Impacts of lateral and vertical heat transfers associated with subsurface water flow on the thermal regime of road embankment subbase and subgrade

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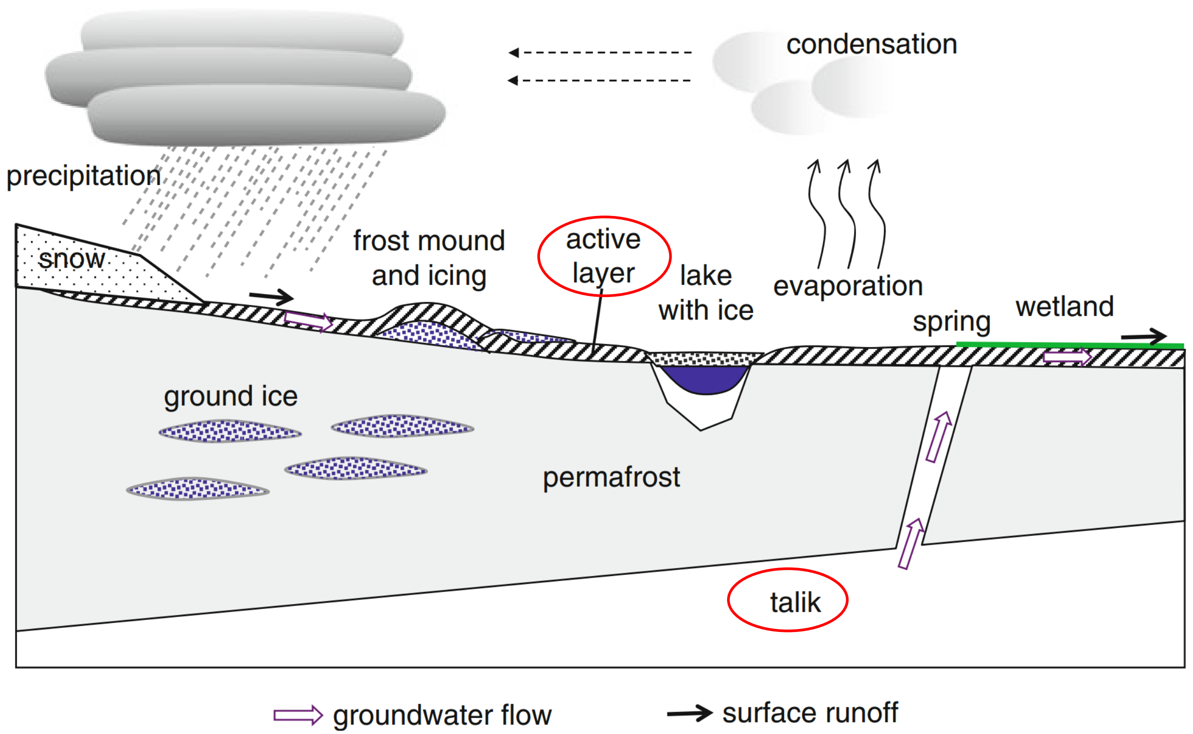
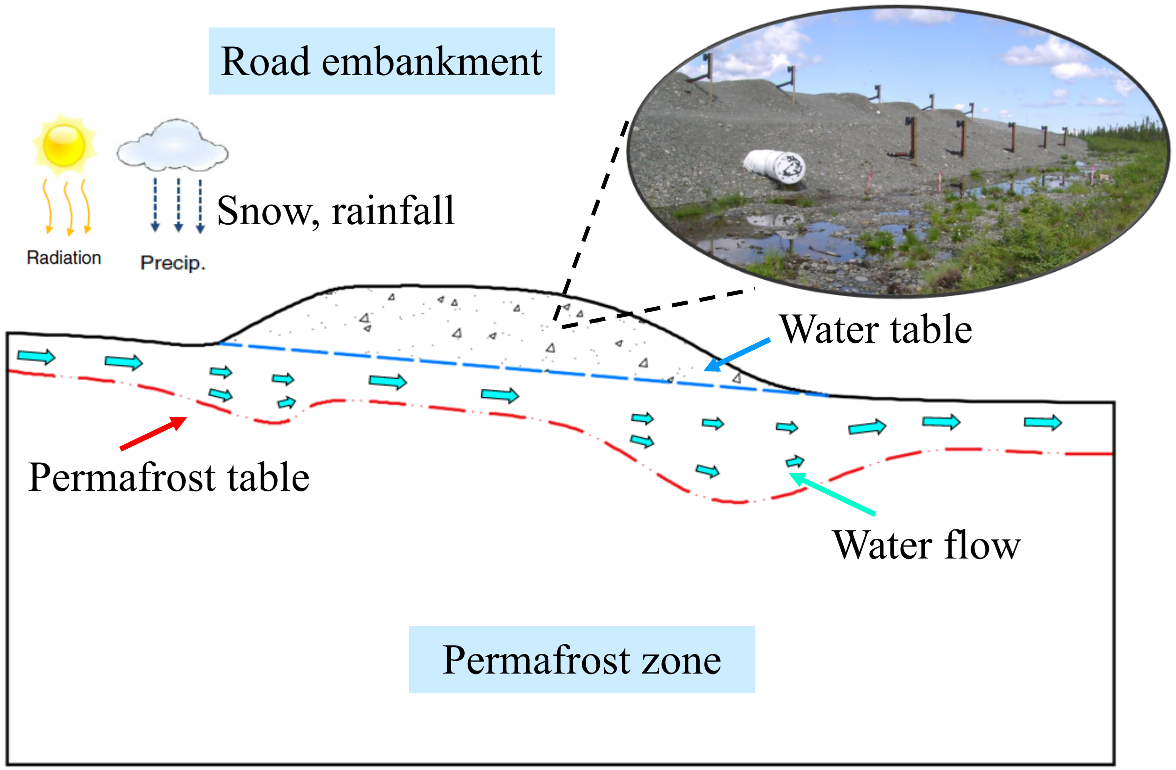
1 Introduction



(Modified from Woo 2012)



Convective heat transfer, including **precipitation infiltration, evaporation, and groundwater flow**, can transport mass (water and water vapor) and energy (sensible and latent heat). Moreover, the interaction between transportation infrastructure and the underlying permafrost is more complicated.

2 Study site & Methods

Figure. Water ponding on the uphill side of the Alaska Highway embankment, near Beaver Creek (Photography courtesy of D. Fortier).

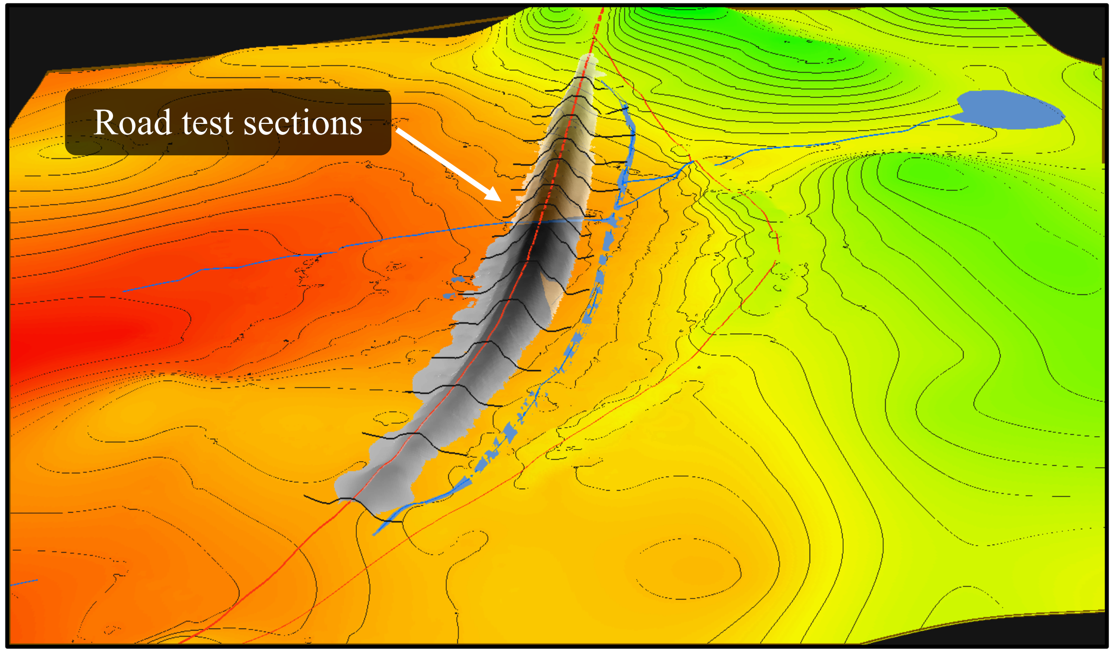


Figure. Digital elevation model of Alaska Highway embankment (made by M. Sliger).

- **Long-term field observation**
  - Climate data (air temperature, precipitation, and wind)
  - Ground temperature variations
  - Seasonal groundwater elevation variations
- **Physical model**
- **Fully-coupled heat and water transfer model**
  - Impacts of surface water infiltration on the thermal regime of permafrost
  - Impacts of groundwater flow on the thermal stability of transportation infrastructure

3 Results

- ❑ **Influence of snowmelt water infiltration**
- ❑ Influence of rainfall infiltration
- ❑ Influence of groundwater flow

3.1 Impacts of convective heat transfer linked with snowmelt water infiltration

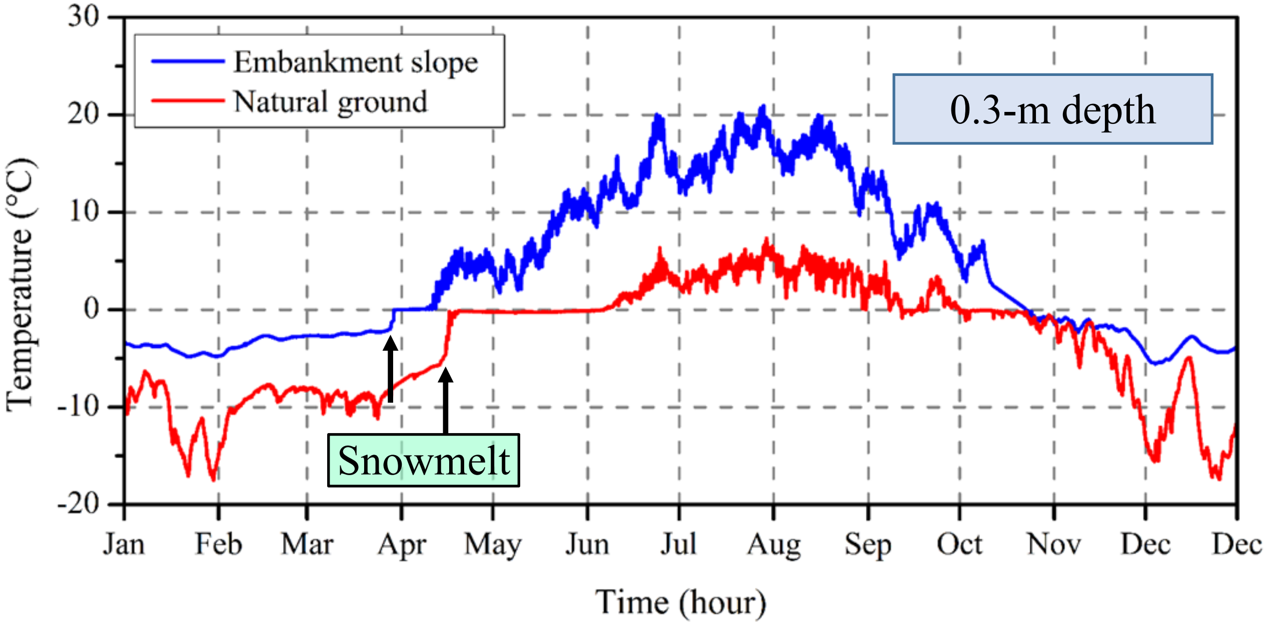


Figure. Temperature variation at depths of 0.3 m under the embankment slope and the natural ground in 2012.

Table. Heat influence depth at the different surface situations from 2009 to 2015

	Heat influence depth (m)	Heat influence amplitude (°C)	Duration of zero curtain effect (days)
Natural ground	**1.1**	**3.9-7.0**	**29-51**
Bare surface embankment	3.6	5.1-6.2	7-14
Uncovered rock layer embankment	3.2	9.0-10.5	5-10
Snow plow embankment	1.3-2.0	2.0-6.5	2-7
Grass cover embankment	2.0	3.0-4.4	22-32

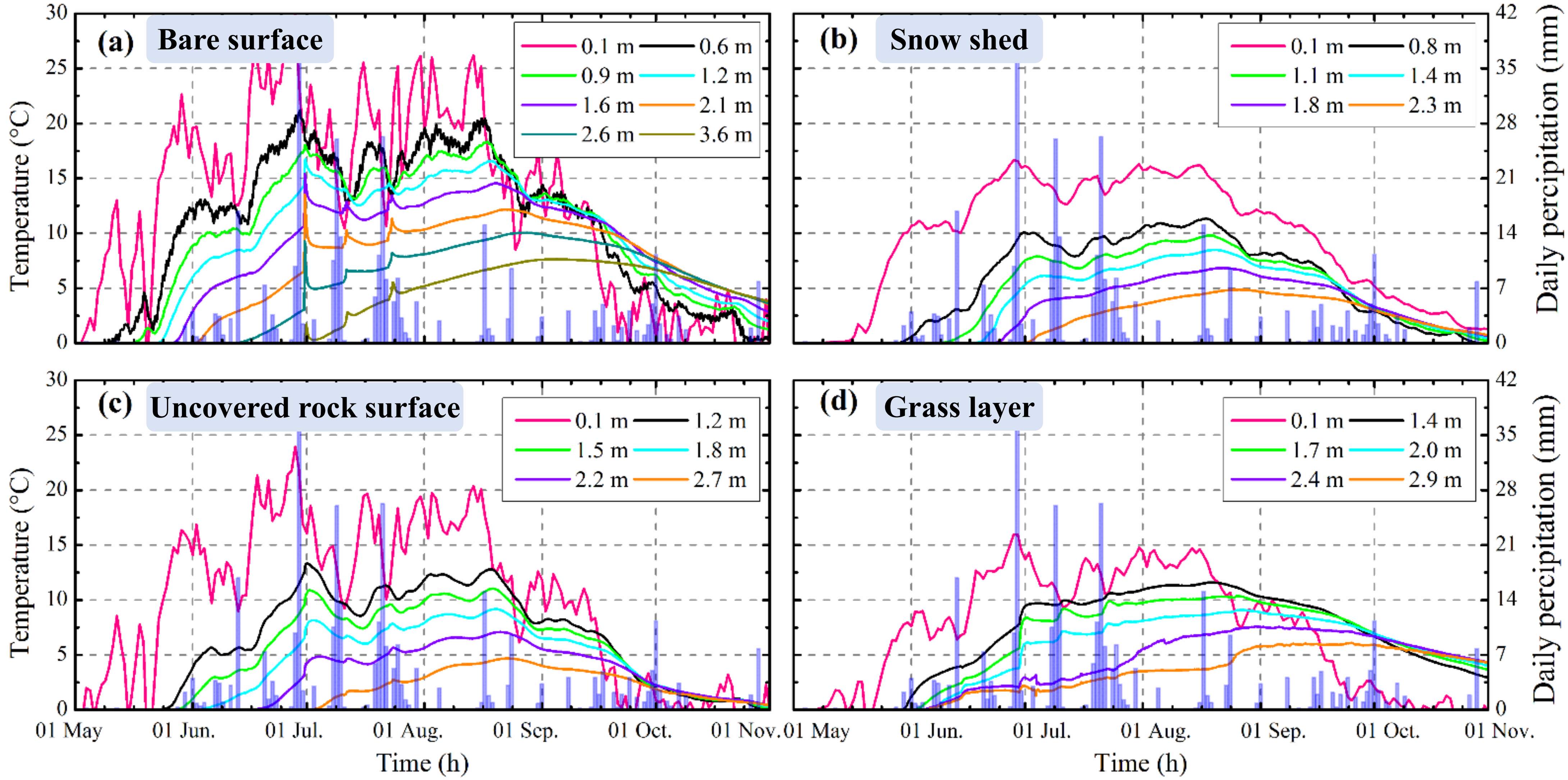
❖ **Impact factors of heat influencing depth and magnitude:**

- Embankment materials thickness and type
- Surface cover conditions
- Air temperature rising rate
- Snow thickness
- Thermal regimes of embankment (the cooling effect of mitigation techniques)
- Soil moisture (dry & wet)

3 Results

- ❑ Influence of snowmelt water infiltration
- ❑ **Influence of rainfall infiltration**
- ❑ Influence of groundwater flow

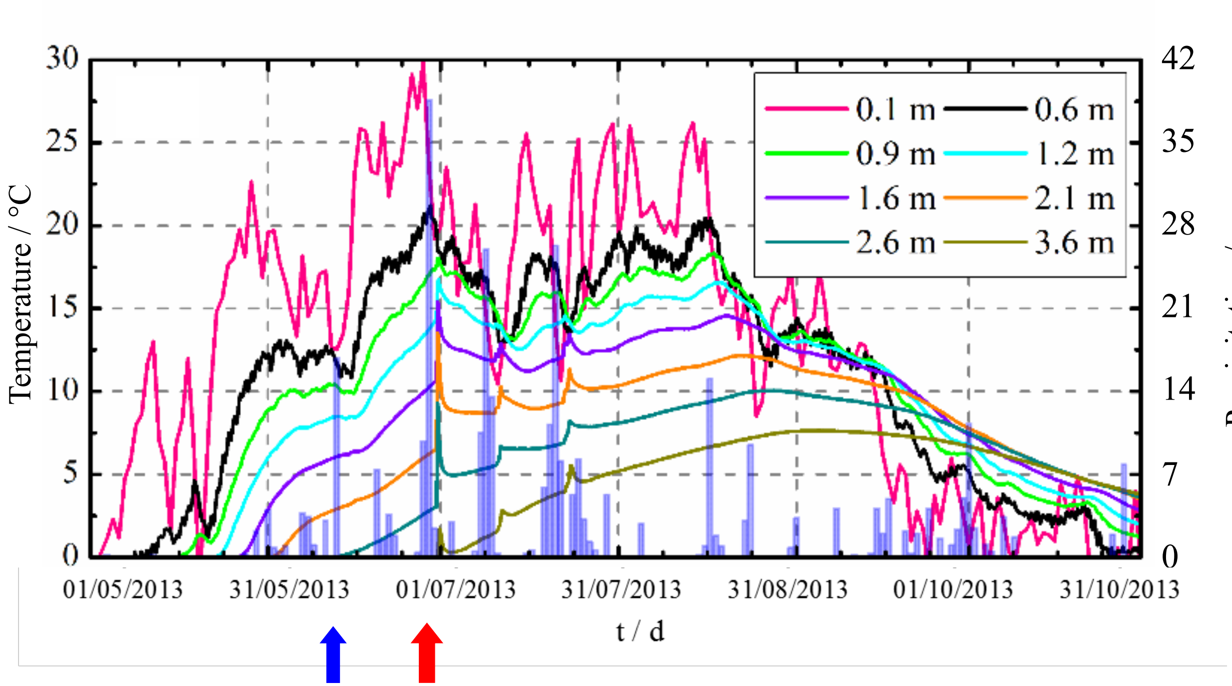
3.2 Impacts of convective heat transfer linked with rainfall water infiltration



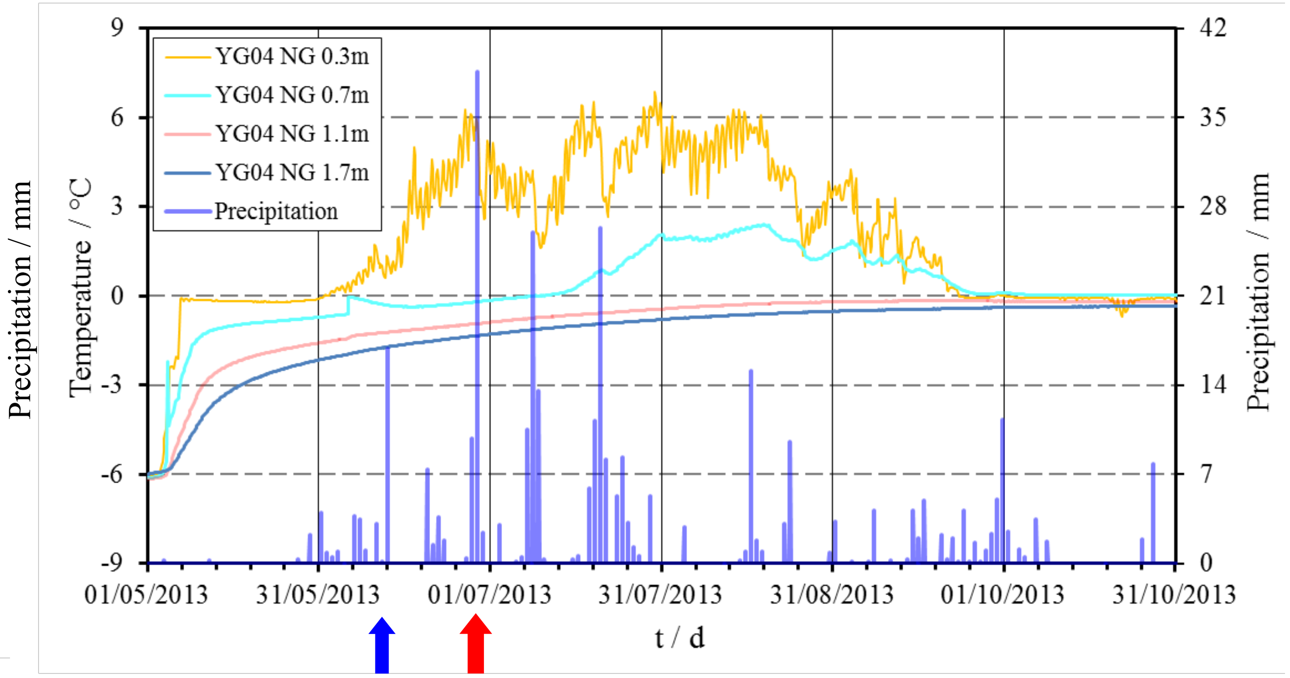
The heat influencing depth and magnitude is strongly associated to **rainfall intensity and duration**, **thickness and type of embankment materials**, **embankment thermal regim**e and **surface cover conditions**.

3.2 Impacts of convective heat transfer linked with rainfall water infiltration

Embankment



Natural ground



- **Influence of slight/intense rainfall event**
  - **Light and individual rainfall events (12 mm on 13 June)**

  The soil temperatures at the depth of **0.1 m** decrease by **5 °C**, while the temperatures at **1.2-m** depth remain stable.

  - **Intense and consecutive rainfall events (50.8 mm in 28-30 June)**

  The soil temperatures at depth of **2.6 m** rise by **6 °C.**
- **The impact of rainfall water infiltration on natural ground is smaller.**

3 Results

- ❑ Influence of snowmelt water infiltration
- ❑ Influence of rainfall infiltration
- ❑ **Influence of groundwater flow**

3.3 Impacts of convective heat transfer linked with groundwater flow

- The step temperature increase is related to the movement of groundwater.
- Lateral water flow in the active layer triggers convective heat transfers.
- The temperature increasing rates linked with subsurface water flow is 1 to 2 order of magnitude over typical values induced by pure conduction.

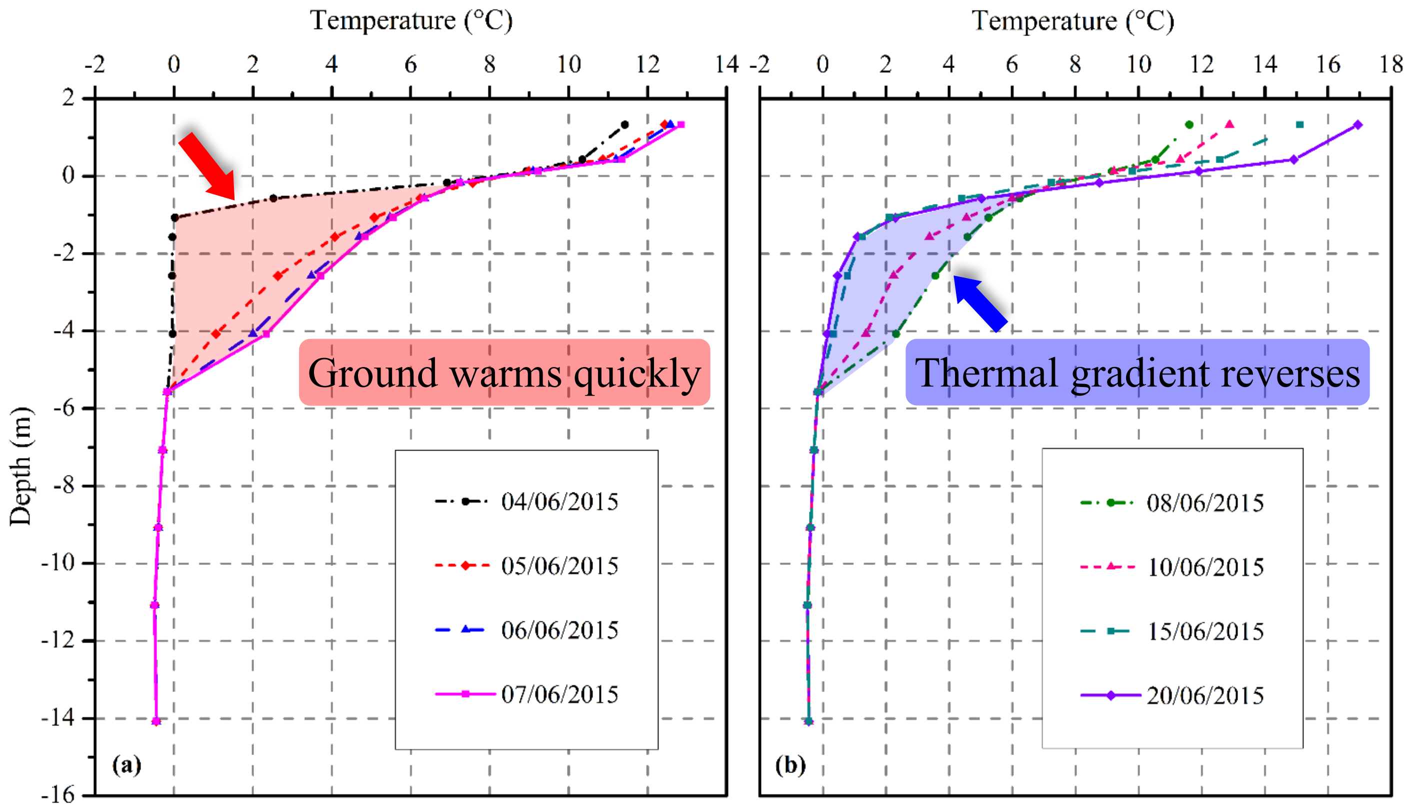


Figure. Variation of temperatures with depth at the slope of the embankments

Table. The daily temperature increasing rates

Depth (m)	Smooth temperature increasing rates (°C/d)*	Maximum step temperature increasing rates (°C/d)	Ratios
0.1	0.239	0.06	0
-0.2	0.098	0.64	7
-0.6	**0.023**	**3.72**	**162**
-1.1	**0.023**	**5.05**	**220**
-1.6	**0.028**	**4.11**	**147**
-2.6	**0.030**	**2.68**	**89**
-4.1	**0.019**	**1.09**	**57**
-5.6	0.010	0.01	1
-7.1	0.014	0.00	0

Note: The smooth temperature increasing rates were calculated without taking into consideration the period from 4th to 20th June, 2015.

3.4 Thermal regime dynamics of the embankment subbase and subgrade

- Lateral heat flow accelerates discontinuous permafrost thaw and promotes the development of talik.
- The depth of permafrost table increased from 4.0 m to 4.7 m, at a thaw rate of **0.1 m·year^{-1}**.
- The significant increasing rate is induced by the vertical and lateral heat transfer, clearly associated with snowmelt water, rainfall water infiltration, and shallow groundwater flow.

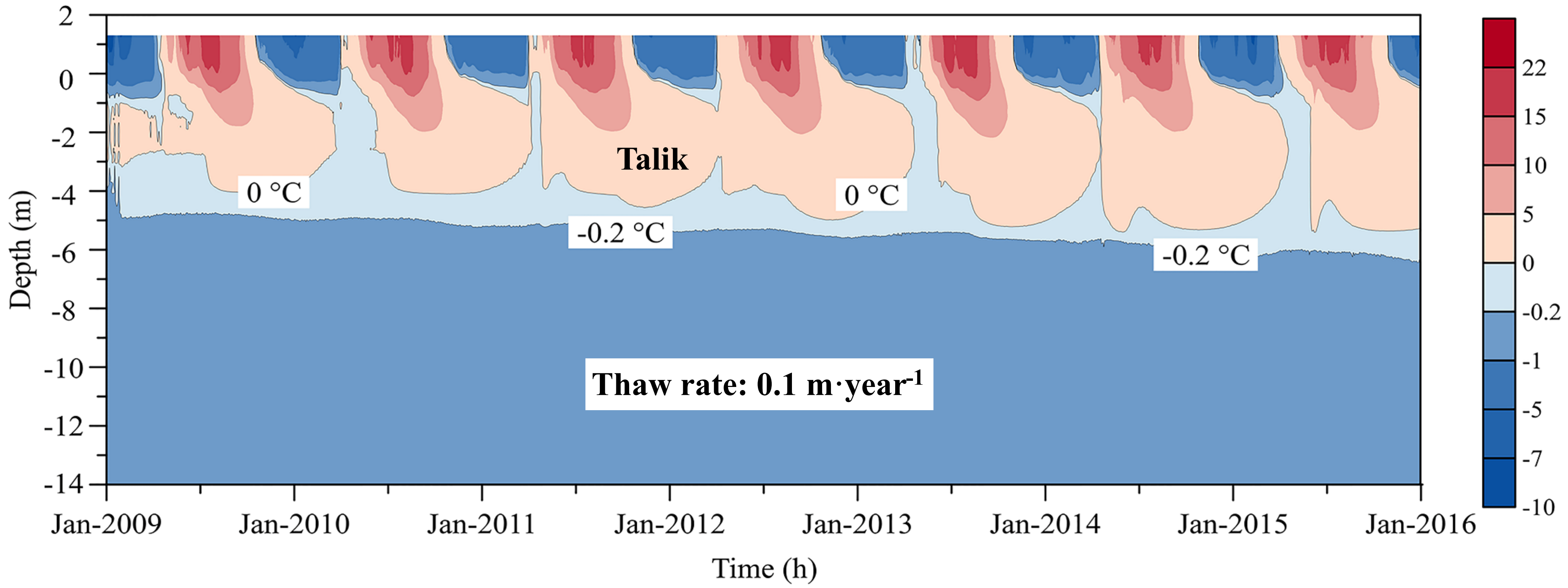


Figure. Annual freezing-thawing process beneath the embankment slope from 2009 to 2015.

4 Conclusion

Infiltration of snowmelt water and rainfall has a limited impact on the thickness of active layer. While, the groundwater flow can accelerate permafrost thawing and promote the development of talik.

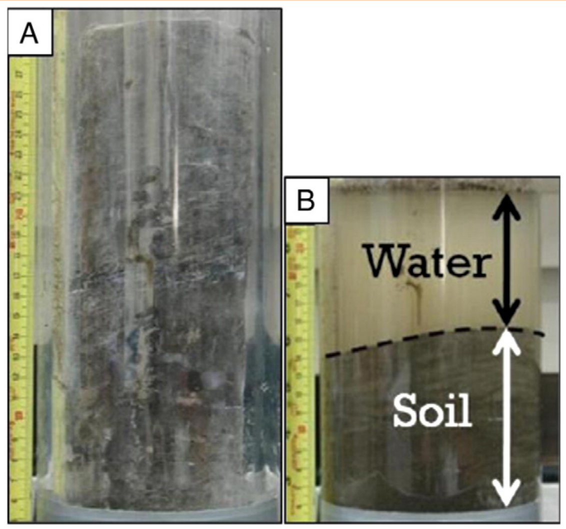
Table. The relative importance of surface water infiltration and groundwater flow

Water flow	Relative importance				Resources
	Rate and magnitude	**Infiltration rate**	**Heat influence depth**	**Duration**	
Meltwater penetration (unsaturated/saturated zone)	**several degree in several hours** **Maximum: 1.3 °C/hour**	**0.1×10^{-2} m/h**	**0.3-1 m** (natural ground) **2-3 m** (road embankment)	**several days** (until basal ice began to form)	Kane et al., 1991, 1989; Woo 2012; Hinkel and Nelson 2003; Ishikawa, et al., 2006; **Beaver Creek**.
Rainfall infiltration (unsaturated/saturated zone)	**several degree (1-7 °C) in several hours** **Maximum: 1.8 °C/hour**	**10^{-2} - 10^{-1} m/h** (intense rain)	**0.3-1 m** (natural ground) **2-3 m** (road embankment)	**several days** (determined by **light/intense** rainfall event)	Hinkel et al., 1997, 1994; Kane et al., 1991, 1989; Dunne, et al. 1991; **Beaver Creek.**
Groundwater flow (saturated zone)	**several degree (1-6 °C) per day** **Maximum: 0.7 °C/hour**	**0.1-3 m/day** (silt, gravel) **1-10^2 m/day** (organic material)	**3-5 m** (depend on thickness of active layer and talik)	**thaw season,** or **whole year** (unfrozen zone)	McKenzie et al., 2007; Bense et al., 2009; Jiang et al., 2012; Kurylyk et al., 2016; **Beaver Creek.**

4 Conclusion

Permafrost thawing/warming:

- **Climate warming**
- **Groundwater flow**



Frozen core Thaw core

(Modified from Stephani et al., 2010)

Melting ground ice
Thaw consolidation

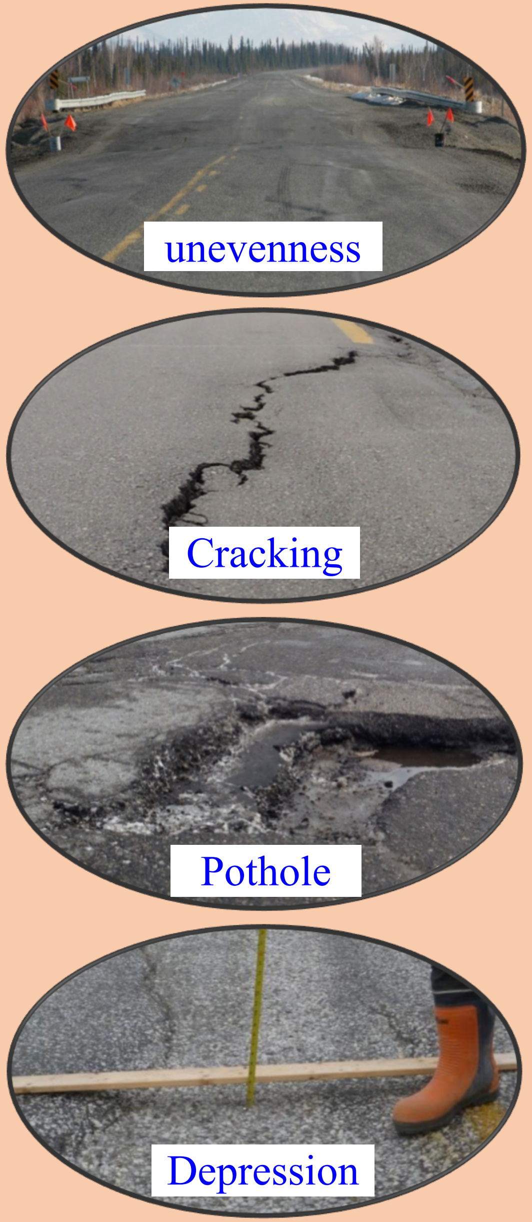


Figure. Embankment deformation due to permafrost degradation. (Photograph courtesy of D. Fortier)

Thank you for your attention!