Stopping runaway wells in permafrost: the cryogenic freezeback method

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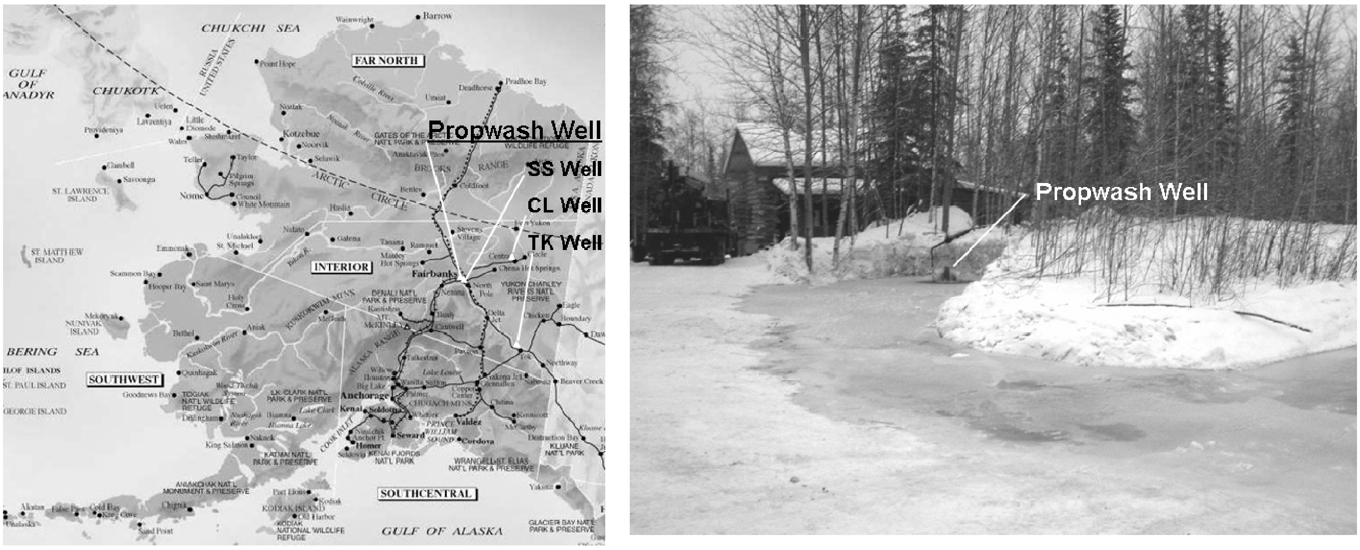
Abstract Artesian wells are often encountered in permafrost valleys where aquifer pressures beneath confining sub-permafrost vary between 135 and 1035 kPa (20 to 150 psi). These wells must be heated to prevent freeze-up. However, there are no standards for well heating in North America, and overheating can thaw the permafrost around the casing and lead to loss of control of the well. Further, Arctic warming may be playing a role in the increased frequency of occurrence of uncontrolled wells. With runaway wells, impacts to property and infrastructure can be catastrophic, and the costs to regain control of the well and mitigate damages high. Methods to regain control of artesian wells in permafrost are not well developed and are risky. A new method, cryogenic freezeback with liquid nitrogen, was successfully used to mitigate a runaway artesian well in a permafrost valley north of Fairbanks, Alaska. The well was stopped and infrastructure saved and restored to pre-icing conditions for approximately 63% of the insured property value. Three years of heat exchange and thermal monitoring indicate permafrost restoration and permanent freezeback. The event is documented from massive icing, emergency action to save the residence, well mitigation, to damage assessment and foundation restoration. The cryogenic freezeback method is presented complete with seepage and thermal analyses, well conversion, and thermal monitoring data. Remediation costs and lessons learned are summarized.

Key words permafrost hydrology; artesian wells; cryogenic freezeback; climate change

1 INTRODUCTION

There are few documented instances of uncontrolled artesian flows in permafrost in the literature (Muller, 1945; USACE, 1950; Linell, 1973; Péwé, 1982; Wheaton, 1990). Muller (1945) describes the case of groundwater moving downslope under hydrostatic pressure between a thickening seasonal-frost layer and underlying permafrost, until it reaches the thawed zone beneath a heated house and exits upward and through the structure, ultimately encasing the house in ice. USACE (1950) and Linell (1973) document the COE Well, an artesian well that was problematic from 1946 to 1949 at a research station near Fairbanks, Alaska. The reports chronicle attempts to regain control of the well after installation into a sub-permafrost aquifer with frost tubes and passive refrigeration, and observations of surface icing, frost blisters, ground subsidence, and erosion and thermokarst development around the wellhead. Wheaton (1990) documents the infamous runaway Steese Well that was problematic in Fairbanks during 1976–1977, when a test hole drilled into a sub-permafrost aquifer under high pressure resulted in significant residential damage, several law suits, and a remediation cost of ~US $1.2 million (1977 dollars). Perhaps the most salient points in the Wheaton paper relate to the descriptions of the various grouting and passive and mechanical cooling schemes tried over 18 months to stop the flow. North American records suggest few instances of runaway permafrost wells since 1946, that is, until 2005.

Between 2005 and 2010, four instances of runaway artesian wells occurred in rural developments in interior Alaska (Fig. 1). Well overheating is attributed as the cause of two of the well failures, and the cause of a third is still under investigation, as of this writing. However, the fourth *Propwash Well* failed mysteriously after 23 years of normal operation. Through investigation of these wells, cryogenic freezeback was developed as a new cost-effective method for stopping runaway wells in permafrost. The method entails wellhead access and preparation (i.e. removal of heating elements and scale build-up inside the casing), insertion of a constructed evaporator for injection of liquid nitrogen (LN2), cryogenic freezeback of the well over time, and well retrofit with a thermosyphon for long-term ground heat liberation. The Propwash Well experience and Cryogenic Freezeback Method (CFM) are summarized here.



(a) (b)

Fig. 1 (a) Runaway artesian wells in Alaska (2005–2010), and (b) the Propwash Well setting.

2 THE PROPWASH RUNAWAY WELL

The Propwash Well was installed at a Goldstream Valley residence in 1982. Cased through thaw-unstable permafrost into a schistose bedrock artesian aquifer (Table 1), it operated with regulated heat for 23 years before seepage began to emerge from around the wellhead in December 2005. The homeowner called their insurance company, an appraiser inspected and reported 12 days later, and the insurer spent the next 42 days deciding limits of liability and response. All the while, a 9500-m^3 icing developed over two acres of insured property during the winter's deep freeze at –40°C to –45°C air temperatures.

Table 1 Well geology and operating characteristics.

Geology (m below ground surface)		Characteristics	
0–2.1 m	Wet organic silt	Aquifer pressure:	140 kPa (~20 psi)
2.1–5.5 m	Frozen silt	Well flow rate:	11.4 m^3/h (50 gpm)
5.5–8.9 m	Massive ice	Well dimensions:	15.2 cm diameter steel casing
8.9–34.3 m	Permafrost (unsaturated silt with gravel)		– length 46.3 m – screened from 42.6 to 46.3 m
34.3–46.3 m	Schistose bedrock	Well heating: 0–3 m	Regulated heat tape through the seasonal frost layer
		0–46.3 m	Unregulated heat cable

The icing progressed from the wellhead outward and upward in layers over the landscape initially as a function of ground-surface relief, and then according to water movements beneath and over the ice. Once the ice was sufficiently thick to insulate the ground beneath it, seepage water travelled outward under the icing to its perimeters, and upward around tree trunks and through pressure cracks to grow the *naled*. The naled grew to an average height of 1.9 m, reached a maximum thickness of 3.4 m, and created an icescape of ice terraces, frost mounds (or frost blisters), ice domes around trees, and hydraulic pressure ridges and cracks among its many features (Fig. 2). Ultimately, the icing filled the metre-high crawl space (under the house) and encased the home up to within centimetres of the windows, and encroached on the frontage road and two adjacent properties. Although infrastructure impacts were confined to the Propwash property, area well pressures were reduced by as much as 60% in response to a depleted aquifer.

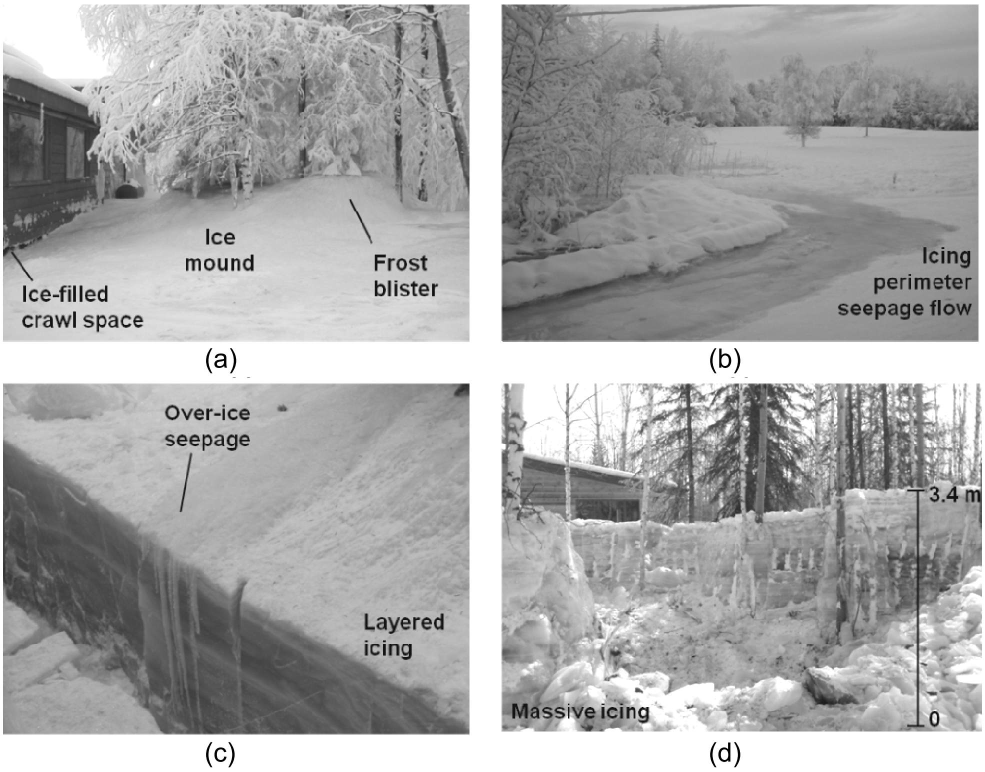


Fig. 2 Icing features.

Emergency corrective action

Work at the Propwash site was conducted in four stages: emergency corrective action, well mitigation, ice abatement, and infrastructure assessment and rehabilitation. Emergency corrective action to save the house was first initiated because the icing had engulfed the heating-oil tank and risen to near window level, water had begun to seep through the floor of the house, and because of concerns for foundation undermining. The water intrusion issue, a consequence of house heating and melting of the crawl space ice, was alleviated by drilling weep-holes through the ice at the corners of the crawl space (Fig. 3(a)). Icing progression at the house was then interrupted with an elaborate system of sloped intercept trenches and heated collection pipes (Fig. 3(b)) that diverted water away from the house to down-slope woodlands. Ice excavation with a frost bucket exposed the wellhead and seepage zone to assess and develop a mitigation strategy.

(a) (b)

Fig. 3 Emergency corrective action measures: (a) crawl space drainage, and (b) intercept trench.

3 CRYOGENIC FREEZEBACK METHODOLOGY

Cryogenic freezeback makes use of liquid nitrogen (LN2) at −196°C to create a massive ice plug inside the well, refreeze the seepage zone outside the well casing, and restore the surrounding permafrost. Freezeback design is a function of well, permafrost, and aquifer characteristics (Table 1), seepage and thermal analyses, and determination of LN2 requirements. Site-specific information is critical to the analyses, and accurate determination of LN2 requirements for the desired freezeback. After freezeback, soil erosion zones are grouted and the well retrofit with a thermosyphon to ensure lasting freezeback.

Seepage analysis

Paramount to stopping the runaway well were seepage analysis and a feasibility study of viable well mitigation methods. Seepage analysis required an understanding of the well installation and permafrost characteristics, and development of plausible seepage progression scenarios. Two seepage scenarios were hypothesized for the Propwash Well: (1) narrow thaw along the full length of well casing above bedrock, and (2) conical thaw. Narrow thaw results from over-heating, wherein the well *short-circuited* from prolonged use of the heat cable and resulted in rapid uniform thaw of permafrost around the casing. Conical thaw implies greater permafrost degradation (i.e. thaw and erosion) at the schistose-permafrost interface, having been eroded under the influence of water for the longest time. Conical thaw is not an anthropogenic failure scenario, but rather a consequence of hydrological erosion of basal permafrost, in which intermittent and infrequent well heating may or may not have played a minor contributing role. These seepage erosion scenarios are illustrated in Fig. 4. Conical thaw is the worst case scenario because of its greater extents of permafrost degradation.

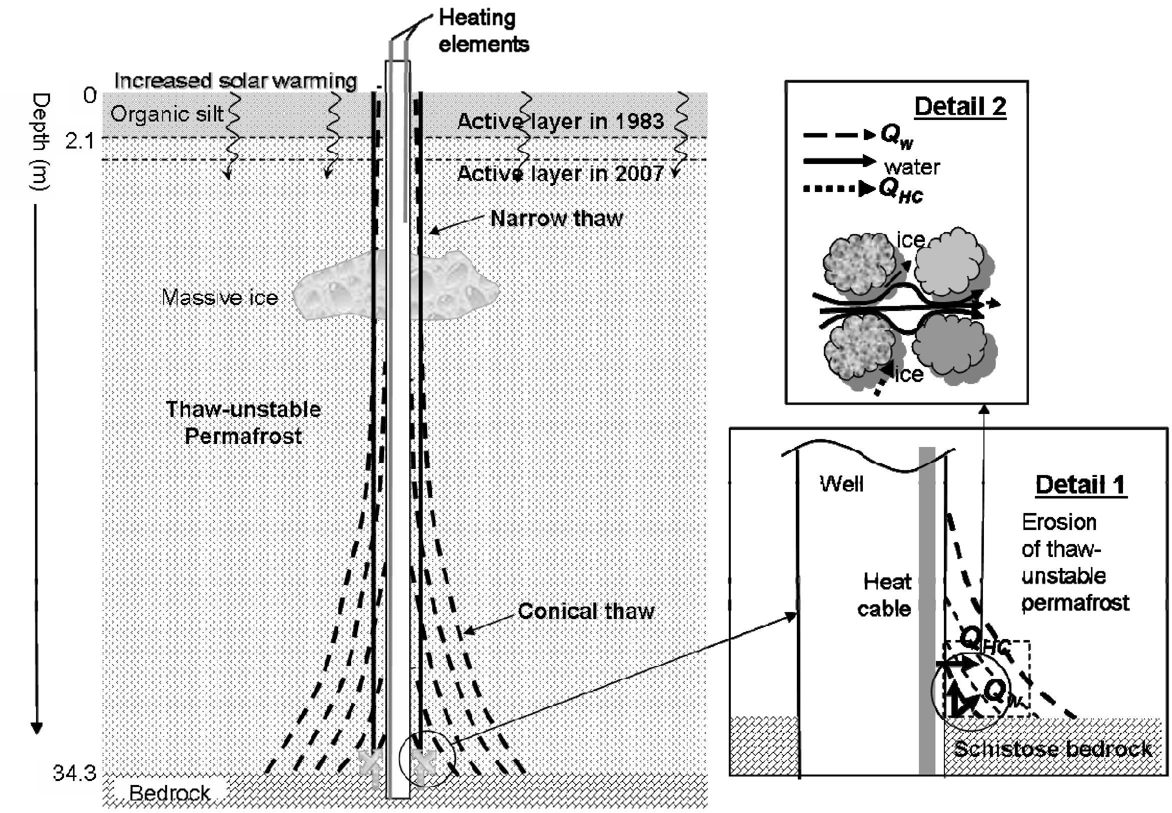


Fig. 4 Well seepage erosion scenarios. Detail 1 depicts the inception of conical thaw, and Detail 2 the influence of water sensible heat and that from the heat cable to thaw erosion of permafrost.

Four methods were evaluated based on potential for success, availability or resources, and cost. Top-down and bottom-up grouting methods were deemed too risky for the conical thaw scenario; chance of seepage re-emergence was too great. Passive refrigeration using freeze pipes, a proven method for well freezeback, was too expensive given that resources were not locally available at the time. Cryogenic freezeback, with its moderate cost and potential high chance of success, was chosen as most resources were locally available. CFM was developed and implemented with a multi-disciplinary team of engineers and an expert well installer. Freezeback success would hinge upon the critical thermal analysis.

Thermal analysis

An energy-balance analysis across the well-permafrost regime was performed to determine the well's heat removal rate, soil thaw radii, and freezeback parameters (i.e. LN2 requirements and freezeback radius). First, analysis of the phase change interface between frozen and thawed soil as a function of heat conduction and rate of thaw from the well was considered. For a well in permafrost, the energy balance can be expressed in cylindrical coordinates as:

$$q = \frac{2\pi k(T_w - T_r)}{\ln(r/r_w)} = 2\pi r L \frac{\mathrm{d}r}{\mathrm{d}t} \tag{1}$$

where q is the energy transferred (or heat conducted), T_w and T_r are the respective temperatures at the well casing and soil freeze-thaw interface, r_w and r are the outside radius of the well and the soil thaw radius, k is soil thermal conductivity (the inverse of thermal resistance), and L is volumetric latent heat (Freitag & McFadden, 1997). Sensible heat is neglected since the Stefan number for freezing soil is small, and the heat tape temperature is constant at r_w when turned on. By rearranging and integrating both sides of the energy balance equation, we obtain an expression for thaw radii as a function of the freezing index, I_f, (Andersland & Ladanyi, 2004):

$$I_f = \int (T_w - T_r)\mathrm{d}t = \frac{L}{k}\left\{\frac{r^2}{2}\ln(r/r_w) - \left(\frac{r^2 - r_w^2}{4}\right)\right\} \tag{2}$$

For the Propwash Well, the confining layer above bedrock was frozen Fairbanks silt with massive ice. An average value of thermal conductivity for Fairbanks silt is 1.1 W/m/°C, and the volumetric latent heat of Fairbanks silt and pure water/ice are 150 000 kJ/m^3 and 333 000 kJ/m^3, respectively. The equation was then used to plot thaw radius as a function of the freezing index (Fig. 5) for freezeback design. From this plot we see that as the freezing index increases so does the thaw radius, which implies that the longer thawing occurs the more extensive is permafrost

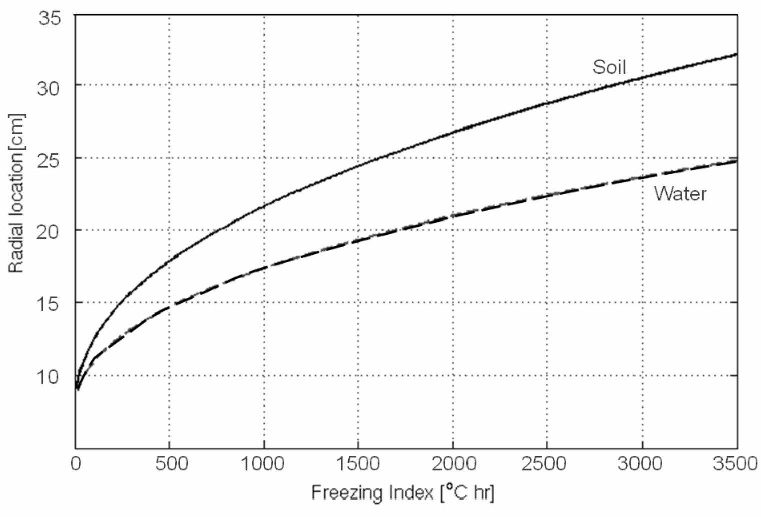


Fig. 5 Permafrost thaw radius as a function of freezing index.

degradation. Further, a larger thaw radius results from warmer seepage water. For example, the difference between 2°C and 4°C water seeping up the well casing for four weeks is an increase in soil thaw radius from about 23 cm to 29 cm.

Next, determination of seepage parameters and observations of the seepage area at the wellhead were required for conservative freezeback design. The seepage rate was estimated at ~1 kg/s (~15 gpm) and the water temperature measured at 2.5°C. The freezing index for 54 days of seepage flow (the time from seepage inception at the ground surface to implementation of mitigation measures) was calculated at 3240°C-h, resulting in a minimum desired freezeback radius of 25 cm.

Finally, LN2 requirements were then computed based on heat removal rates of water and Fairbanks silt. The heat removal rate for flowing water was quantified from $q_w = m_w C_p \Delta T$ as 10.5 kJ/s. The energy required to re-freeze soil to the desired radius of 32 cm, from the ground surface down to 11.6 m (the bottom of the LN2 evaporator), was calculated from $E = \pi(r^2 - r_w^2)HL$ as 530 MJ, or a rate of 6.1 kJ/s for 24 h. Thus, the total heat removal rate required for ground freezing was about 17 kJ/s, and the heat removal rate provided by LN2, as the product of the average LN2 injection rate (0.1 kg/s) and nitrogen's vaporization energy (~200 kJ/kg), was 20 kJ/s. With consideration for subsurface heterogeneity, uncertainties about the soil thaw and freezeback profiles, and potential for seepage re-emergence, a factor of safety of 4 was incorporated for freezeback design. The desired freezeback radius was achieved with 10 400 kg of LN2 injected over 24 h.

Well preparation, freezeback and monitoring

Well preparation required de-icing, removal of obstructions, and water management. With aged wells, scale (i.e. build-up of mineral precipitates) on the inside casing walls is common. Scale was removed from the casing's upper reach with a metal brush; the LN2 evaporator was used to further detach scale at greater depths to accommodate its installation. Water management during the preparation work was accomplished with a sump pump and heated over-the-ice pipeline to drain the wellhead reservoir (Fig. 1(b)) to downslope woodlands. Subsequent to de-icing, removal of the heating elements and scale, and water management implementation, the well was ready for permanent installation of the evaporator.

The evaporator was a discharge cylinder for LN2 injection. Designed to optimize freezeback effectiveness, important design parameters are length and diameter, clearance, and well seating. Constructed as a 10-cm diameter and 13-m long steel cylinder, welded shut at the bottom, the diameter afforded clearance to bypass residual scale and a bend in the well casing, and was sufficient to accommodate a thermosyphon. The evaporator was sufficiently long to span the active layer and massive ice (Fig. 4) zone. Once properly seated on the wellhead with a thick rubber doughnut gasket, the well's discharge flow rate was sufficiently diverted to prevent interference with LN2 discharge (Fig. 6(a)).

A cryogenic tanker regulated LN2 discharge into the evaporator through a 2.5-cm diameter copper *tremmie* tube (Fig. 6(b)), with its end suspended two metres above the bottom of the evaporator to accommodate LN2 boiling, which occurs at –196°C. The LN2 discharge rate, initially set at 1350 kg/h to quickly freeze-off the well flow, was optimized to a constant rate for uniform discharge over 24 h. The thermal gradient across the evaporator opening with the atmosphere was monitored to ensure uniform freezeback with depth.

Once freezeback was complete and the evaporator frozen in place inside the well, the annulus between the evaporator and well casing was filled with a thermal bentonite-grout seal. A thermosyphon 8.9-cm in diameter and 11.6-m long, charged with CO_2, and fitted with thermistors and a data logger was then inserted and sealed in the evaporator with a custom low-temperature thermal grout. The well was abandoned and converted to a heat exchanger to enhance freezeback over the next few years (Fig. 6(c)). The data logger provided a continuous hourly record of ambient air and the temperature at the base of the evaporator inside the abandoned well.

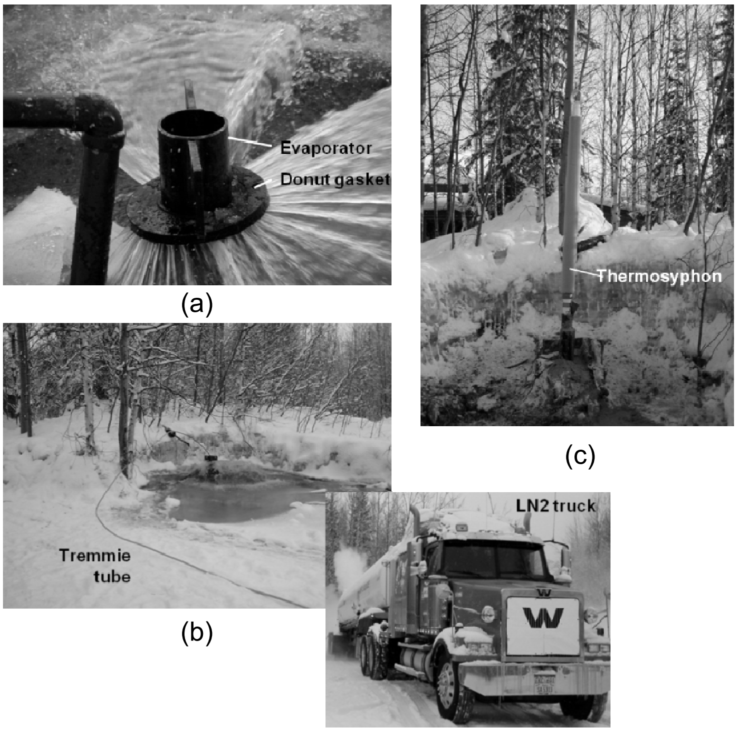


Fig. 6 Cryogenic freezeback and well conversion: (a) evaporator seated in well, (b) LN2 truck and tremmie tube set for LN2 discharge, and (c) thermosyphon installed.

4 DAMAGES, RESTORATION AND MITIGATION COSTS

Damage to infrastructure was largely confined to the home's foundation. The house was supported by 34 independent post-and-pier foundations that formed an open-air crawl space beneath the structure. (It is common practice to raise a house above the frozen ground to preserve underlying permafrost.) The concrete piers of various sizes supported stacked timbers or single square or circular posts. Some posts were anchored to their piers; others were not. Depending on configuration and anchoring, impacted posts and piers experienced shove, tilt and/or rotation, separation and lift, or frost heave and collapse. Because the foundation system was completely encased in ice, extreme care was given to foundation stability during ice abatement to minimize potential for additional distress to the house. Temporary shoring replaced toppled foundations before comprehensive foundation rehabilitation with adjustable foundations. Settling was monitored for two years and the new foundations adjusted accordingly as supersaturated ground drained and resettled.

Several mitigation strategies were considered to stop the runaway well. These included bottom-up grouting, top-down grouting, passive refrigeration using freeze pipes, and cryogenic freezeback with LN2. Evaluation criteria used for decision making were cost, chance of success, and consequences. Although CFM had the highest cost at $150 000, the method offered the greatest chance of success. Evaluation criteria and implementation costs for the various mitigation strategies considered are summarized in Table 2.

The total cost to stop the Propwash Well and restore the house and grounds to pre-icing conditions was approx. US $220 000, or about 63% of the insured property value. This includes $25 000 for emergency corrective action, $150 000 for well preparation, cryogenic freezeback, and well retrofit, and $45 000 for ice abatement and foundation assessment and rehabilitation. Emergency corrective action limited structural damage to the home's foundation system. Other infrastructure losses were the well and septic system. The well was replaced with an above-ground insulated holding-tank water supply system. The underground septic was abandoned and replaced with an above-ground, arctic-grade residential wastewater treatment plant.

Table 2 Feasibility study of Propwash Well mitigation strategies.

Strategy/ Method	Chance of success	Cost to implement (US $)*	Consequences
Do nothing	Low	0	Loss of house and other infra-structure; decreased property value; high potential for extraneous liability.
Bottom-up grouting	Low	65 000	Injection rate must be >> aquifer pressure; potential for grout dissociation; entire seepage zone may not be sealed; no permafrost restoration potential; high potential for seepage reoccurrence.
Top-down grouting	Low to moderate	45 000	Injection holes could collapse; possible formation of alternate seepage pathways and blowout (method has a history of blowout failure); no permafrost restoration potential; high potential for seepage re-occurrence.
Passive refrigeration	Moderate	95 000	Requires multiple freeze pipes; limited penetration depth; well abandoned; expertise and equipment not locally available. How long will it last?
Cryogenic freezeback (CFM)	Moderate to high	150 000	Sufficient freezeback radius and depth; 3-yr low-maintenance enhanced freezeback; some permafrost restoration; greatest potential for permanent solution; well abandoned.

*Includes planning and all labour, equipment and material costs through implementation.

Potential changes in permafrost hydrology

Of the three runaway wells investigated in Alaska since 2005, only with the Propwash Well can we attribute loss of control to natural causes with confidence. The Propwash Well homeowner was adamant that the well was operated consistently as designed, and that without exception, the heat cable had not been used during the three years prior to the failure. Further, the shorter heat tape had influence only through the seasonal frost realm. The presumption that well heating was not a significant factor in the Propwash Well failure bears the question: Could climate change be a factor in permafrost well failures?

The authors sought regional and local data to investigate potential influence of climate change on local hydrogeological regimes, permafrost hydrology in particular. Two data sets relevant to the Propwash site are an unbroken 100-year record of meteorological data for Fairbanks (Wendler & Shulski, 2009), and a 27-year uninterrupted record of permafrost temperatures along the International Geosphere–Biosphere Program Alaskan transect, a north–south transect of permafrost monitoring stations from Prudhoe Bay to Gulkana. The Propwash Well site lies along this transect, between Livengood and Gulkana, in interior Alaska.

The Fairbanks meteorological data set includes a time series of mean annual air temperature (MAAT) in Fairbanks from 1906 to 2006. This data shows that the MAAT rose 1.4°C over the century (compared to 0.8°C worldwide), the last three decades combined have on average the highest temperature of the record, and winter monthly changes in MAAT were greatest for December and January (2.4°C and 2.6°C, respectively). Further, the number of days with air temperatures less than –40°C decreased on average from 14 to 8 days annually, and warm days with temperatures above 26.7°C increased from 11 to 12 days. Finally, the length of the growing season, which is the time period when the air temperature in summer never dips below the freezing point, increased from 85 to 123 days (a 45% increase) over the century, with an earlier spring and a later autumn contributing about equally to the overall increase. However, an 11% decrease in annual precipitation and corresponding decrease in winter precipitation since 1916 does not help us to understand the hydrological changes that may have occurred.

Evidence of warming and thawing of discontinuous permafrost has been measured in Alaska since the 1980s. Estimates of the magnitude of warming at the top of permafrost in interior Alaska since the mid-1980s range from 0.5°C to 1.5°C (Osterkamp & Romanovsky, 1999; Osterkamp, 2008; Brown & Romanovsky, 2008). Based on the prevailing warming trend, time scales on the order of a century to thaw the top 10 m of ice-rich permafrost, and an order of magnitude smaller at the permafrost base have been estimated (Osterkamp & Romanovsky, 1999).

The Fairbanks meteorological data corresponds well with the 0.4 m thickening of the active layer in the vicinity of the Propwash Well. While we can conclude that the permafrost table is degrading and there is a corresponding recharge contribution to the overall hydrological system in the Goldstream Valley, little can be said about the impacts from these changes on the permafrost base. Despite predictions made about climate-change impacts in permafrost regions, i.e. more active recharge and discharge to hydrogeological regimes and warmer aquifers (Michel & VanEverdingen, 2006), the science of permafrost hydrology is not yet sufficiently developed to fully understand permafrost degradation processes, time scales, and geophysical relationships, e.g. topographic to sub-permafrost hydrological links (Woo *et al.*, 2008). Nevertheless, we will have to deal with the impacts as they occur, and sometimes at great expense.

5 CONCLUSION AND DISCUSSION

Previous permafrost well failures resulted in catastrophic losses and great expense to regain their control. The Propwash Well experience demonstrated that CFM can be a viable and cost-effective method to mitigate a runaway artesian well in permafrost with comparatively light damage and property devaluation. Further, the experience attests to the importance of problem recognition and resolution early on. By doing so, the risk of catastrophic loss and mitigation costs can be significantly reduced.

Although artesian wells in permafrost can operate with moderate but continual maintenance for many years, it is clear that uncontrolled seepage outside of the well due to thaw can be catastrophic. There is need for design principles that might aid the preservation of a functioning well while avoiding thermal degradation of permafrost. This type of design begins with a first-order model of the thermal regime surrounding the well.

The steady-state thermal regime outside the casing of an operating well is described by:

$$\frac{\partial T}{\partial t} = 0 = \frac{1}{r}\frac{\partial}{dr}\left(r k \frac{\partial T}{\partial r}\right) \tag{3}$$

The non-zero thermal gradient is maintained by a heat flux from the well into the permafrost, which is supplied by both the liquid water brought from depth and the heat cable. This equation can be solved with the boundary conditions of heat flux (q) and well temperature (T_w) at the inside radius, and constant permafrost temperature (T_r) at some distance r away, resulting in:

$$q = \frac{k}{r_w}\frac{T_w - T_r}{\ln(r/r_w)} \tag{4}$$

Figure 7 shows the heat flux as a function of r, the distance at which the outer thermal boundary is at the permafrost temperature (≈ –1°C). It is reasonable to assume that this distance is on the order of 1 to 2 metres beyond the well, which requires a flux of the order of 5 W/m^2 to maintain. For a 15-cm diameter well, this corresponds to a linear heat flux of 2.4 W/m that is supplied from the heat cable, well water, or combination of both.

This dynamic balance of heat supplied from the well to the permafrost poses the interesting question of where the 0°C isotherm resides in a permafrost well? Clearly it should not be outside of the well casing, because that implies the uncontrolled flow problem discussed here. It must therefore reside somewhere inside the well. (The large thermal conductivity of steel relative to ice and water means it is highly unlikely to reside within the casing itself.) Figure 8 shows the radial liquid/ice interface location as a function of heat flux, with an asterisk at the well casing radius (7.5 cm) and a flux of 4.85 W/m^2 (see Fig. 7).

For this particular situation, the well should be operated with a maximum average heat flux of 4.85 W/m^2 so as not to induce thawing outside of the casing. A slightly lower heat flux leads to a layer of ice forming on the inside of the casing, which is the desired operational point. Most

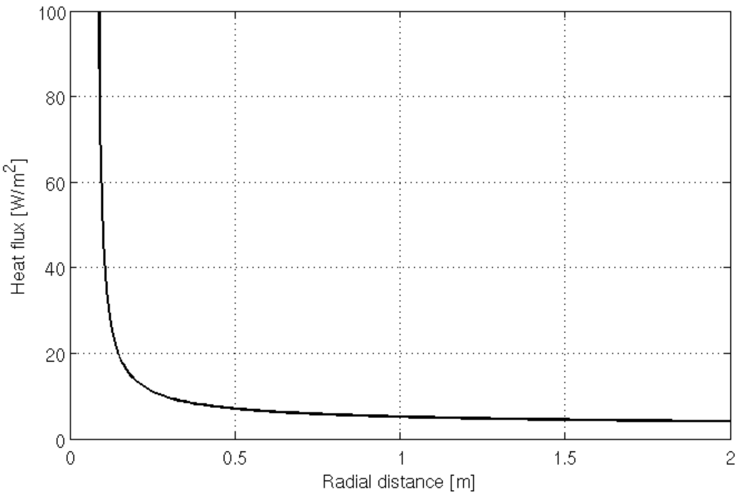


Fig. 7 Heat flux as a function of the radial distance away from a permafrost well.

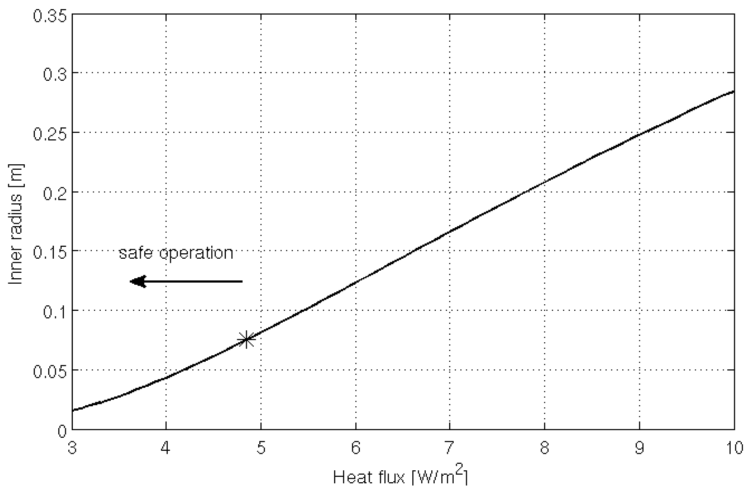


Fig. 8 Safe heating of an artesian well in permafrost.

commercial heat tape provides energy at a higher rate and therefore cycling the heat tape is required. Alternatively, if the energy is provided only by the sensible heat of the well's liquid water, an energy balance indicates a 45-m deep well drawing water at +2°C from depth would need to flow at 91.5 L/h (or 2.2 m^3/d) to prevent well freeze-up. Most residential wells would likely operate somewhere between these two extremes. Fortunately, the large latent heat of water allows for significant fluctuations in the instantaneous heat flux before complete well freezing (or catastrophic thawing) would occur.

Although the quantitative numbers discussed here apply only to this particular situation of permafrost temperature and well diameter, the general design principle should carry over to other artesian wells in permafrost. Maintaining the dynamic energy balance that avoids both complete freeze-up and thaw outside the casing could be assisted by using a double-walled casing with insulation. For this design, it would be easier to maintain the 0°C isotherm either within the well or the double-wall casing. However, the additional material and logistical costs of such an installation are likely a significant disincentive when the probability of well failure is difficult to assess.

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