., Jansen A., 2010. *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions*, Transportation Association of Canada. 177p.

Zhang, X., et Wang X., 2007. *Impact of Railway Culvert Construction on the Ground Temperature of Foundation Soil in Permafrost Regions*, Central South University, Chine.

Côté, J., Konrad, J.M, 2005. *Thermal conductivity of base-course materials*, Revue canadienne de géotechnique, 2005, p61-78.

Van Everdingen, R., 2005 *Multi-language glossary of permafrost and related ground-ice terms*, National Snow ans Ice Data Center/World Data center for Glaciology.

Achour, B., Bouziane, T., Nebbar, K., 2003. *Débitmètre triangulaire à paroi épaisse dans un canal rectangulaire*, Larhyss Journal, Algérie, ISSN 1112-3680 n° 02, p. 14.

Junikis, A.R., *The soil-culvert-temperature-system upon freezing*, Symponium on Frost Action on Roads, Paris, *1973* , p. 235-248.