WINTER SOIL WATER DYNAMICS

COMPLETION REPORT

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TABLE OF CONTENTS

FIGURES

INTRODUCTION

The movement of soil moisture through cold regions soils is an active process that continues throughout the year. It represents one mechanism of heat transport in subsurface soil, conduction being the main mode of heat flow. In frozen soils, this moisture may undergo phase change resulting in two significant events:

1. deformation of the near-surface layer, and
2. liberation or uptake of heat at the point of phase change.

Where deformation (induced by either frost heaving or thaw consolidation) occurs in man-made embankments, it is readily apparent at the surface. Restoration of the deformed surface requires large sums of money.

It has been demonstrated that soil moisture moves in the direction of cold surfaces, and that this movement is a function of both the thermal and moisture regimes. In order for moisture to move toward a heat sink, there must to be a pore pressure gradient that decreases in the direction of flow. With both frozen and unsaturated soils, the hydraulic conductivity is variable. If the hydraulic conductivity and pore pressure gradients are known, then the quantity of flow can be determined. In a saturated frozen soil the hydraulic conductivity is found to vary with soil type and temperature. In unfrozen, unsaturated soils, the hydraulic conductivity is found to vary with soil type and soil moisture content; soils with low moisture contents have lower hydraulic conductivities.

Vapor phase transport is occurring continuously; however, this is considered to be minimal in dry soils. Therefore, in order to predict the quantity of moisture movement in frozen soils, the soil moisture content, temperature gradient, and pore pressure gradient of a given soil type need to be known. The purpose of this study was to gather some of this data for use in the prediction of frost heaving magnitude and general hydraulic applications.

Much of this information has been collected in a similar study sponsored by the U.S. Forest Service. The goals of the Forest Service study were to examine summer field soil and thermal conditions in a black spruce forest. These forests are very susceptible to fire, primarily because of the surface organic layer they help support. Large quantities of nutrients are tied up in these organic layers, and following a fire these nutrients are released. Surface water and soil water represent the major mechanisms for redistribution of the nutrients. Because permafrost is often found to be underlying these forests, a very shallow flow system of one meter or less exists. So nutrient contributions to the surface streams may be very rapid for this type of system.

Land management people are aware that fire abatement has become quite efficient. Statistics verify this point: although the number of fires have increased over the past 30 years, the total average number of acres burned has decreased by a factor of two. Consideration has been given to allowing certain fires to burn uncontrolled and even having prescribed burns. The major unknown at this time is the long-term impact on the water quality of surface streams.

Two major periods of runoff occur during the summer in cold regions: one follows the spring snowmelt breakup and the other occurs after periods of substantial rainfall. The snowpack that accumulates over a 6- to 7-month period converts to several inches of available water for seepage and runoff during the spring. The soil condition just prior to this event is an unknown factor of major importance. Prior to these events, the moisture movement was upward out of the soil. Once this excess of water is available the flow direction rapidly changes.

OBJECTIVES

Several factors related to heat and mass transfer with regard to frozen soil must be researched. The two major goals of this study were

1. to evaluate and develop methods of measuring soil tension in advance of the freezing front, and

2. to collect some preliminary soil tension data beneath the the seasonal frost throughout a winter.

RESEARCH PROCEDURES

Soil tension measurements had been made during the previous summer with conventional water-filled tensiometers and mercury manometers. Fluid freezes in those portions of the tensiometers filled with water that are exposed to freezing temperatures. Mixtures of fluids, such as ethylene glycol and water, that suppress the freezing point, do not have the same properties as pure water.

Two techniques were tried for measuring pore pressure. In the first, water was replaced in the tensiometers with a solution of ethylene glycol and water. As previously alluded to, this technique is questionable since the interaction of this antifreeze solution and the porous media is not known.

The second scheme consisted of filling a small tensiometer with water and filling the tube running from it to the mercury manometer with an antifreeze solution. A mercury plug separated the two fluids to prevent mixing. The placement of the tensiometers as well as other instrumentation is shown in Figure 1.

The measurement of pore pressures during the winter was envisioned as both a laboratory and field exercise. The field data was collected at Washington Creek, an area with extensive permafrost. In some areas at Washington Creek, permafrost is absent; in others the permafrost table is only 50-100 cm below the ground surface. The soil profile is described as 20-25 cm of organic material over a mineral soil of silt loam. Highly weathered schist is the predominant bedrock geology. The significance of the organic layer is that it acts as a buffer to both heat and moisture flow.

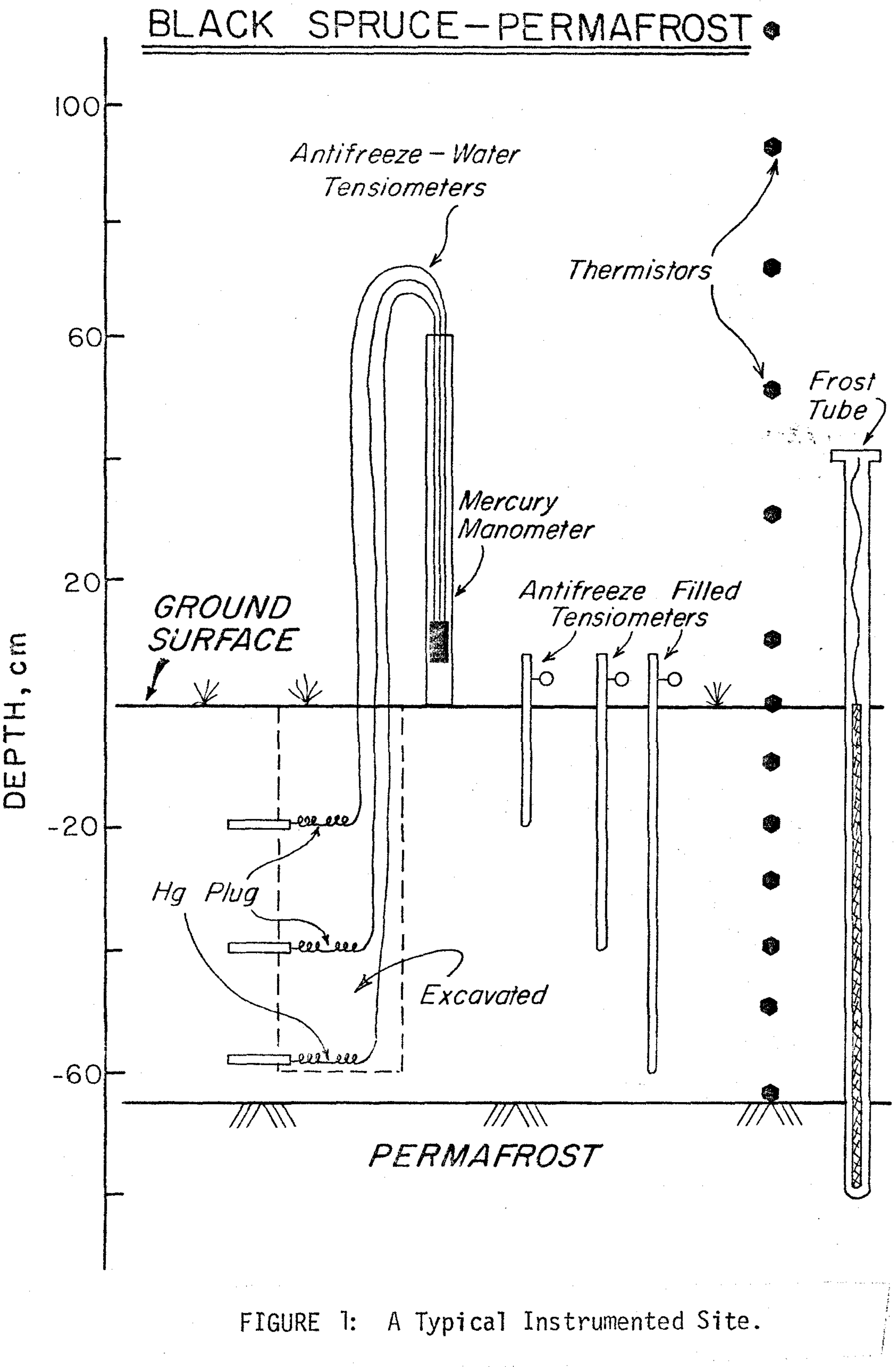

FIGURE 1: A Typical Instrumented Site.

Soils sampled from this same area were taken back to the laboratory to be frozen artificially. Freezing rate and pore pressure measurements were made. Inability to freeze the sample completely from top to bottom was experienced as the rate of heat gain exceeded the cooling capacity of our refrigeration unit.

Several field parameters were measured during the course of field program: snowpack and gravel temperatures, soil moisture content, snow depth, and air temperature.

Partial results of this study are to be found in the following two publications:

Kane, D. L.; Luthin, J. N.; and Taylor, R. S. (1975). Physical Transfer Processes in Subarctic Soils Influenced by Forest Fires. Proceedings, Conference on Soil-Water Problems in Cold Regions, American Geophysical Union, Calgary, Alberta, pp. 128-147.

Kane, D. L.; Luthin, J. N.; and Taylor, G. S. (1975). Heat and Mass Transfer in Cold Regions Soils, Institute of Water Resources, University of Alaska, Fairbanks, IWR-65, 50 pp.

Figures 2 and 3 illustrate the results of measured soil tensions at two sites for the two types of instrumentation used in the field. It is obvious that the negative pore pressures are much greater during the winter months, indicating an overall decrease in soil moisture. It is also apparent that the pore pressures are much greater near the surface indicating that at times moisture movement is in that direction. Gravimetric soil moisture contents indicate an overall decrease of moisture in the soil column within 1 meter of the surface.

Data on soil tensions were collected only to January; at that time, the liquid loss in the tensiometers was substantial. It was assumed that the fluid in the tensiometers froze, thus breaking the tubes and allowing the fluid to drain. When these tensiometers were removed in the summer, they were found to operate satisfactorily. During the period in which they failed, record-setting temperatures of -55 to -57°F prevailed. Apparently, the tension exceeded the operational range (≈0.8 atmospheres - 800 cm of water) of the ceramic porous cups, causing large losses of fluid.

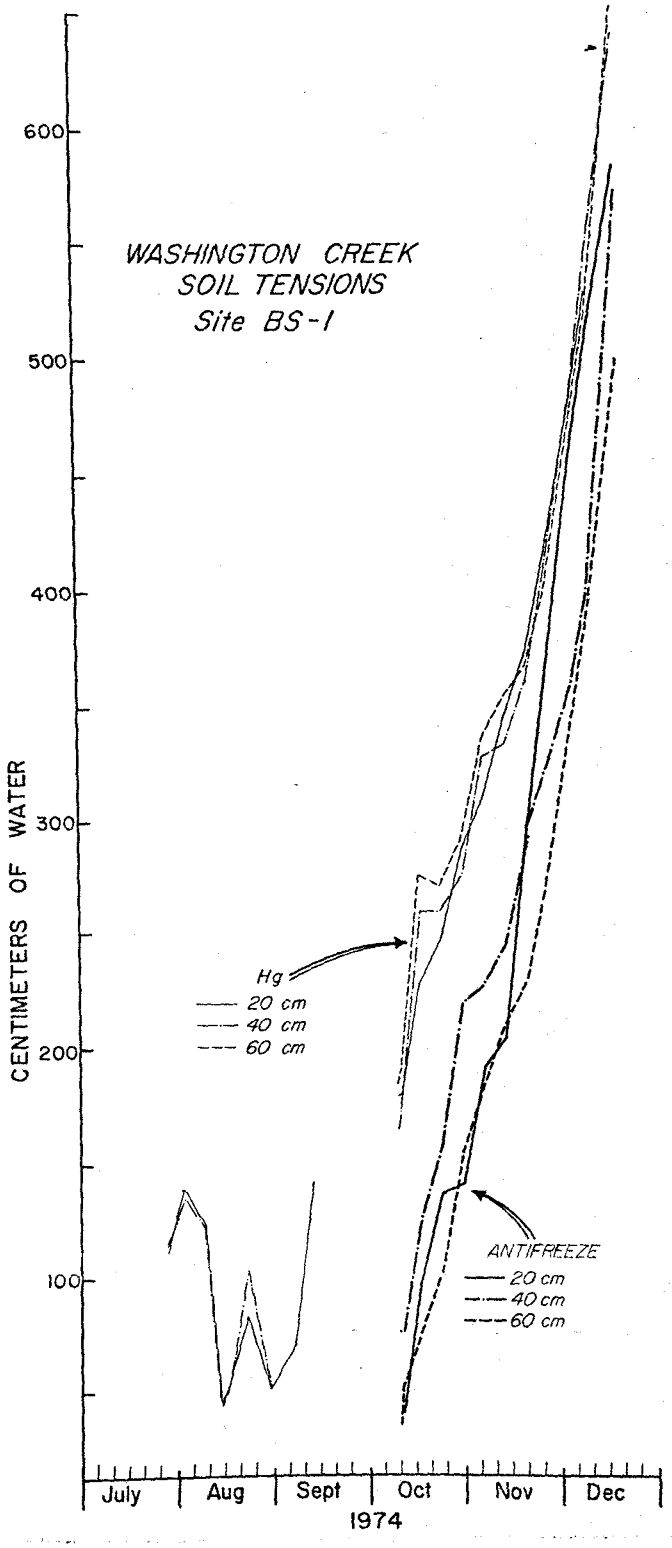

FIGURE 2: Measured Soil Tensions at Site BS-1.

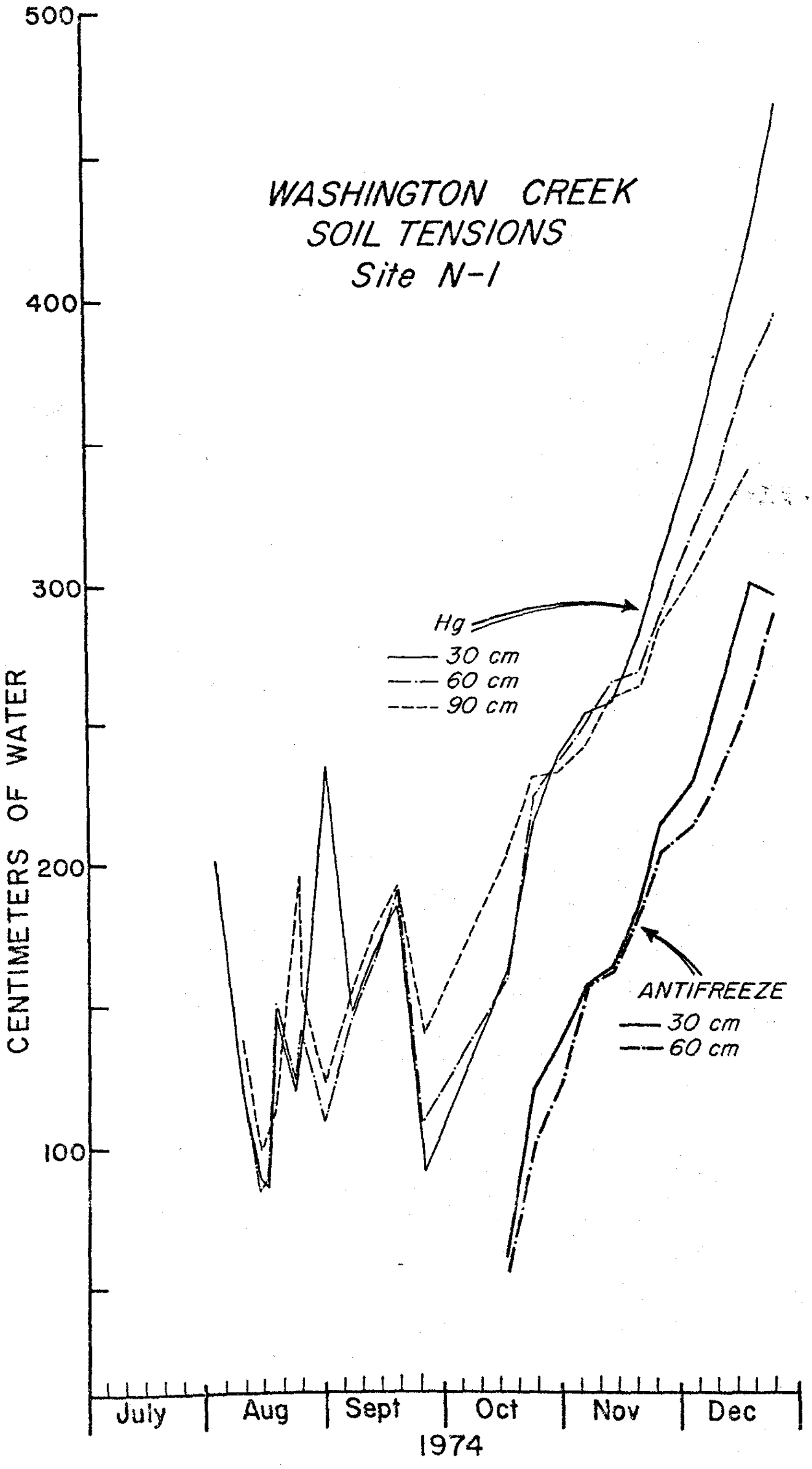

FIGURE 3: Measured Soil Tensions at Site N-1.

CONCLUSIONS AND RECOMMENDATIONS

The recognition of many beneficial effects of fire has altered the present fire control philosophy. From our field data, it is clear that both the thermal and moisture regimes undergo considerable alterations because of fires. The degree to which these systems are influenced depends upon many factors, primarily the intensity of the burn. Prior to any fire, natural variations occur because of slope, aspect, vegetation, and soil conditions. Basically, fires tend to add more variability to the natural setting.

It is this variability that makes modeling on a watershed scale very difficult. Alteration of the system will have to be linked with the intensity of the burn. Assuming acceptable models are generated and prescribed burning becomes a reality, models for predicting the fire intensity will have to be developed. These models will be based on weather and fuel conditions prior to and during the fire, as well as terrain features.

The conclusions reached from the temperature and soil moisture data are

1. That thermal regime is substantially altered by fire; it appears that the conceptual model presented accurately defines the long-range pattern of the thermal regime. It is apparent from the field data that soil temperatures in the burned area are much higher than those in the unburned area for both summer and winter seasons. The variation in the thermal regimes of the two unburned sites is not as extreme. It should be emphasized that the difference in the depth to the permafrost table differs by a factor near 2. This represents the magnitude of variance expected due to differences in vegetation, slope, slope aspect, drainage, etc. The depth to the permafrost table in the burned area was never determined. From the measured temperatures, it is clear that it is now at a depth of several meters (and degrading); prior to the burn, it was probably at a depth near 1 meter.

2. The near-surface moisture regime is influenced by fire, but not to the same degree as the thermal regime. Due to a decrease in evapotranspiration losses, the total moisture content in a column of soil should increase. It is obvious from our data, however, that the natural variability that exists in undisturbed areas exceeds our observed variability between an unburned site and a burned site. One reason is that, where permafrost exists, the water is confined to a thin layer near the surface. As the permafrost degrades, however, there is a much thicker near-surface layer in which this water may be retained or through which it may be transmitted. The role of the organic layer in a burned environment depends upon the intensity of the fire. In organic soils in unburned settings, the tensiometer data shows that water is retained by this layer and is later lost by evapotranspiration. It would be expected that saturated conditions would develop only during heavy rains. This would result in a lateral flow as well as an addition of water to the lower mineral soil. The tensiometer data for early winter reveals that the movement of soil moisture is upward towards the surface, resulting in some depletion in both the organic and mineral layers. The part played by heat conduction in thawing frozen soils is well understood; however, the amount of heat transmitted by convection (flowing water) above or through a frozen soil is not known.

3. The flow results from the computer model give some insight into the length of time associated with drainage of the organic layer and the rate of outflow from a slope of given width. During the period in which the summer field data was collected, rainfall was exceedingly light and was never sufficient to produce saturated conditions in the organic layer. Saturation levels for these organic soils generally exceed 600% (by weight) and the maximum moisture content we measured was near 400%. Since the conditions necessary to cause lateral flow never occurred, no comparison with theoretical results is possible.

The collected data on pore pressures clearly indicates the dynamic nature of near-surface soil moisture activity during the winter months. What needs to be developed is instrumentation to measure negative pore pressures of greater magnitude. This study concentrated on measuring pore pressures in advance of the freezing front because of the lower expected values. This approach is valid because the moisture must migrate from the unfrozen zone to the freezing front. However, movement of water through the frozen zone does occur. This can only be determined accurately by measuring the pore pressures in this zone. Theoretical thermodynamic equations predict very high negative pore pressures for this zone. The volume of water movement will depend upon the natural pore pressure gradient and the hydraulic conductivity of this frozen element. The collection of such data would not only shed light on this complex process, but would also help prove the usefulness of many of the present heat and mass transfer models.