THERMAL AND HYDROLOGICAL EFFECTS OF SLOPE DISTURBANCES IN A CONTINUOUS PERMAFROST ENVIRONMENT

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Abstract

In a continuous permafrost area near Resolute, N.W.T., a berm, a trench and an impermeable subsurface flow barrier were emplaced across a slope, and compared with two undisturbed segments. These plots enabled the observation of thermal and hydrological effects of these disturbances in a continuous permafrost environment, during the course of an Arctic summer. The disturbed slope plots interrupted the downslope movement of water. Where the snow distribution was affected by the presence of a trench or a berm, the pattern of ground thaw was modified also. Additionally, a section of a vehicular track across a wet depression was examined. Compared with the dry road bed, the wet section had a shallower frost table, retained more snow in the ruts and, being fed by the wet depression upslope, maintained a high water table for most of the summer.

Résumé

Dans une zone de pergélisol continu située près de Resolute (T.N.-O.), on a mis en place une berme, une tranchée et une barrière impermeable aux écoulements souterrains en travers d'une pente, puis on a comparé cet endroit à deux segments intacts. Ces parcelles ont permis d'observer les effets thermiques et hydrologiques de ces perturbations dans un milieu de pergélisol continu, au cours d'un été arctique. Sur les parcelles à pente perturbée, le mouvement de l'eau vers le bas de la pente a été interrompu. Aux endroits où la répartition de la neige a été affectée par la présence d'une tranchée ou d'une berme, la configuration du dégel dans le sol a aussi été modifiée. En outre, un bout de piste pour véhicules à travers une dépression humide a été examiné. Comparativement à la partie sèche du chemin, le tronçon humide possédait un front de gel moins profond; retenait plus de neige dans les ornières et, étant alimentée par les versants, a maintenu une nappe phréatique élevée pendant la plus grande partie de l'été.

Introduction

As development and human settlement continues in the North, terrain disturbances become more frequent. Many studies have been conducted to examine the environmental effects of various forms of disturbance in the region underlain by permafrost (French 1975 and 1987, Lawson 1986, Rickard and Brown 1974, van Everdingen 1974). Only a limited number of studies pertain specifically to the hydrological impacts (e.g. Harlan 1974, Klinger et al. 1983, Stanley and Cronin 1983). Few controlled experiments to determine how the disturbances influence the hydrology of Arctic slopes have been conducted(Soulis and Reid 1978). This paper reports on experiments performed on a slope in continuous permafrost terrain, and compares the result with observations made along segments of an existing roadbed that crosses a wet depression. The purpose is to understand how human interference modifies the thermal and hydrological processes. Only the highlights of the experimental results are presented

Experimental design and instrumentation

Resolute (74° 45' N, 94° 50'W) was chosen as the study site because earlier work there offers a basis for understanding the hydrological and thermal behaviour of the natural slopes (Woo and Steer 1982 and 1983). The nearby weather station provides long-term climatic record, while the proximity to a settlement offered existing examples of terrain disturbances such as roads, ditches and buried pipes. Continuous permafrost underlies the area, usually at a depth of 0.3-0.7 m. The January-to-March mean minimum temperature is -36°C, and the summer mean maximum of 7°C is reached in July. The reported mean annual rainfall is 59 mm and the mean annual snowfall of 78 mm is considered to be an underestimate (Woo *et al.* 1983).

Two sites were chosen, one being a slope where treatments were introduced to simulate terrain disturbance, the other being an example of disturbance already created by human activities. The experimental slope, at 3 km northeast of Resolute, has a gradient of 0.06 and is relatively uniform except for minor undulations that give slight convexities and concavities to its profile. Slope materials consist of mixtures of gravel and silt, with certain zones having a slightly larger content of fines. There are only minor patches of tundra vegetation cover, but a large semi-permanent snowbank occupies the zone upslope of the experimental plots. This provided a steady supply of water during summer (Young and Lewkowicz 1988). Five plots were set up, two of which to act as controls, and were located on the western and eastern edges of the study site. The other treatment plots were emplaced in early September 1987. They included a subsurface barrier, a trench and a berm, to represent respectively buried impermeable structures, ditches and roadbeds. The subsurface barrier was a plastic sheet inserted from the ground surface to a depth of 1 m. The trench was 0.6 m wide and 1.1 m deep. The berm was created by piling gravels on the slope to a width of 1.5 m and a height of 0.75 m. Although these treatment plots were scaled down representations of such features as road berms or ditches, their effects on slope hydrology will indicate qualitatively the impacts expected of such terrain disturbances. All the plots, oriented across the slope, were 6 m wide and their centre lines were separated from one another by 20 m. Running along the centre lines were transects of snow survey, groundwater wells and frost table survey points (Fig. 1). Surface runoff was measured at a point 10 m downslope of each plot.

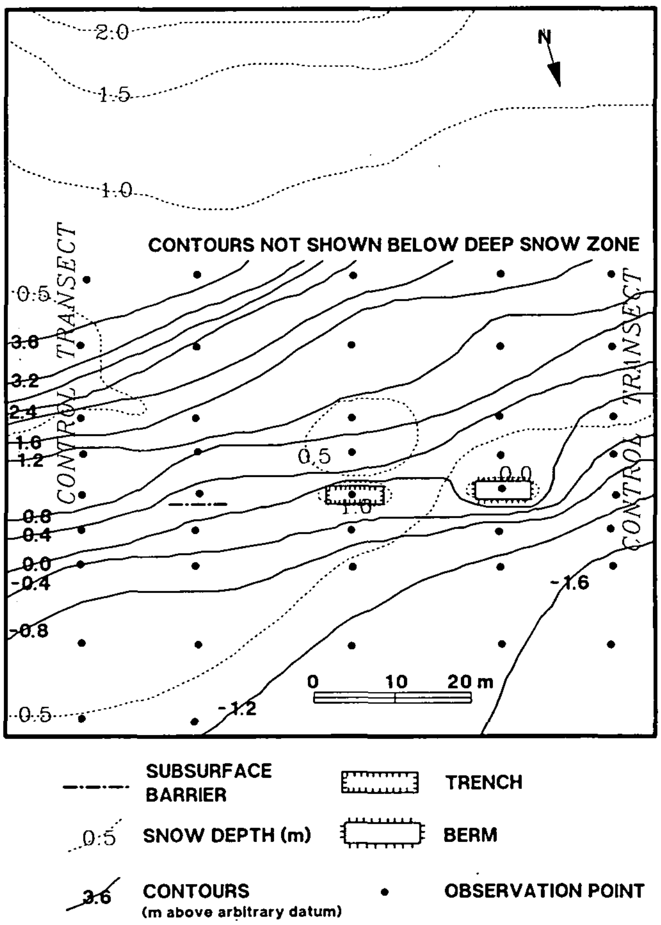

Figure 1. Topography and snow distribution on experimental slope.

The other study site was located 3 km north of Resolute where a gravel road crosses a wet depression. The road was created mainly by veneering the ground with a thin layer of gravel. A transect of groundwater wells and frost table measurement sites was laid out diagonally across the road, from the depression, across the rutted road surface, to the streambed and then up a gravel slope. A parallel transect, 30 m away, was used to measure frost table depths in drier parts of the road and the slope (Fig. 2).

At each study site, a snow survey in early June provided information on snow distribution (see Woo et al., 1983, for method). Snowmelt was computed with the energy balance method (Heron and Woo 1978) using data acquired at a meteorological site set up on flat terrain below the experimental slope. Rainfall was recorded with a tipping-bucket gauge. Frost table was probed by hammering a steel rod into the ground. Water table was measured at the groundwater wells which were reinforced by perforated plastic pipes. Both the frost and the water tables were measured daily at the early part of the field season, but frost table data were gathered at longer intervals after the ground began to thaw more slowly at depth. Surface flow was recorded using the method described by Woo and Steer (1982).

Experimental plot results

Snowmelt in 1988 came early, in May, because of unusual warmth in the Arctic. This melt period was brief, however, and did not generate any slope runoff. Cold condition and more snowfall followed, and the primary melt season did not begin until late June. The shallower snow cover was depleted rapidly, but upslope of the experimental plots, the deep snowbank lingered throughout the summer to yield meltwater continuously to the slope. Summer temperature was above normal for Resolute (Fig. 3) and the arrival of frost in mid-August arrested the melt of the snowbank.

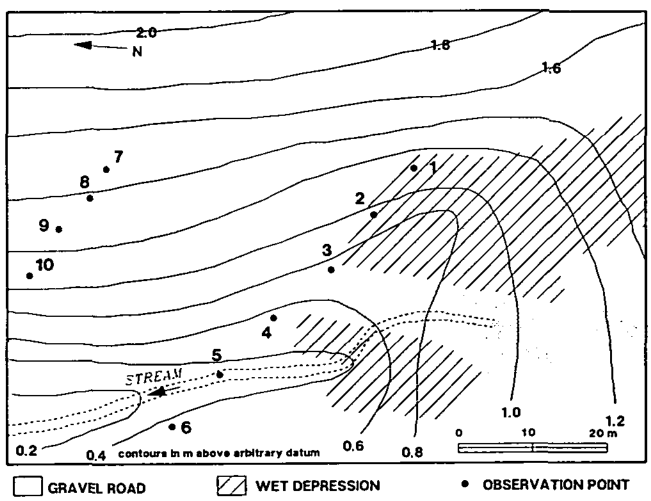

Figure 2. Gravel road crossing at wet depression site. Numbers refer to various groundwater wells.

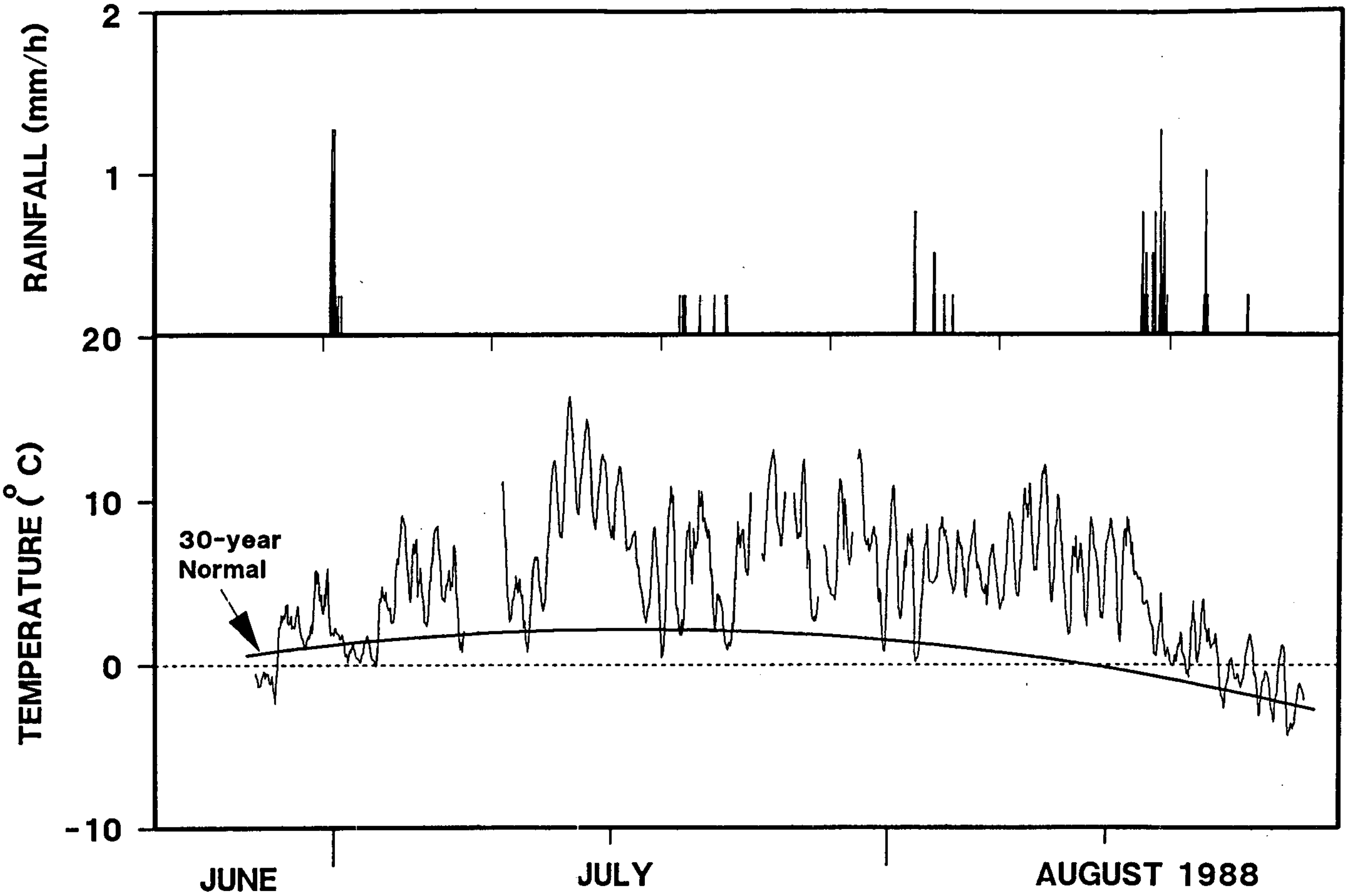

Figure 3. Hourly temperature and hourly rainfall for the study period in 1988. Resolute 30-year normal temperatures are added for comparison.

CONTROL PLOTS

The deployment of the control plots on either side of the treatment plots brackets the spatial variation of the natural slope. The western plot was more gravelly while the eastern plot had a slight concavity.

The first day of ground thaw varied on the slope, depending on the time when the snow cover disappeared at the site (Fig.4). Deeper snow often stayed on longer and thawing was delayed accordingly, as was the case for the eastern control plot. Once started, the initial thaw was rapid but the summer depth of thaw varied depending on the soil

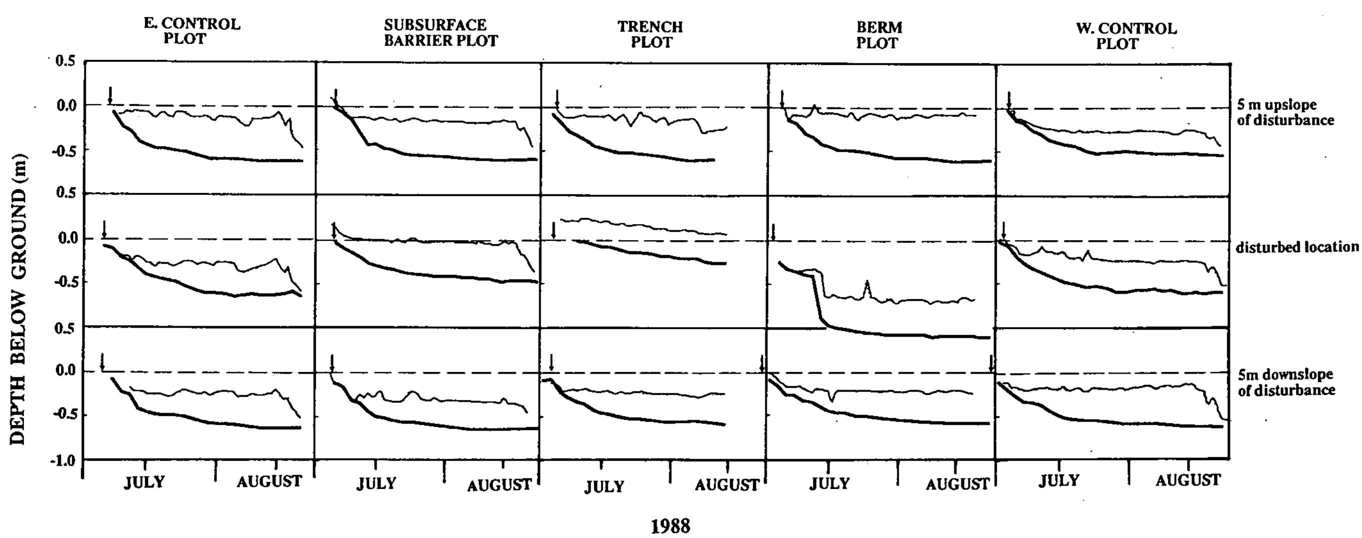

Figure 4. Fluctuations of water table (dotted lines) and frost table (full lines) at the experimental plots between July 1 and August 23, 1988. Surface runoff occurred when the water table was above the ground, except in the trench where water was ponded. Arrows indicate dates when particular sites became snow-free.

thermal properties. All the observation points at the eastern control plots reached similar depths of thaw by early August. The western plot was more variable, reflecting a larger range of soil conditions on that side of the slope.

Surface runoff was generated when the water table rose above the ground. This condition occurred at the early part of snowmelt when the thinly thawed active layer was unable to retain the abundant meltwater produced on the slope. As ground thaw progressed, more storage capacity for the suprapermafrost groundwater became available, and the water table dropped. Throughout the summer, meltwater from the deep snowbank continued to feed the experimental plots, and a moderate to high water table was always maintained. After mid-August, however, melting was halted by cold conditions, and the loss of meltwater supply caused a rapid drop of the water table (Fig.4).

Subsurface barrier plot

As expected, the presence of a subsurface barrier did not interfere with snow accumulation and the depth of snow was similar to those for the control plots. The evenly distributed snow disappeared early and ground thaw began simultaneously at the zones above and below the barrier. However, thawing was considerably slower at the treated location. One possible explanation is that the water table there was above the surface for a protracted period in summer. Having consumed much of the atmospheric energy input while it was warmed, the surface water moved downslope, convecting with it the heat thus gained. The positions above and below the barrier did not suffer from such lateral advective loss of energy and therefore more heat was transferred vertically to thaw the active layer.

In early July, the ground was thawed thinly and the water table remained above the surface to generate surface flow (Fig. 5). Gradually, thawing the active layer provided more

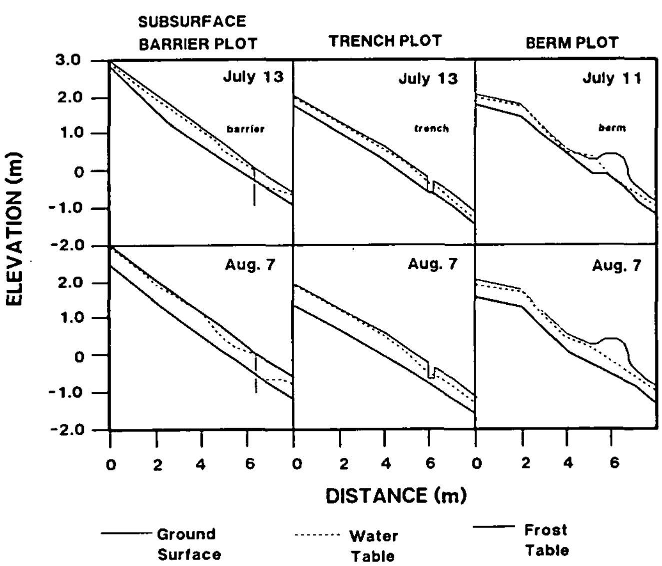

Figure 5. Profiles of the slope, water table and frost table at the treatment sites in midJuly and early August, 1988.

storage capacity for the suprapermafrost groundwater and the water table generally declined. The exception was at the barrier where impermeability prevented downslope groundwater movement. Consequently, water was impounded upslope of it to maintain a high water table and to sustain surface flow over a longer time (8 days here, vs 6 days at the adjacent control site). Immediately below the barrier, groundwater supply from upslope was cut off (though some water could seep in from across the slope) and the water table was depressed. This configuration of the water table corresponds with the pattern reported by Soulis and Reid (1978).

Trench plot

As a topographic depression, the trench was filled with snow to a depth of 1.2 m. As melt began, the percolation of meltwater from upslope and from the *in situ* snow refroze, inhibiting the thaw of the trench floor until the snow and ice melted. Not only was ground thaw delayed, but the thawing front advanced more slowly than the adjacent control areas because much heat was consumed to warm and to evaporate the water which remained in the trench until mid-August (Fig. 4).

Initially, when the ground was frozen and the trench was filled with ice, surface flow swept across the trench to the lower slope. Surface flow terminated on July 3 as the water table dropped. Being topographically lower than the adjacent zones, the trench then acted as a storage tank that intercepted the water from upslope. Water level in the trench dropped continuously in summer as evaporation and lateral flow removed much of the water (Fig. 5).

Berm plot

The top of the berm was blown free of snow and ground thaw started much earlier than elsewhere on the entire slope. Earlier thaw and the gravelly and drier nature of the berm (which yields higher thermal conductivity) combined to produce the deepest thaw depth (Fig. 4). The stepped descent of the thawing front shown in the diagram was probably caused by frost table measurement error. The probe hit a large gravel fragment and the observer thought that it had encountered the frozen soil.

The frost table along the slope transect was quite close to the ground surface on July 7, and the berm with a frozen core was thus relatively impermeable to soil water movement. Like the subsurface barrier, the berm then impounded water so that surface water occurred upslope of the berm, but not below it. The berm itself did not have a saturated zone until the rapid frost table descent eliminated the subsurface frozen core to allow groundwater movement down the slope.

Gravel road site results

The gravel road has been in use for several decades, though the volume of traffic was minimal. Unlike a wellplanned highway, this road was roughly levelled by a grader and for most parts where it traverses the slopes, does not have an elevated berm above its surrounding. Where this road crosses wet depressions, erosional forces from runoff have exploited the vehicular tracks to form ruts and holes up to 0.2 m depth, and part of the road bed was breached by running water. A comparison with the zones on either side of the road may indicate the disturbance effects.

At the end of the 1987-88 winter, the depression was an area with thick snow drift. Abundant runoff was generated during the melt season and surface flow from the depression swept across the road into a small stream. The stream level was kept high until much of the snow was gone, and then it fell rapidly (Fig. 6). The ruts in the road retained much water even after the stream level dropped. Where the road crossed the shallow valley, ground thaw was delayed until the snow and ice in the hollows have melted. Postponement of thaw and an often saturated condition during the summer led to a thinner active layer compared with the drier gravel slopes. The transect of the road segment on the dry portion of the slope revealed that the thaw under the road bed was earlier, and the active layer was deeper than at the depression crossing site.

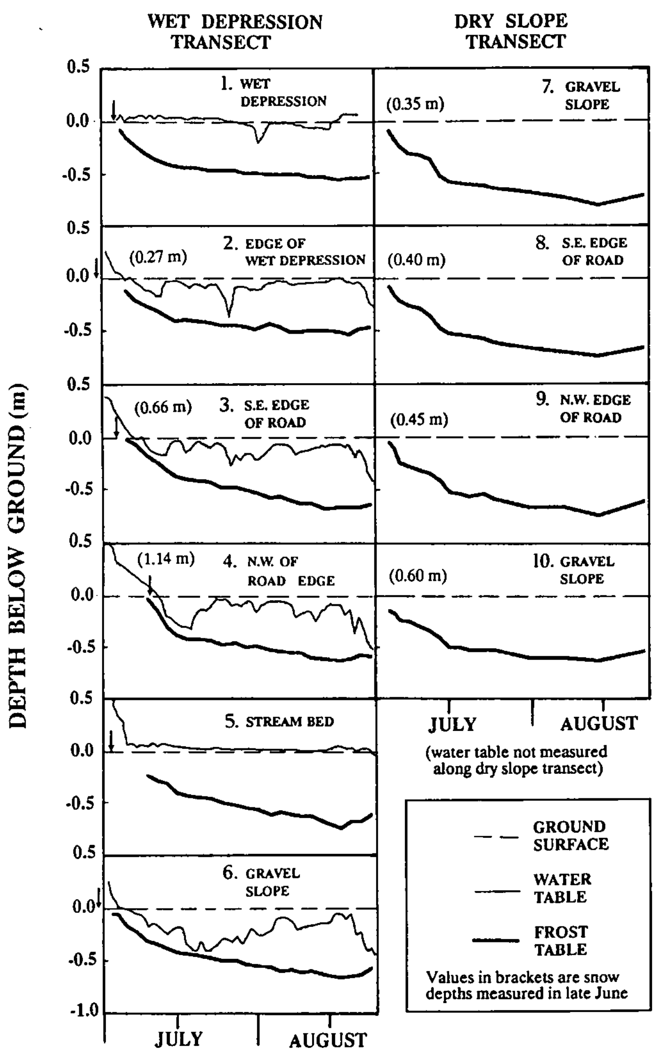

Figure 6. Fluctuations of water table and frost table along transects across the gravel road Numbers refer to the locations shown in Figure 2, and arrows indicate dates when particular sites became snow-free.

A dry period following the initial snowmelt led to a drop in the water table, but this was reversed as rainfall raised the water in the depression to feed the areas downslope. The road bed at the crossing acted as a berm while its ruts were analogous to shallow trenches, separating the depression from the stream. The stream did not rise to high flow again during the summer, despite the occurrence of several rainstorm events.

Conclusion

The two control plots revealed that there are notable spatial differences in the thermal and hydrological behaviour on a relatively uniform slope. Differences in snow distribution, hence the timing of snow disappearance, affected the date of initial ground thaw. Despite such natural variabilities, the slope treatment effects were readily discernible. Thermal and hydrological responses to the treatment plots suggest that the disturbance effect extends over a broad zone upslope and downslope of the actually disturbed locations. Ground thaw was retarded or accelerated compared with the undisturbed sites, depending on whether snow accumulation was affected. Water movement in and on the slope were both interrupted, either because of the subsurface imperviousness introduced, or because of topographical hindrance to flow. In all cases, the strong feedback between the heat and water status reinforced the impacts of disturbances on the permafrost slopes.

In the case of the road bed, the road acts as a low barrier that separates the depression from the stream, though this road was breached at several places, permitting some water to pass through. The vehicular tracks have developed into deep ruts which are equivalent to shallow trenches. The thermal and hydrological effects of the road crossing are the outcome of processes similar to those for the treatments on the experimental slope. This study illustrates the usefulness of conducting field experiments to gain understanding of the physical processes operating in disturbed terrain.

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