# Reclamation of material sites in continuous permafrost of Alaska: an example of groundwater flow between pits

Eva Stephani, Mark Musial & Steve Anderson
*Golder Associates, Anchorage, Alaska, USA*

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
Development of material sites in northern Alaska can result in multiple pits separated by buffer zones with some pits partially filled with water as they are reclaimed. This common reclamation concept relies on cold frozen ground to prevent hydraulic connection between the pits. However, mining operations and the presence of water bodies that do not entirely freeze in winter can trigger changes in the thermal regime. As a result, groundwater flow paths can develop in the buffer zone separating the former and active pits. This paper presents a case study example where groundwater flow through a buffer zone separating a pit in reclamation and an active pit was assessed using a combination of geophysical methods and borehole data. Preliminary review of the instrument data results suggest that the reclamation concept, which allows pits to be filled with surface water while adjacent pits are still active, should be assessed and possibly modified.

RÉSUMÉ
L'exploitation de matériaux granulaires dans le nord de l'Alaska peut résulter en une multitude de fossés séparés par des bermes, incluant certains fossés partiellement remplis d'eau lorsqu'ils sont au stade de réclamation. Un concept de réclamation couramment adopté est basé sur l'hypothèse que le pergélisol froid constitue une barrière imperméable entre les fossés. Toutefois, les opérations minières et la présence d'eau de surface qui ne gèle par entièrement en hiver peuvent entrainer un impact sur le régime thermique. Un écoulement d'eau souterraine peut ainsi se développer dans les bermes. Cet article présente un exemple d'écoulement d'eau souterraine à travers une berme qui a été étudiée à l'aide de méthodes géophysiques et de données de forages. Les résultats préliminaires suggèrent que le concept de réclamation permettant de remplir partiellement un fossé, tandis qu'un fossé adjacent est en opération, devrait faire l'objet d'études additionnelles et possiblement être modifié.

## 1 INTRODUCTION

Occurrence of groundwater in permafrost regions is typically categorized as supra- (above), intra- (within), or subpermafrost (below) (Tolstikhin and Tolstikhin 1976). In areas of cold and continuous permafrost, such as on the North Slope of Alaska, groundwater is typically limited although it can be present in open, closed, or isolated taliks. For instance, groundwater can be found in open or closed taliks underlying surface water bodies that do not entirely freeze in winter time (Woo 2012). In the Colville River Delta (North Slope, Alaska), taliks will typically develop underneath surface water bodies that have a depth greater than about 2 meters (Walker 1983). In open-taliks located below deep surface water bodies, the intra-permafrost groundwater can be connected to sub-permafrost groundwater. Springs are another example of intra-permafrost groundwater connected to sub-permafrost groundwater. Many springs discharging on the North Slope of Alaska have been identified in the eastern part of the region, while very few were identified in the western part (Kane et al. 2013). Groundwater can also be found where high pore water salinity of soils decreases the freezing point of water, such as was observed in an isolated talik along the Sagavanirktok River (North Slope, Alaska) (Sherman 1973).

Development of material sites in areas of cold and continuous permafrost can result in multiple pits separated by buffer zones. One of the pit reclamation concepts implemented on the North Slope of Alaska often includes a lake developed in the former pit along with a zone refilled with soils (spoil pile) where vegetation is allowed to grow and create wetlands. The historic pit reclamation process can start while the adjacent pits are still actively mined. In such situations, the reclaimed pits are sometimes allowed to gradually fill with water that is naturally draining from adjacent terrain. The common reclamation concept adopted on the North Slope is that the cold temperatures of the frozen ground prevent a hydraulic connection between the pit in reclamation and any adjacent active pits.

This paper presents a case study example at a material site on the North Slope where potential groundwater flow through a buffer zone separating a pit in reclamation and an active pit was assessed using a combination of geophysical methods and borehole data. This case study example aims to provide preliminary data that can be used to manage pit reclamation in areas of cold and continuous permafrost.

## 2 STUDY SITE

The study site is located on the coastal plain of Alaska between the Colville River and Kuparuk River. It is comprised in the continuous zone of permafrost where ground temperatures at the depth of zero annual amplitude reaches about −9°C (Jorgenson et al. 2008). The mean (1981-2010) annual air temperature (MAAT) measured at a nearby site (Prudhoe Bay) is −11.1°C (Alaska Climate Research Center 2015).

The study site consists of two mining pits: one active (Cell B) and one in the process of reclamation (Cell A) (Figure 1). These two pits are separated by a buffer zone generally composed of in-situ material, but also includes an upper portion composed of reworked material to an unknown depth. The western edge of Cell A and the eastern and northern edges of Cell B intersect old drained lake basins. Few small size (< 50-m diameter) lakes were observed in the vicinity of the buffer zone on historical aerial imagery from 1980 (prior to mine development). There is no known spring occurrence in this area (Kane et al. 2013).

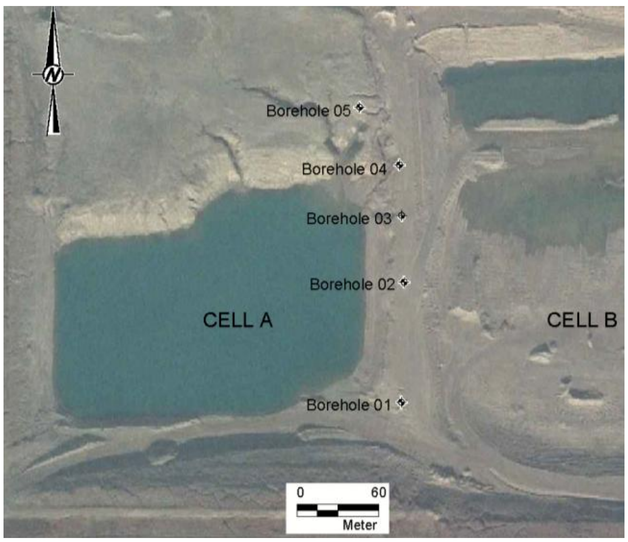



Figure 1. Boreholes Location (Satellite Imagery from Google Earth, September 2009)

The original size of Cell A was about 285 m by 200 m. The northern part of Cell A was refilled with mining soils and is covered by tundra vegetation in an early growth stage. This northern part of Cell A is also characterized by the presence of gullies (up to about 1.5 m deep) in the spoil pile that drain into Cell A. This natural runoff drainage has been allowed to partially fill Cell A with water. When groundwater flow appeared in the adjacent Cell B, ponded water was pumped out of Cell A. However, there is no record of the maximum pond water level in Cell A prior to pumping or how long the Cell A pond was maintained before it was pumped out.

At the time of this study, the buffer zone separating Cells A and B was about 24 m high and about 130 m wide at its widest part (bottom). The buffer zone had two levels: a lower level at about 14 m high that included a driving surface, and a top level that was less than about 7 m wide. Vegetation was absent on most of the buffer zone, except on the top level that had a thin vegetation cover at an early growth stage.

# 3 METHODOLOGY

## 3.1 Drilling and Soil Sampling

The field program was conducted in early September 2014. After completing a site reconnaissance to identify areas of seepage and other signs of permafrost degradation, five boreholes were drilled along the buffer zone between Cells A and B. This included four boreholes about 60 feet deep on the driving surface of the buffer zone (Boreholes 01 to 04), and one borehole about 70 feet deep on the top part of the buffer zone (Borehole 05) (Figure 1).

The boreholes were advanced using a track-mounted Geoprobe 8040DT drill rig with a 194-mm outside diameter (OD) hollow-stem auger. Samples were collected with a 89-mm inside diameter (ID) continuous-core sampler as the borehole was advanced. This technique allowed for recovery of moderately disturbed material and observation of ice bonding and cryostructure.

The soils observed were described according to the Unified Soils Classification System (USCS). The frozen soil characteristics were classified according to American Society for Testing and Materials (ASTM) D4083 (2007) method for frozen soil classification as well as described in terms of cryostructure assemblages. Representative portions of the recovered soil samples were double sealed in bags to retain moisture content and shipped in an unfrozen state to Golder's Anchorage Geotechnical Laboratory for testing to verify field soil classifications and to select samples for further laboratory testing.

Laboratory testing procedures were conducted in accordance with ASTM methods to determine the soil index properties. Laboratory testing on select soil samples included: soil moisture content as percentage of dry weight (ASTM D2216, 2010); pore water salinity based on conductivity (industry standards); grain size analysis (ASTM C136, 2006 and ASTM D422, 2007); organic content by ignition (ASTM D2974, 2013); plasticity index (ASTM D4318, 2010); and U.S. Number 200 Sieve Wash (ASTM C117, 2013).

## 3.2 Monitoring Instrumentation

Two standpipes were installed in each borehole for monitoring instrumentation. Each installation consisted of a closed-end 25-mm diameter polyvinyl chloride (PVC) solid standpipe used to house a temperature acquisition cable (TAC) manufactured by BeadedStream LLC, and a closed-end 25-mm diameter PVC slotted standpipe piezometer to facilitate periodic groundwater level measurements. The annular space between the borehole and the PVC standpipe was backfilled with cuttings or imported sand to approximately 1.2 m below grade. Bentonite chips were used to provide a seal from 1.2 m below grade to the ground surface.

3.2.1 Ground Temperature Measurements

Ground temperatures were measured twice a day to an accuracy of ±0.1°C using the TACs that were fabricated with measurement nodes at 0.9 m intervals to a depth 4.5 m, and at 1.5-m intervals thereafter to the bottom of the cable. Recorded data were transmitted daily via satellite following installation to a secured website. At the time of this paper publication, the ground temperature monitoring program is still underway.

3.2.2 Surface Water and Groundwater Measurements

Groundwater levels were measured during drilling operations and again a few days later after drilling completion and installation of the piezometer standpipes. During drilling operations groundwater levels were measured in the hollow-stem augers. Groundwater levels were measured in the piezometers after drilling completion. Measurements were taken using an electronic water level sounder. The surface water level in Cell A was surveyed on September 3, 2014 during our field program.

3.3 Geophysical Surveys

Geophysical surveys were conducted along the boreholes alignment and concurrently to the drilling operations to assess the location and depth of potential groundwater pathways connecting Cells A and B. The geophysical methods used included electrical resistivity imaging (ERI). By performing this investigation concurrently with the drilling operation it allowed for adjustment of the boreholes locations to target specific zones identified in the geophysical preliminary results, as well as providing data to ground-truth the geophysical survey interpretation.

ERI data collection required minimal surface disturbance by pounding stainless steel electrodes into the surface. Apparent resistivity measurements were obtained with an IRIS Instruments Syscal Pro96 Switch engineering resistivity meter operating 84 electrodes arranged in a dipole-dipole electrode configuration. Stainless steel electrodes were driven into the soil between 130 and 250 mm deep at each electrode station. The ERI acquisition parameters included a spacing of 3 meters, 400 volts, 2 to 6 readings per measurement, and a 0.5 second cycle time. ERI data collection was completed in accordance with ASTM International D6431 (2010).

4 RESULTS

4.1 Site Observations

During the field assessment, most gullies located on the northern part of Cell A were filled with water draining into this former pit. Few signs of potential permafrost degradation and water seepage were observed during the field program. Water seepage was observed entering at the bottom of Cell B, near the buffer zone, after surface grading by machinery. Also, a settlement area about 0.3 m deep developed on the lower level of the buffer zone between Boreholes 03 and 04 during the drilling operations (Figure 2).

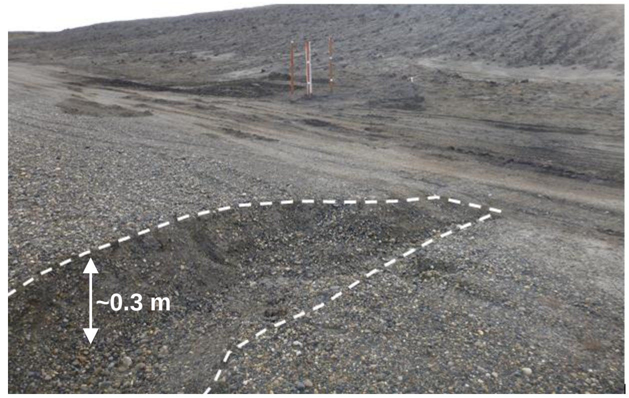



Figure 2. Dotted line indicates settlement area developed between Boreholes 3 and 4 during drilling operations on the buffer zone separating Cells A and B

4.2 Soil Stratigraphy and Geotechnical Properties

The ground surface at each borehole was composed of mineral material without an organic cover, except at Borehole 05 that had a thin organic cover. The soils observed in all boreholes were mainly composed of gravelly and sandy soil, although silty sand characterized the upper 11 m of Borehole 05. Some layers of clay and silty sand were also observed in the bottom part of various boreholes. The volumetric ice content of frozen sandy and gravelly soil evaluated in the field reached values up to 50 percent. Poorly bonded frozen soils were observed in the upper part of the Boreholes 01 to 04. Some layers at depth were also poorly bonded in Boreholes 03 and 04. A thin layer of unfrozen silty sand soil was observed at depth in Borehole 03. Moisture content of the few fine-grained soils encountered reached 99 percent by weight; however, most gravelly and sandy soils were typically characterized by moisture content in the 3 to 29 percent by weight range. The dominant cryostructure observed on site was composed of interstitial ice.

Soil pore water salinity values indicated that fresh to brackish water was present at most locations and elevations. Most soil pore water salinity values ranged between 1 to 4 parts per thousand (ppt) with a few values non-detect and up to 10 ppt.

4.3 Surface Water and Groundwater

The surface water elevation in Cell A was 10 m below sea level (b.s.l.). Given that Cell A was excavated to an elevation of about 14 m b.s.l. in 2004, the new lake developed in the former pit was about 4 m deep at the time of the field program.

Groundwater was observed during drilling operations only in Borehole 03. After drilling completion, groundwater was only observed in the piezometers installed in Boreholes 03 and 04. The groundwater levels measured in Boreholes 03 and 04 were 10.4 and 7.4 m b.s.l., respectively.

### 4.4 Ground Temperatures

Ground temperatures measured in Boreholes 01, 02, and 05 were similar and represented the coldest temperatures measured on site (Figure 3). The maximum thaw depth measured in these boreholes ranged from approximately 1.0 to 1.7 m below ground surface (bgs). Temperatures at depth ranged between about −5°C and −7°C. Ground temperatures measured in Borehole 04 below the active layer were warmer, although they remained under 0°C. At depths, ground temperatures reached about −3°C in Borehole 04, while the maximum thaw depth was about 2.3 m bgs. The depth of zero annual amplitude was below the bottom of Boreholes 01, 02, 04, and 05.

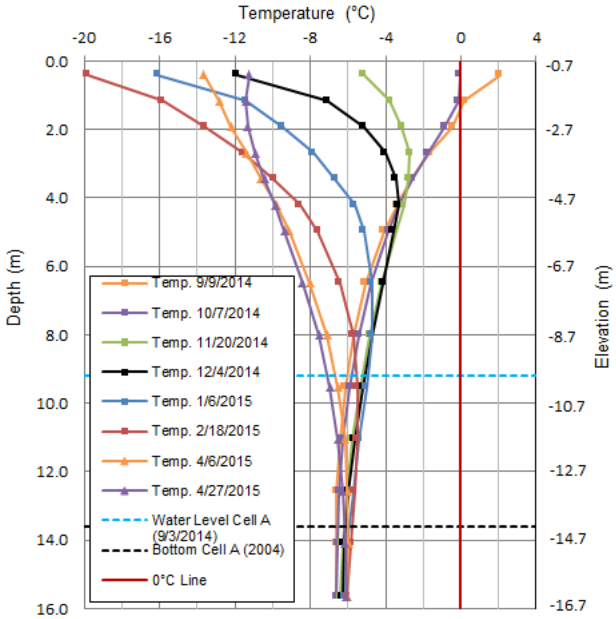



Figure 3. Example of ground temperatures in Borehole 01

The maximum thaw depth measured in Borehole 03 was about 3.7 m bgs, which was deeper than the other boreholes. Ground temperatures in Borehole 03 were also significantly warmer than in other boreholes. Borehole 3 included an unfrozen zone (talik) at depth, although the temperatures in this zone were at or slightly above about 0°C (Figure 4). The warmest ground temperatures measured below the active layer and above the talik zone in Borehole 03 during the monitoring period were slightly below 0°C. A cooling trend of ground temperatures with depth was observed below the talik, although the coldest temperature reached at the bottom of the borehole was about −1.0°C. The talik extended from a depth of about 10.7 to 14.3 m bgs, which corresponded to the approximate depth of the bottom of Cell A filled with surface water. The temperatures in the talik zone decreased slightly during the fall season, although the freezing front from the surface had not yet reached the talik depth. The near-isothermal conditions were maintained during the entire preliminary monitoring period from September 2014 to April 2015 (monitoring is still in progress at the time of this paper publication).

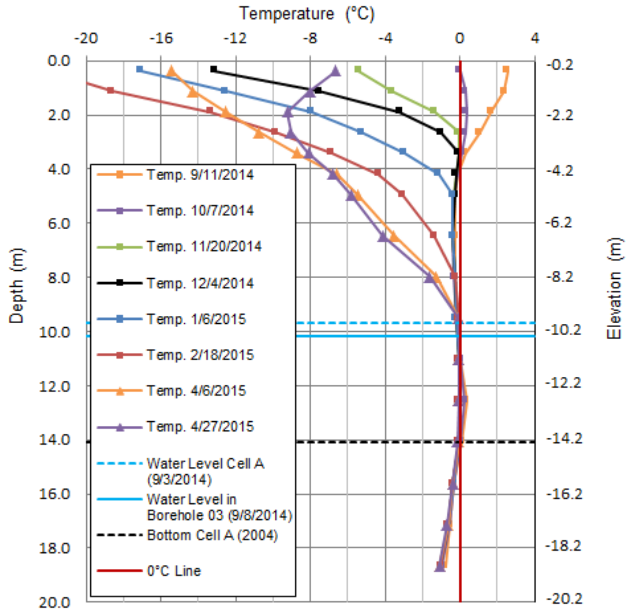


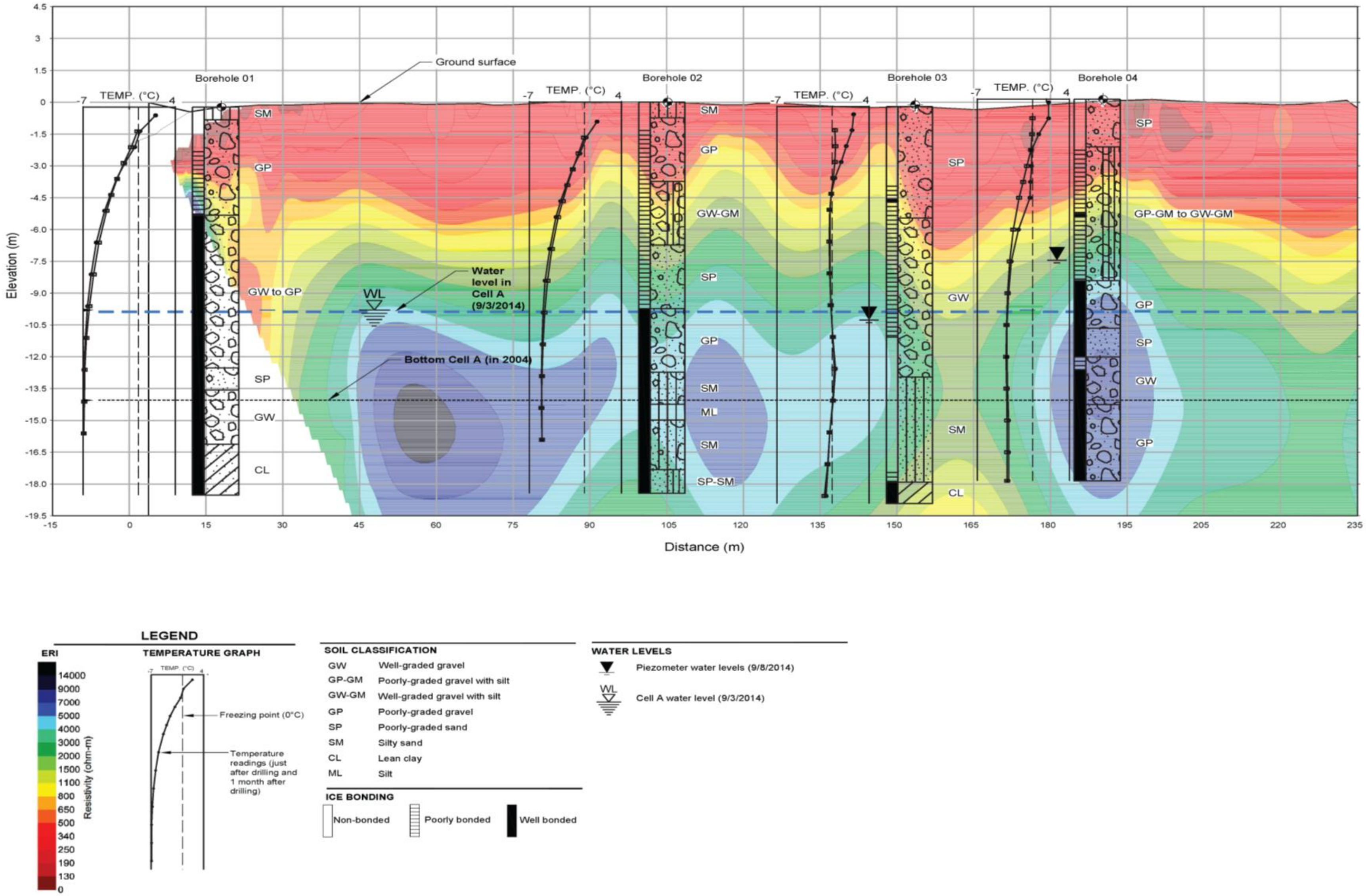

Figure 4. Example of ground temperatures in Borehole 03

### 4.5 Geophysical Surveys

The ERI survey that paralleled the boreholes on the buffer zone separating Cells A and B showed a distinct two layer system; a surface layer with low resistivity values (less than about 1,500 ohm-m) and a deeper layer with higher (greater than 1,5000 ohm-m) resistivity values (Figure 5). This trend was different in the vicinity of Borehole 03 and extending near Borehole 04 where lower resistivity values were also measured at depths.

## 5 DISCUSSION

The various subsurface conditions encountered at Borehole 03 suggest that there is groundwater flowing through the buffer zone separating Cells A and B near this location (Figure 5). Unfrozen soil samples retrieved during the drilling operations and the near-isothermal ground temperatures measured during the preliminary monitoring period (Figure 4) confirmed that there is at least one talik located at depth in the vicinity of Borehole 03 where groundwater could flow. Also, groundwater was observed at depth at this location and it appeared to be almost at the same level as the surface water surveyed in Cell A. Although the freezing front from the surface had not yet reached the talik depth, the slight decrease in ground temperatures observed in the talik zone during the fall period also suggest that there is a connection between the groundwater observed in Borehole 03 and the surface water in Cell A that was cooling down as air temperatures decreased.



Ground surface
Borehole 01
Borehole 02
Borehole 03
Borehole 04
TEMP. (°C)
-7
4
SM
GP
GW to GP
SP
GW
CL
GW-GM
ML
SP-SM
GP-GM to GW-GM
Water level in Cell A (9/3/2014)
WL
Bottom Cell A (in 2004)
Elevation (m)
Distance (m)
LEGEND
ERI
Resistivity (ohm-m)
14000
9000
7000
5000
4000
3000
2000
1500
1100
800
650
500
340
250
190
130
0
TEMPERATURE GRAPH
Freezing point (0°C)
Temperature readings (just after drilling and 1 month after drilling)
SOIL CLASSIFICATION
GW Well-graded gravel
GP-GM Poorly-graded gravel with silt
GW-GM Well-graded gravel with silt
GP Poorly-graded gravel
SP Poorly-graded sand
SM Silty sand
CL Lean clay
ML Silt
ICE BONDING
Non-bonded
Poorly bonded
Well bonded
WATER LEVELS
Piezometer water levels (9/8/2014)
Cell A water level (9/3/2014)

The ERI model that parallels the buffer zone between Cells A and B also supports the potential of groundwater flowing in a lower resistivity zone in the vicinity of Borehole 03 that would correspond to unfrozen or poorly bonded soils (Figure 5). Given that the dominant cryostructure observed throughout the boreholes was composed of interstitial ice, the change in resistivity values observed in the ERI model could be related mainly to variation in unfrozen water content (Fortier et al. 1994). The ERI model suggests that the zone favorable to groundwater flow at depth extends at least between Boreholes 3 and 4, which also corresponds to the location on the buffer zone where the ground surface settled during the drilling operations (Figure 2).

If the pond water level in Cell A is raised high enough there is a concern that persistent groundwater flow will occur from Cell A to Cell B through the shallow low resistivity layer and poorly bonded soils. Due to surface water exceeding the approximate 2 m critical water depth that could trigger talik development in this region (Walter 1983), a potential talik has likely developed under Cell A and may expand further. Groundwater flow occurring in permafrost soils implies that heat transfer is not limited to heat conduction, but also combined to advective heat transfer, which can be about one order of magnitude greater then heat conduction alone (Kane et al. 2001). A study on the impact of groundwater flow under a road embankment has shown that the groundwater flow accelerates permafrost degradation by advective heat transfer (de Grandpré et al. 2012). Therefore, there is concern that an increase in groundwater flow through the buffer zone due to a higher surface water level in Cell A may exacerbate permafrost degradation. This may initiate positive feedback effects resulting in additional groundwater flow and permafrost degradation in the buffer zone. Ultimately, raising the water level in Cell A while Cell B is still active will threaten the structural integrity of the buffer zone while raising serious safety concerns for the active mining activities in Cell B.

The groundwater level measured in the Borehole 04 piezometer, which was higher than the water level in Cell A, and the presence of poorly bonded soils in the upper part of this borehole suggest that the groundwater in Borehole 04 was coming from a different source than the surface water accumulated in Cell A. One hypothesis is that the poorly bonded and warm soils in the upper part of Borehole 04 would have offered little resistance to the shallow groundwater flow associated to water infiltration in the gullies located in the northern part of Cell A and nearby Borehole 04. Although the short-term impact of this groundwater flow on mining activities in Cell B can be minor relatively to the groundwater flow associated to raising the surface water level in Cell A, if groundwater flows persist at this location, it may exacerbate local permafrost degradation and trigger this positive feedback effect where additional groundwater flow and permafrost degradation occur. Eventually, this may also threaten the structural integrity of the buffer zone separating Cell A in reclamation from active Cell B.

## 6 CONCLUSION

The preliminary results of this case study example indicate the presence of groundwater flow through a buffer zone that separates an active mining pit (Cell B) from a pit in reclamation (Cell A) where surface water has been accumulated at least to a depth of 4 m. Preliminary results suggest that raising the surface water level in Cell A while Cell B is still active will increase the potential of groundwater flow between Cells A and B, and may trigger positive feedback effects where additional groundwater flow and permafrost degradation occur. Ultimately this may affect the structural integrity and stability of the buffer zone separating the reclaimed pit from the active pit leading to potential safety concerns for mining operations in Cell B. Preliminary results of this case study example suggest that the reclamation concept commonly adopted in cold and continuous permafrost areas of Alaska, which allows former pits to be filled with water while adjacent pits are still currently mined, should be assessed based on site conditions and possibly revised.

## ACKNOWLEDGEMENTS

The writers would like to acknowledge the contribution of Jan Deick, Peter Fahringer, and Michael Angelopoulos.

## REFERENCES

Alaska Climate Center. 2015. Climate Normals (1981-2010). Accessed online at: <http://akclimate.org/Climate/Normals>

ASTM Standard C117. 2013. Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing. ASTM International, West Conshohocken, PA, DOI: 10.1520/C0117-13, www.astm.org.

ASTM Standard C136. 2006. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International, West Conshohocken, PA, DOI: 10.1520/C0136-06, www.astm.org.

ASTM Standard D2216. 2010. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock Mass. ASTM International, West Conshohocken, PA, DOI:10.1520/D2216-10, www.astm.org.

ASTM Standard D2974. 2013. Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils. ASTM International, West Conshohocken, PA, DOI: 10.1520/D2974, www.astm.org.

ASTM Standard D4083. 1989 (2007). Standard Practice for Description of Frozen Soils (Visual-Manual Procedure). ASTM International, West Conshohocken, PA, DOI: 10.1520/D4083-89R07, www.astm.org.

ASTM Standard D422. 1963 (2007)e2. Standard Test Method for Particle-Size Analysis of Soils. ASTM International, West Conshohocken, PA, DOI: 10.1520/D0422-63R07E02, www.astm.org.

ASTM Standard D4318. 2010e1. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA, DOI: 10.1520/D4318, www.astm.org.

ASTM Standard D6431. 1999 (2010). Standard Guide for Using the Direct Current Resistivity Method for Subsurface Investigation. ASTM International, West Conshohocken, PA, DOI: 10.1520/D6431-99R10, www.astm.org.

de Grandpré, I., Fortier, D., Stephani, E. 2012. Degradation of permafrost beneath a road embankment enhanced by heat advected in groundwater. Canadian Journal of Earth Sciences, 49: 953-962.

Fortier, R., Allard, M., Seguin, M.K. 1994. Effects of physical properties of frozen ground on electrical resistivity logging. Cold Regions Science and Technology, 22: 361-384.

Jorgenson, T. Yoshikawa, K. Kanevskiy, M., Shur, Y. Romanvoksy, V. Marchenko, S., Grosse, G., Brown, J., Jones, B. 2008. Permafrost Characteristics of Alaska. In: Proceedings of the Ninth International Conference on Permafrost. Accessed online at: <http://permafrost.gi.alaska.edu/sites/default/files/AlaskaPermafrostMap_Front_Dec2008_Jorgenson_etal_2008.pdf>.

Kane, D.L., Yoshikawa, K., McNamara, J.P. 2013. Regional groundwater flow in an area mapped as continuous permafrost, NE Alaska (USA). Hydrogeology Journal, 21: 41-52.

Kane, D.L., Hinkel, K.M., Goering, D.J., Hinzman, L.D., Outcalt, S.I. 2001. Non-conductive heat transfer associated with frozen soils. Global and Planetary Change, 29: 275-292.

Sherman, R.G. 1973. A Groundwater Supply for an Oil Camp Near Prudhoe Bay, Arctic Alaska. In: Proceedings of the Second International Conference on Permafrost, Yakutsk, USSR, North American Contribution, Washington D.C., U.S.A., pp.469-472.

Tolstikhin, N.I., Tolstikhin, O.N. 1976. Groundwater and Surface Water in the Permafrost Region (translation). Inland Waters Directorate Tech Bull 97, Ottawa, Ontario, 22 p.

Walker, J. 1983. Guidebook to Permafrost and Related Features of the Colville River Delta. *In*: Fourth International Conference on Permafrost, University of Alaska Fairbanks, 34 p.

Woo, M. 2012. Permafrost Hydrology. Springer-Verlag, Berlin Heidelberg, 574 p.