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SCIENTIFIC BRIEFING

A portable experimental hillslope for frozen ground studies

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Abstract

Frozen ground hydrological effects on runoff, storage, and release have been observed in the field and tested in numerical models, but few physical models of frozen slopes (at scales from 1 to 15 m) exist partly because the design of such an experiment requires new engineering design for realistic whole-slope freezing and physical model innovation. Here, we present a new freezable tilting hillslope physical model for hydrological system testing under a variety of climate conditions with the ability to perform multiple (up to 20 per year) freeze–thaw cycles. The 4 × 2 m hillslope is mobile and tiltable on the basis of a modified tri-axle 4.88-m (16′) dump trailer to facilitate testing multiple configurations. The system includes controllable boundary conditions on all surfaces; examples of side and baseflow boundary conditions include permeable membranes, impermeable barriers, semipermeable configurations, and constant head conditions. To simulate cold regions and to freeze the hillslope in a realistic and controlled manner, insulation and a removable freezer system are incorporated onto the top boundary of the hillslope. The freezing system is designed to expedite the freezing process by the addition of a 10,130-KJ (9,600-BTU) refrigeration coil to the top-centre of the insulated ceiling. Centre placement provides radial freezing of the hillslope in a top-down fashion, similar to what natural systems encounter in the environment. The perimeter walls are insulated with 100 mm of spray foam insulation, whereas the base of the hillslope is not insulated to simulate natural heat fluxes beneath the frozen layer of soil. Our preliminary testing shows that covers can be frozen down to −10 °C in approximately 7 days, with subsequent thaw on a similar time frame.

KEYWORDS

cold regions hydrology, freeze–thaw cycling, laboratory hillslope, scaled hillslopes

1 | INTRODUCTION

Laboratory hillslopes are an effective means for hypothesis testing and linking to field and numerical model analysis (Blöschl & Sivapalan, 1995; Hopp et al., 2009; Stomph, De Ridder, Steenhuis, & Van de Giesen, 2002). Although 1D column experiments are very common in soil physics studies (Lawrence et al., 1993; Lewis & Sjöstrom, 2010; Salas-García, Garfias, Martel, & Bibiano-Cruz, 2017; Yang, Rahardjo, Wibawa, & Leong, 2004), 3D hillslopes that can represent field-scale infiltration and lateral flow processes are much less common. Nevertheless, use of such experimental hillslopes has led to the discovery of new behaviour in terms of tracer mobilization (Scudeler et al., 2016), time variance confirmation of transit time and storage selection distributions (Pangle et al., 2017), understanding of coupled hydrological and geochemical evolutionary processes (Pangle et al., 2015), and has allowed for testing of new numerical model schemes (Hazenberg et al., 2016).

Although some sophisticated slope physical models do now exist (Bryan, 1979; Hopp et al., 2009; Kendall, McDonnell, & Gu, 2001; Michaelides & Wainwright, 2008; Smit, van der Ploeg, & Teuling, 2016), none, that we are aware of, have yet tackled frozen ground processes. This is an issue because much of the key hydrological processes of interest today experience subzero temperatures and about half of the world's population receive their water from cold regions where soil can freeze (Kummu, de Moel, Ward, & Varis, 2011). Thawing of frozen ground is one of the most important components of change in northern regions (Sun, Perlwitz, & Hoerling, 2016; Walvoord & Kurylyk, 2016; Zhou et al., 2014), and understanding frozen ground effects on infiltration, storage, and runoff generation is a major research challenge (Coles, Appels, McConkey, & McDonnell, 2016). Laboratory hillslopes could play an important role in developing new understanding. But beyond natural hillslopes, many artificial slopes are now being created in cold regions as mine covers to store and release water and isolate waste rock and tailings from aquatic systems following mine closure. At sites where reclamation covers are seasonally frozen, hydrological properties vary through seasonal freeze–thaw cycles. Here too, laboratory hillslopes could enhance our ability to test scenarios for these engineered systems at a realistic scale to better inform designs and numerical model development. There is thus a pressing need for laboratory-based experimental hillslopes to incorporate frozen ground effects for the study of natural and engineered hillslopes.

Here, we outline the development of a new portable indoor experimental hillslope for basic and applied research for hillslope-scale frozen ground studies. In this briefing, we

1. describe the construction of the hillslope system (including the design objectives and construction details of the tilting hillslope),
2. outline the development of the slope freezer system, and
3. show proof of concept of its operation.

2 | METHODS

The overall objective for the indoor experimental hillslope was to design and construct a hillslope capable of simulating rainfall-runoff and melt-runoff on a sloping test plot that could be frozen to mimic temperatures encountered in the field. Another key design objective was mobility of the constructed hillslope, including the ability to easily adjust slope angle. We used a standard tri-axle dump trailer (Load-Trail™) as the basis for the design.

2.1 | Trailer design

Figure 1 shows the layout of the 4 m × 2 m × 1 m deep basic hillslope system (soil depth is adjustable; other trailer sizes can be used) based on a Load-Trail DT16 dump trailer. The dump trailer presents many advantages over the construction of a custom designed and built hillslope system. The service life for a properly cared for trailer extends over decades. Solid steel construction provides a solid, simple surface for adaptations and is generally simple to repair. New components are easily attached via MIG welding, bolt fasteners, or other forms of tooling. Because the system is based on a standard highway-rated dumping trailer, the ability to utilize the hillslope for material transport before or after an experiment is a cost-saving strategy and cuts down on equipment needs in the lab. The trailering system described here has a gross vehicle weight rating of 10,800 kg (24,000 pounds) and is towable by a standard 1-ton truck.

Slope angle changes are accomplished via manual jacking for low-angle slopes <5°, or using the hydraulically actuated dumping mechanism incorporated into the dump trailer for slopes >5°. We added pedestrian walkways on the exterior of the hillslope (Figure 1) to prevent any compaction issues related to walking on the soil surface. The ramp frame was constructed from 25-mm square steel tubing with an expanded metal base for enhanced traction and the free flow of debris or water from the ramp to the floor. The ramps were attached to the trailer at five points along the external side wall with a slip-fit system. The trailer tie-down couplers presented an ideal structural location for a slip-fit slide to support the weight of the ramps and up to five pedestrians on each side. Ramps are easily attached by hand with four people supporting the load or two people if the heavy lifting is done via forklift. If a forklift is utilized, one person can line up the ramps, whereas the other adjusts the fork height to engage the slip couplers. The removal of the ramp system is supported by performing the above steps in reverse.

2.2 | Hillslope boundary control

Control on the boundary conditions of this system is critical and includes slope toe seepage systems, base systems, and surface layer systems. The toe of the slope end is easily changeable utilizing an expandable rear-plate system. This system is constructed from a series of telescoping tubing welded onto each sidewall of the trailer. Hole spacing of 50 mm in the telescoping tubing was used for cross bracing and accommodating a variety of toe end systems with a simple bolt on/off configuration.

Figure 2 shows the collection system for baseflow and overland runoff. A simple change in the toe plate enables measurement of interflow at soil depths by screening and subcollecting the flow from those sections in a similar manner (see Figure 2b). This design enables easy changes to the downslope boundary condition. Swapping out midexperiment without destruction and rebuilding of the entire hillslope is possible.

FIGURE 1 Photo of the trailer-based hillslope system

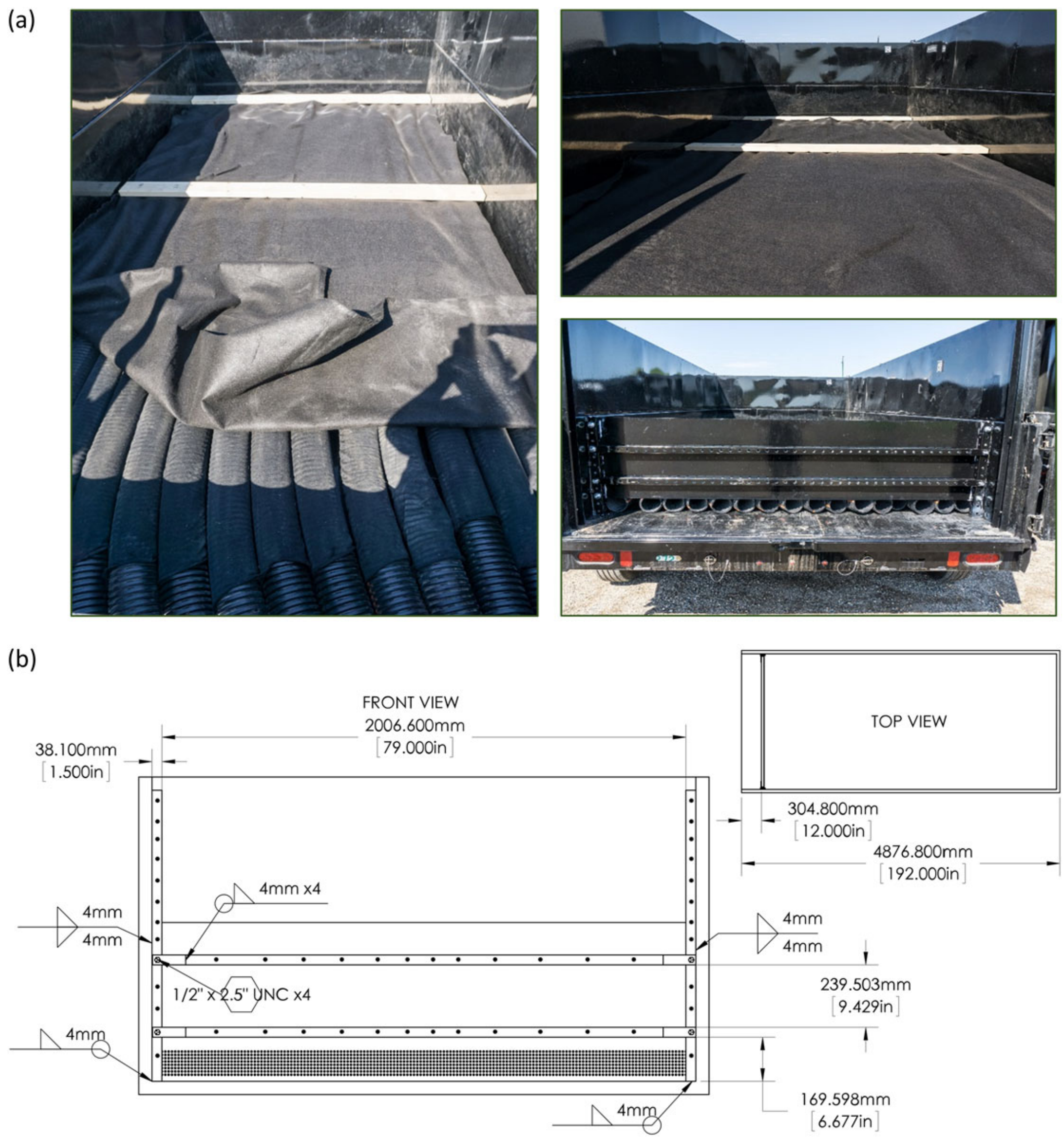

FIGURE 2 (a) Photos of baseflow and toe-end design utilized in current configuration; (b) schematic of current slope toe-end boundary condition

Figure 2a shows an experimental set-up with a base layer of side-by-side stacked weeping tile covered in a 3.2 mm (1/8″) thick nonwoven geotextile. This set-up provided a freely draining boundary layer that enabled the collection of soil base exfiltrate for groundwater recharge quantification and associated geochemical analyses. Other configurations could include gravel layers, sand layers, geotextile (woven or nonwoven), specialty geomembrane products, and other designs. Precipitation events are simulated with a needle drop-former rainfall simulator at rates ranging from 2 to 50 mm per hour. (Higher rainfall intensities can be achieved with additional nozzle-based systems.) Drying conditions such as higher temperatures and wind are simulated with heating and fans.

Flux into and out of the system due to precipitation events, or evaporation, is monitored with a system of load cells. The entirety of the trailer load is borne on a system of four load cells, each capable of measuring up to 4,500 kg (Loadstar Sensors—RAL1-10K-S) placed equilaterally via jacks on the trailer frame perimeter. The summation of the four load results equates to total trailer load with a precision of 0.002% of the full measurement capacity.

2.3 | Freezer components and design

To facilitate the hillslope freezing, the exterior side walls of the dump trailer were modified to accommodate a 100-mm layer of closed cell spray foam insulation (Figure 3a; PolyPlus Insulators, Saskatoon, SK, Canada). A ceiling system was also designed and constructed for the top of the hillslope and insulated in the same manner. A refrigeration unit (Heatcraft—Pro 3-PTN069L6BH) was placed in the centre of the top ceiling. It produced 9,600 BTU's of energy for targeting soil temperatures down to −30 °C.

We constructed the ceiling mounted system based on a triptych segment frame in which each piece was moveable easily by a forklift and two people. The frame construction incorporated 50 × 200 mm wood frames topped with 16-mm plywood

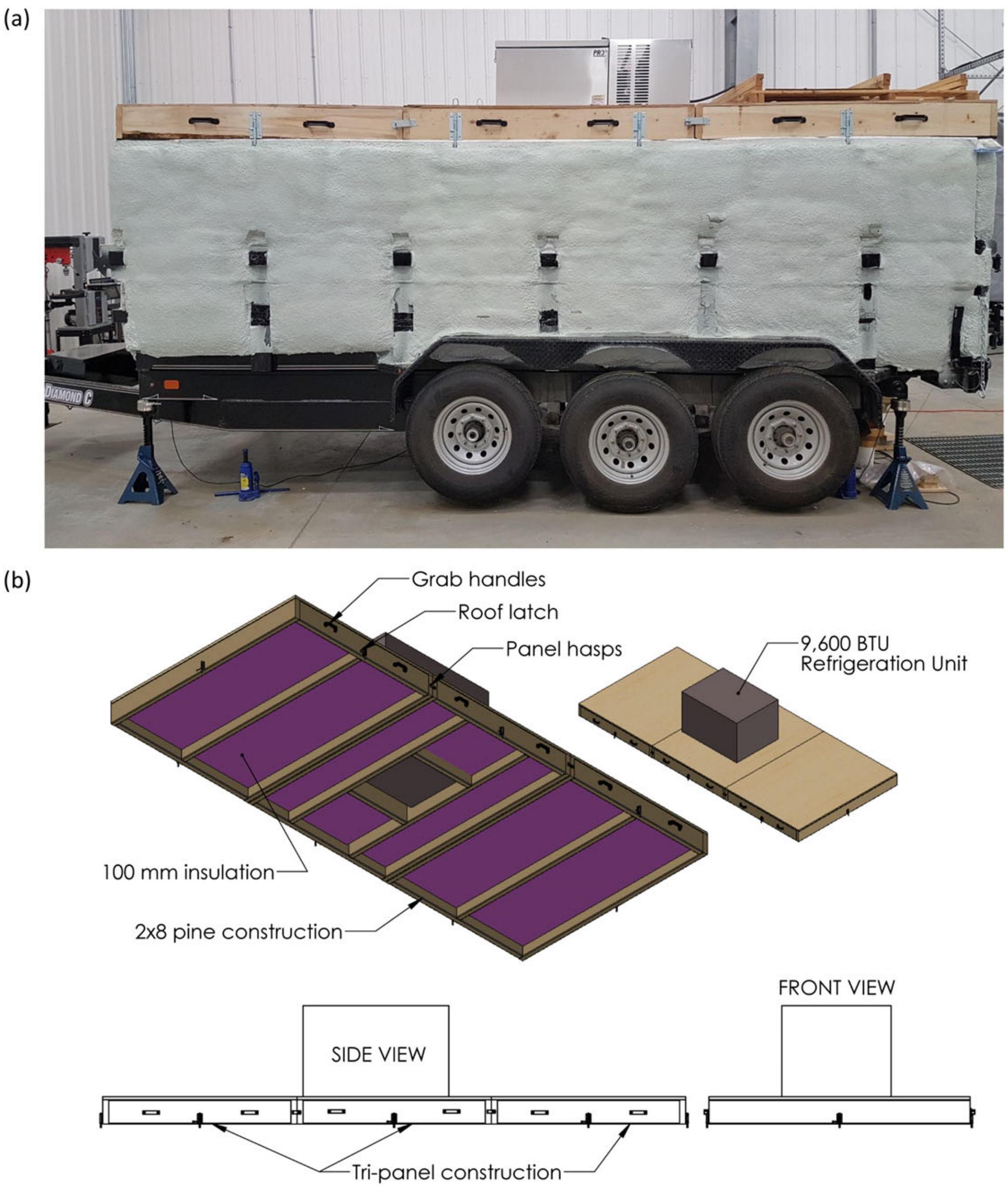

FIGURE 3 (a) Insulated hillslope with complete operational refrigeration system; (b) CAD drawing of the freezer design

(Figure 3b). The interior was insulated with 100 mm of closed-cell spray foam insulation. The centre frame was constructed to accommodate the refrigeration unit. To determine energy requirements and time to freeze the system, approximation calculations were performed (see Appendix) on the basis of a material thickness of 0.5 and 1 m at two water contents (20% and 25%) and verified experimentally (as discussed later).

The freezing refrigeration system has the capability to be programmed at specific freeze temperatures (in 0.1 °C increments) ranging from +10 to −35 °C. This enables the system to simulate realistic freezing scenarios or diurnal cycles seen throughout a typical winter freeze-up. This first scenario would most likely be time-consuming, and in order to expedite the process, the ability to set the system to rapidly freeze the hillslope by setting the temperature to maintain maximal subzero temperatures for the duration is crucial for high-throughput freeze–thaw cycle studies. This second scenario is demonstrated in the proof-of-concept testing that follows.

2.4 | The dry-down system for setting initial conditions

To prescribe and control initial conditions for each experiment, a dry-down system was developed. The dry-down system was aimed at both increased surface drying and injection of warm and dry air through the base of the hillslope for internal soil layer drying. Increased surface drying was accomplished through the use of accelerated airflow via surface fans and warmed low humidity air over an extended period of time. Drying was also accomplished in the same manner for systems incorporating baseflow drainage by the addition of a manifold at the baseflow exit that injected and circulated warm and dry air.

3 | PROOF OF CONCEPT RESULTS

We filled the tilt trailer with 15 m^3 of silt loam soil from Swift Current, Saskatchewan, the site of frozen ground hillslope research by Coles (2017). A hydromechanical sifting bucket attached to a skid steer was used to sift to particle sizes <25 mm. The sifted soil was then placed into the trailer in five 100-mm layers. Each layer was raked smooth and packed with a walk-behind vibratory plate packer (to a target bulk density of 1.2–1.5 g/cm^3, as measured at the Swift Current hillslopes). We installed thermocouples (Type K PFA Insulated, 24 AWG) at four depths—in between each soil layer—at 18 locations (on a 6 × 3 grid with 600 mm × 760 mm spacing; Figure 4). We installed soil moisture sensors (5TM Water Content and Temperature Sensors; Decagon Devices, Inc.) at four depths—laid horizontally in between each soil layer—at four locations (to represent four key landscape units on the hillslope). At the soil surface, we installed a denser array of soil moisture sensors (oriented vertically, with a measurement depth of 0–52 mm) at 18 locations (same 6 × 3 grid). Thermocouples were used to monitor temperature changes in the hillslope to quantify the timeline effects of freeze-up and thawing time. Soil moisture sensors are used to chronicle changing soil moisture conditions in each soil layer and the progression of infiltrated water during subsequent simulated precipitation events.

3.1 | Load cell tests and hillslope storage change

We tested the accuracy of the hillslope load cell system by adding approximately 11.6 mm of rainfall through our rain simulator at a rate of 35 mm/hr and measured load response utilizing the load cell system. Figure 5 shows the relation between rainfall depth and load cell response. Figure 4 also compared this to a modelled response assuming 100% rainfall distribution over the surface area. Modelled versus actual response was similar and followed the same trendline with end points that matched. Discrepancies between modelled and actual load changes can be accounted for by assuming oscillations in load due to velocity impacts of the raindrops on the surface. A closer look at higher frequency load cell data demonstrated this phenomenon. Surface soil moisture measurements also responded in a similar fashion with a 12.6% average increase in surface soil moisture in the top 52 mm of soil (results of 18 locations averaged; Figure 5) over the

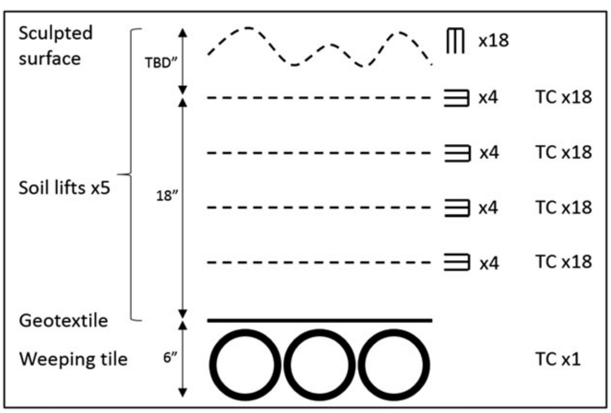

FIGURE 4 Schematic of sensor locations for freeze–thaw experimentation

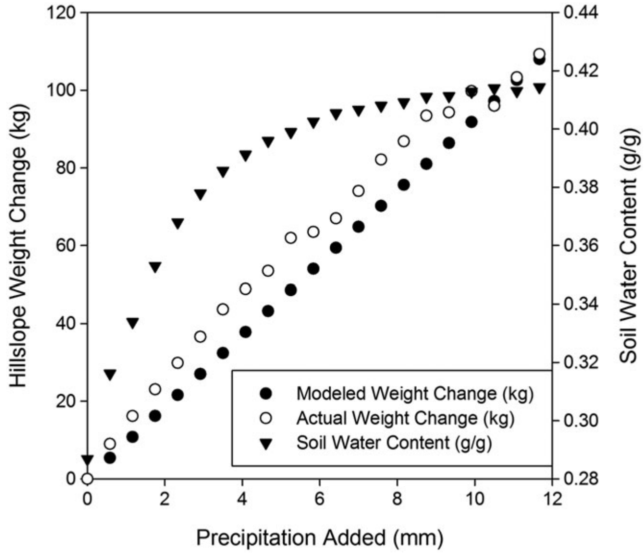

FIGURE 5 Load cell response to precipitation, actual versus modelled, coupled with concurrent volumetric soil moisture response

20-min precipitation/infiltration event. Precipitation not accounted for via soil moisture measurement can be explained, where once saturation levels were reached at this depth interval, water then passed below the 52-mm threshold of the soil moisture sensor into the subsurface.

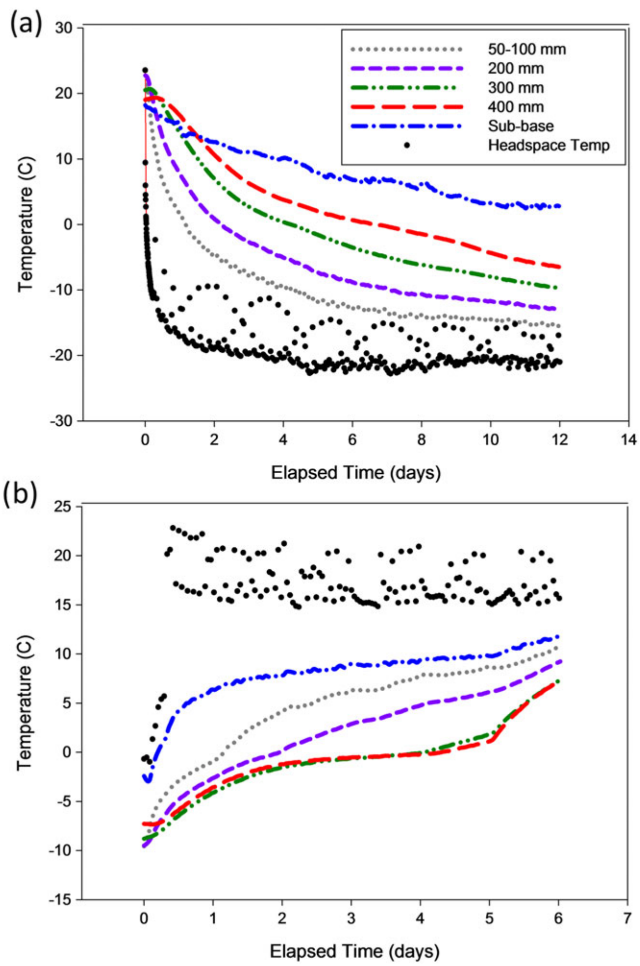

FIGURE 6 (a) Soil profile freezing test; (b) soil profile thaw test

3.2 | Soil freezing testing

We performed three tests to determine the soil freezing rate. Figure 6a shows the results of soil freezing depths versus time for the initial test at a profile mean soil water content of approximately 15%. Mean internal soil temperature at the beginning of the test was ~20 °C. Internal building temperature was reduced to ~10 °C and was maintained for the duration in order to expedite the process. The refrigeration coil was set to maintain a hillslope headspace temperature of −25 °C for the duration of the freeze cycle (refrigeration unit cycles between on/off as necessary for motor heat management). Approximately 7 days were required to freeze the entirety of the hillslope soil profile (from the top-down). As expected, the surface was frozen within 24 hr, with deeper soil layers freezing and reducing further in temperature over the following 6 days. Soil temperature reduction decreased exponentially through the profile. Figure 7 shows a two-dimensional cross-sectional through the centreline of the hillslope at Days 1, 4, and 7 of the experiment. Similar trends were observed for soil profiles with higher water contents, with freezing at higher water contents taking slightly more time, similar to the thermodynamic calculations in the Appendix. Hillslope thaw data for ambient temperatures of approximately 20 °C and 15% water content are shown in Figure 6b.

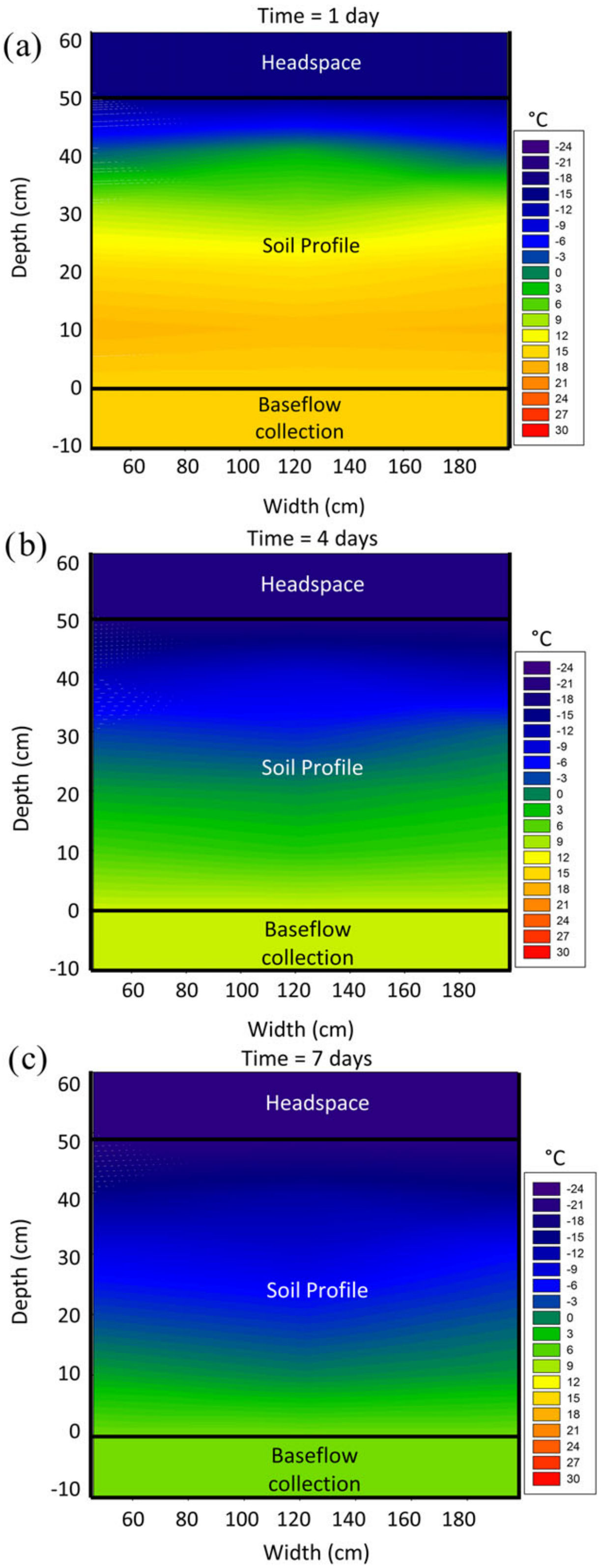

FIGURE 7 Two-dimensional cross-sectional slice of temperature profiles for elapsed time during freezing at (a) 1 day, (b) 4 days, and (c) 7 days

3.3 | Dry-down tests

Ambient headspace temperature of the hillslope was increased to 30 °C, and surface fans were added to the perimeter of the hillslope for three test days. Soil moisture dynamics and trailer load change were measured. The slope showed a drop in soil water content of 3–5% for the top 5 cm. To further facilitate drying through the soil profile, the surface drying system can be coupled with a manifold air injection system temporarily attached to the base of the toe slope boundary. Air can be either pulled through the hillslope by the attachment of a vacuum or pushed into the hillslope by injection into the base boundary layer. Calculated drying rates utilizing laminar flow rates at a minimum of 1×10^{-4} m^3/s at a relative humidity lower than 30% will achieve a drying rate of approximately 2.2 kg of water removed per day. The dry-down rate is determined by soil type, water content, air flow rate, humidity of injected air, and temperature. Soils with lower clay contents, lower water contents, higher hydraulic conductivities, and warmer temperatures will increase the rate of drying.

4 | CONCLUSIONS AND OUTLOOK

This paper presents the design and evaluation of a portable experimental hillslope for frozen ground studies. We describe the construction of the hillslope system including the design objectives and construction details of the tilting hillslope, the development of the freezer system and initial proof of concept of its operation. Fluxes and storage change into and out of the system are recorded using load cells.

We see much potential for the portable experimental hillslope for frozen ground studies in the future—for examining preferential flow development under freeze–thaw cycles, permafrost thaw impacts on flow and transport, temperature induced viscosity effects on slope-scale hydraulic conductivity, and moisture release conditions (building on early work by Hopmans & Dane 1986a, 1986b, 1986c and McDonnell & Taratoot, 1995).

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APPENDIX A

Table A1 shows common scenarios for freezing times based on the listed input parameters. Table A1 was generated utilizing engineering calculations for artificial ground freezing for earthworks applications. Approximation calculations including heat gain or loss from soil (q) were calculated following earth engineering protocols outlined by Xanthakos, Abramson, and Bruce (1996). This approximation

$$q_{soil} = \frac{1}{R_{soil}} * a((T_{ambient} - T_{target}) * 1.8) \quad \text{(A1)}$$

where T is temperature, a is surface area, and R_{soil} is the approximate insulation r-value of soil, estimated at 1. The heat requirement (C_u for unfrozen and C_f for frozen) to reduce the temperature of the soil by one degree per unit volume was also needed for both unfrozen and frozen soil and was calculated utilizing equations from Xanthakos et al. (1996):

$$C_u = Y_d\left(0.2 + \frac{\theta}{100}\right) \quad \text{(A2)}$$

$$C_f = Y_d\left(0.2 + 0.5\frac{\theta}{100}\right) \quad \text{(A3)}$$

where θ is water content and Y_d is the dry unit weight of soil (assumed to be 105 lb/ft^3 or 1.6 g/cm^3).

Similarly, the latent heat requirement to change water from liquid to ice (L) was calculated:

$$L = Y_d\left(144\frac{\theta}{100}\right) \tag{A4}$$

Once all heat requirements are calculated, the time required for freezing can be calculated using Equation A5:

$$\text{Cooling Time} = \frac{(Q_u + Q_f + Q_L)*V_{soil}}{\text{Capacity of Cooling Coil}} \tag{A5}$$

where the volume of soil (V_{soil}) and the capacity of the cooling coil applied to the system is (in this case) 9,670 BTU/hr. Thaw times will be representative of freezing times under similar heating conditions (20 °C room temperature maintained until complete thaw; Xanthakos et al., 1996):

Where

$$Q_u = C_u(T_{ambient} - T_{target}) \tag{A6}$$

$$Q_f = C_f(T_{freezing} - T_{target}) \tag{A7}$$

$$Q_L = Y_d\left(144\frac{\theta}{100}\right) \tag{A8}$$

TABLE A1 Freezing timeline at 20% and 25% moisture content for two cover thicknesses and three target subsurface temperatures

Cover thickness (m)	Soil moisture (%)	Target temperature (°C)	Time (days)
0.5	25	0	4.53
0.5	25	−10	5
0.5	25	−20	5.5
0.5	20	0	3.77
0.5	20	−10	4.2
0.5	20	−20	4.63
1	25	0	9
1	25	−10	10
1	25	−20	11
1	20	0	7.5
1	20	−10	8.4
1	20	−20	9.27