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PLOT MEASUREMENTS OF SNOWMELT RUNOFF FOR VARYING SOIL CONDITIONS

by

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Abstract

Snowmelt runoff measurements were made for numerous plots with widely varying moisture conditions within the seasonally frozen zone. A wide variation in the runoff volume could be expected depending upon the water equivalent and melt rate of the snowpack and soil conditions. The soils used in this study were normally quite dry prior to the onset of seasonal frost. To ensure a wider range of soil moisture conditions, some of the plots were irrigated 3 to 4 weeks before the soils froze. Winter redistribution of soil moisture from depth toward the descending freezing front resulted in increased moisture levels near the ground surface. The condition of this zone (≅10 to 20 cm) controlled the amount of infiltration during the snowmelt period. Moderate moisture levels (15–30 % by volume) prior to seasonal freezing produced soils with relatively low infiltration rates that resulted in high runoff volumes. Plots with relatively dry soils (<12 % by volume) generally produced little or no measurable runoff.

1. *Introduction*

In northern regions, annual peak runoff events can be generated from either snowmelt rainfall, or a combination of the two. For Alaska, record peak runoff events are generated from rainfall; however, numerous annual peak events are produced by snowmelt.

The magnitude and timing of snowmelt runoff events for a watershed are somehow related to:

1. total snowpack accumulation,
2. rate of ablation, and
3. soil conditions.

This assumes no rainfall contribution during the melt period. Most existing models rely on having a good estimate of the snowpack and using climatic data to predict the rate of ablation. Then, some loss rate function is used to allow meltwater to enter the soil system. However, quantitative data are not available to develop an index or any other suitable indicator that could be used to describe the year-to-year variation in the behaviour of seasonally frozen soils. If such an indicator could be developed, better predictions of snowmelt-generated floods could be made. This would be useful in both determining the volume of runoff and the magnitude of the peak.

This report presents field data for a three-year period where snowmelt runoff was measured from runoff plots that had a wide range of soil moisture conditions prior to the development of seasonal frost.

2. *Physical setting*

The runoff plots were constructed in an area 10 km north of Fairbanks, Alaska, in a region of discontinuous permafrost. The site selected for the plots was a south-facing, permafrost-free 15 % slope. Well-drained Fairbanks silt loam was the predominant near-surface soil type. The regional depth of this wind-deposited soil can vary from little or none on ridgetops to more than 50 m in the valley bottoms. The plots were constructed at an intermediate elevation on the south slope, forested with birch and aspen and considerable understory vegetation.

Generally, these soils in permafrost-free areas are well-drained with a shallow surface layer of slightly decomposed organic material. The role of this organic layer as both a buffer to heat and moisture transfer is discussed by SLAUGHTER and KANE (1979). Most of the runoff produced from these plots occurs not strictly as surface runoff, but as subsurface flow through the organic layer when saturated conditions develop above the mineral soil. Over the winter season, a general drying of the organic soils occurs so that moisture levels are quite low at the time of ablation. Meltwater readily enters the dessicated organic layer. But the underlying mineral soil has a much lower infiltration rate which can produce saturated conditions in the organic layer.

Table 1. Irrigation pattern for the runoff plots (cm).

Year**	Control	East	West	East of East
1980	0	12.7	6.3	*
1981	0	6.3	3.8	*
1982	0	2.5	3.8	1.3

* Plot did not exist.

** Water applied the previous fall season in late September or early October, year given is that of spring runoff.

The plots (6.1 m wide by 12.2 m long) were bounded on all sides to a depth of 30 cm into the mineral soil. A collection system was constructed at the bottom of the slope to capture all runoff that migrated dowslope through the organic layer and over the surface. To alter the moisture levels in the runoff plots, they were irrigated with varying amounts of water three to four weeks prior to the onset of seasonal frost. Each year a control plot was maintained that was not irrigated; the control plot was not bounded the first year. During the first year, relatively high quantities of water were applied to the test plots; each following year the quantity was reduced so that the maximum value was equivalent to the minimum value of the previous year (Table 1).

Substantial data were collected at these plots: soil and snow temperatures, climatic data (air temperature and humidity, radiation, and wind), infiltration data for both frozen and unfrozen conditions, and soil moisture data. Some of these data are found in KANE and STEIN (1983b) and STEIN and KANE (1983).

3. *Data presentation*

The data collected prior to the ablation period included a detailed snow survey in the vicinity of the plots so that maximum accumulation could be determined. Numerous snow cores were taken using an Adirondack sampler to evaluate the snowpack water content. Once the melt had been initiated, considerable error could be introduced on an areal basis because snow-free areas would develop around the base of each tree and considerable variation would occur from plot to plot. No attempt was made to adjust the snow survey data to account for the percentage of snow-free areas. Table 2 shows the maximum water content of the snowpack prior to ablation for the three years that runoff data were collected on the plots.

Meltwater from terrain in this area has four possible hydrologic pathways. During the melt period, water can be lost directly by evaporation. Using small lysimeters, KANE and STEIN (1983c) estimated a loss of 1.5 to 2.0 cm during the ablation season.

Table 2. Water content of snowpack (cm).

Year	Water Quantity
1980	5.3
1981	6.1
1982	8.6

If water enters the soil system, it can satisfy soil moisture deficiencies in both the organic soil and mineral soil (and later lost by evapotranspiration), can migrate deeper into the mineral soil (and represent potential groundwater recharge) or move downslope and leave the area as near-surface runoff. The quantity of water needed to satisfy soil moisture deficiencies in the organic layer will depend upon the late winter moisture content and the thickness of this layer. Again, a typical value would be about 2.5 to 3.0 cm from lysimeter data (KANE and STEIN, 1983c).

The rate of infiltration into seasonally frozen soils can vary by orders of magnitude depending upon the condition of the soil (KANE and STEIN, 1983b). For a frozen soil with a low moisture content, little reduction in the infiltration rate was observed when compared to the unfrozen summer case. Generally, a reduction in the infiltration rate of a factor of two is due to changes in the physical properties of water because of the lower temperatures. At higher moisture contents, substantial reductions in the equilibrium infiltration rate occur because of ice in the soil pores. The quantity of ice and unfrozen water can be predicted at temperatures below 0 °C for a given soil if the total moisture content (ice plus water) is known. For the soils in this study, the reduction in the infiltration rate was approximately two orders of magnitude at high moisture levels. This means that the depth of daily infiltration could range from near 1 mm to over 100 mm. Maximum observed levels of daily snowmelt were about 25 mm.

In this study, the plots were used to show the snowmelt runoff response for a range of soil moisture conditions. Table 3 summarizes the volume of runoff from each plot during the ablation period. It is very difficult to compare between years because of both the annual variation in the total snowpack accumulation and different rates of ablation.

The 1980 snowpack was rather light, and the ablation period lasted from April 16 to April 23 without interruption (Figure 1). Runoff from the plots began shortly after the onset of ablation with 93 % of the runoff for the west plot and 99 % of the runoff for the east plot being completed by the end of the ablation period. Although there was a substantial difference in the quantity of irrigated water for these two plots (12.7 cm for East and 6.3 cm for West), the quantity and timing of runoff was quite similar.

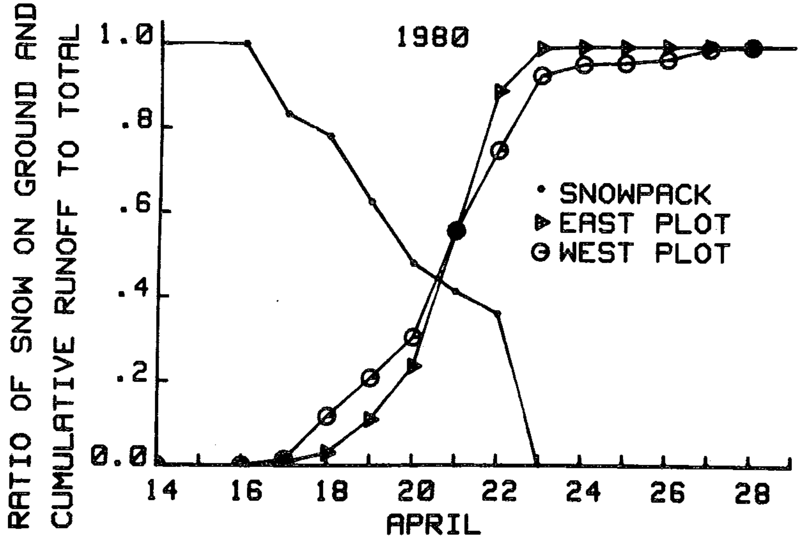

Figure 1. Ratios of remaining snowpack to total maximum snowpack prior to ablation and cumulative runoff to total runoff in 1980.

There was essentially no runoff from areas with the normal soil moisture levels (near 12 % by volume in the upper 1 m) because of the high infiltration rates. The moisture levels were substantially higher in the irrigated plots, particularly in the upper 10 cm of mineral soil where levels were near or in excess of saturation (50 % by volume). Values of snowmelt infiltration (Kane and Stein, 1983b) measured during this period with double ring infiltrometers located adjacent to the irrigated plots varied from 1 to 8 x 10^{-8} m/sec. This corresponds to daily infiltration values of less than 1 mm to 8 mm.

For the control plot, the daily quantity of infiltration was more than two orders of magnitude greater than the irrigated plots; this quantity was in excess of daily ablation rates, so no near-surface runoff occurred. From a water budget

Table 3. Total runoff depth (cm) from plots.

	Control	East	West	East of East
1980	0	0.9	0.9	*
1981	0	3.4	3.4	*
1982	2.2	4.1	2.7	4.6

*Plot did not exist.

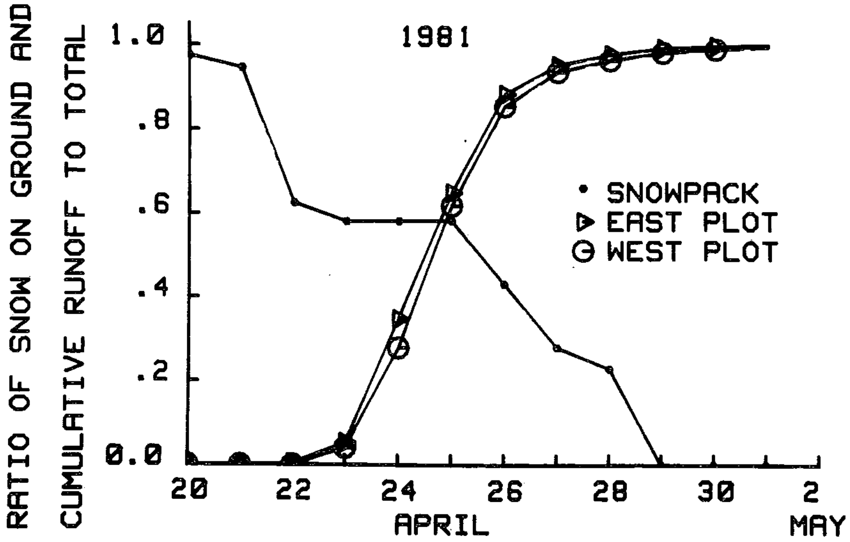

Figure 2. Ratios of remaining snowpack to total maximum snowpack prior to ablation and cumulative runoff to total runoff in 1981.

viewpoint, the meltwater on the nonirrigated control plot either evaporated, satisfied moisture deficits in organic soil, or infiltrated into mineral soil. This pattern was observed for the irrigated plots, except that snowmelt rates exceeded infiltration rates into mineral soil, and near-surface runoff was produced as the amount of water entering the mineral soil was reduced.

Plot data for 1981 (Figure 2) showed a response similar to 1980. As can be seen in Figure 2, there was again no runoff from the control plot that was bounded, and the runoff patterns for the two irrigated plots were similar to each other. Table 1 shows that the West plot had 3.8 cm of water added and the East plot had 6.3 cm added in 1981. Significant melt started on April 21 and was essentially complete by April 29. Most of the total runoff (98 %) was complete by April 29. The quantity of precipitation from the previous fall was not critical (Table 4), so soil moisture levels were affected only by the quantity of water applied during the irrigation period. Measured infiltration rates into the mineral soil were similar to those measured previously. The water content of the snowpack was greater for the 1981 ablation season and the quantity of runoff from the irrigated plots was also greater when compared to the previous 1980 data. It should be observed that the quantity of runoff increased substantially more than the measured increase in the water content of the snowpack.

Table 4. Precipitation during previous fall season (cm).

	August	September	October
1979	3.10	0.48	2.39*
1980	4.27	1.93	0.99
1981	3.43	2.03	2.31

*Primarily snow

As can be seen from Table 1, less water was applied to the plots each year. During 1981–82 winter season, the plots received even smaller quantities of irrigation water, and an additional plot was added. Two events made this year different from the previous year. First, during the previous fall, considerable normal precipitation fell as rain after the irrigation period. This increased near-surface moisture levels just prior to the onset of seasonal frost. Second, considerably more snow fell during this winter season. These events produced measurable runoff from the control plot for the first time. This was also the first time that we had observed runoff in the low depressions that naturally occur in the vicinity of the runoff plots. Generally, the quantity of runoff increased as the quantity of applied irrigation water increased. The new plot

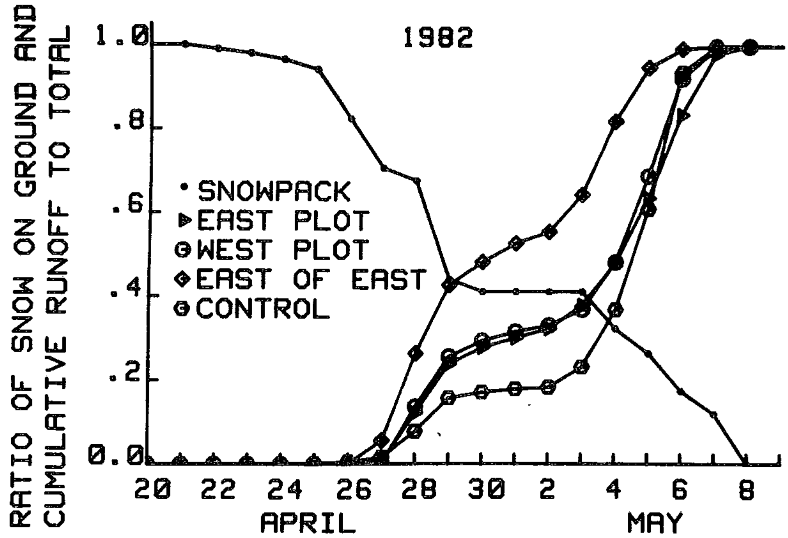

Figure 3. Ratios of remaining snowpack to total maximum snowpack prior to ablation and cumulative runoff to total runoff in 1982.

(East of East) was an exception. It had the greatest quantity of runoff while it received the lowest amount of irrigation water. Runoff from this plot took place several days earlier (Figure 3) than the other plots, so some of this discrepancy could be accounted for by the melt pattern. Also, when irrigating the plots, it was much more difficult to get an even distribution of water on the plots with lighter applications. During this year, the ablation period (April 25 to May 8) was much longer and later than the previous two years, and there was a period of cold weather during the ablation period (April 29 to May 3).

4. *Discussion*

The idea is not new that both the timing and magnitude of snowmelt runoff could be better predicted if the interaction of the snowpack and the underlying seasonally frozen ground were understood. However, the complexity of this system has stalled research in this direction. It is the most difficult soil system to study because of the soil matrix, unfrozen water existing as films on the surface of the soil particles, and ice and air in the soil pores. Numerous attempts have been made to classify soils according to the ice content (STOECKELER and WEITZMAN, 1960; HAUPT, 1967; and BLOOMSBURG and WANG, 1969). In regard to frost heave, considerable work has been done in examining the unfrozen water content of frozen soils. This is summarized in a paper by ANDERSON and MORGENSTERN (1973).

The next logical step has been to examine the hydraulic conductivity of frozen soils. This has been done in the laboratory (BURT and WILLIAMS, 1976; HORIGUCHI and MILLER, 1980) for a range of temperatures and can also be determined from field studies of infiltration rates at 0 °C (KANE and STEIN, 1983b). The following generalizations can be made.

1. For saturated soils, the hydraulic conductivity decreases by orders of magnitude as the temperature decreases,
2. For saturated soil below 0 °C, the hydraulic conductivity is related to the thickness of the unfrozen film of soil water, and
3. For unsaturated soils, the hydraulic conductivity can vary by orders of magnitude and is a function of the unfrozen water content and ice content, which are both temperature dependent.

Although the soil moisture conditions prior to seasonal freezing may be known, redistribution of this soil water can occur during the winter months. In addition to gravity drainage, water can be induced to move upward toward the seasonal frost front. This has been examined under field conditions by WILLIS *et al.* (1964), SHEPPARD *et al.* (1981), KANE and STEIN (1983a, b), and GRAY *et al.* (1983). Kane and Stein found substantial increases in the upper 10 cm of the mineral soil; this is a critical region because it also controls the quantity of infiltration water.

The need to consider the interaction of the seasonally frozen soil and the snowpack are expressed in the papers of GUYMON (1978) and PRICE *et al.* (1978). In our work, we observed that substantial redistribution of soil moisture occurred and that the greatest increase was near the surface of the mineral soil. Both SHEPPARD *et al.* (1981) and GRAY *et al.* (1983) report on the importance of moisture redistribution in agricultural soils. Their pattern of redistribution is somewhat different from ours because we are working with a forested site with an organic layer. For dry soils, Gray *et al.* report that little redistribution occurs. This is the same conclusion we reached.

In modeling the entire system, it is necessary to examine travel times within snowpacks and, in our case, travel times through the surface organic debris. In our shallow snowpacks, travel times within the snowpack appear to be relatively small when compared with overland and channel travel times. Channeling within the snowpack and degradation of the snowpack both contribute to reduced travel times within the snowpack. Also, radial melting outward from the base of a tree alters the traditional concept of surface melting.

The theme of this paper is that snowmelt runoff is influenced by soil conditions. WILLIS *et al.* (1961) observed this when examining agricultural soils in North Dakota. They concluded that snowmelt runoff tends to be less for dry soils providing the surface is not wetted just prior to the soil freezing. In 1981, we experienced late fall precipitation. This produced runoff from our control plot which was rather dry prior to this time. In another plot study, DUNNE and BLACK (1971) attributed large quantities of runoff to the presence of a thin layer of concrete frost.

Using time domain reflectometry to measure unfrozen water contents (KANE and STEIN, 1983a), we observed that, after the ablation period, a site that was originally dry the previous fall had a higher moisture content than a wetter site. This was attributed to the lower snowmelt infiltration rate for the wetter soil. This has certain ramifications when it comes to agricultural practices.

It is useful when making process studies to work with small plots. But can this work be extended to or is it meaningful on a watershed scale? For a nearby watershed (Chena River, drainage area of 5,132 km^2), we have plotted (Figure 4) the ratio of the volume of runoff to the snowpack volume versus the previous August precipitation for 21 annual snowmelt runoff events. The runoff is measured at

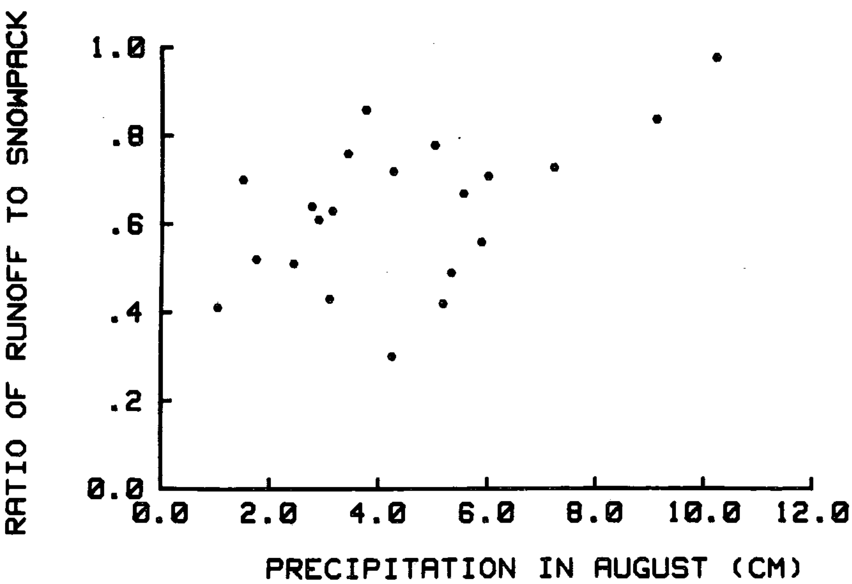

Figure 4. Ratio of the volume of runoff due to snowmelt at outlet of basin and the maximum volume of the snowpack above 300 m in Chena River watershed versus antecedent precipitation for the month of August of the previous fall season.

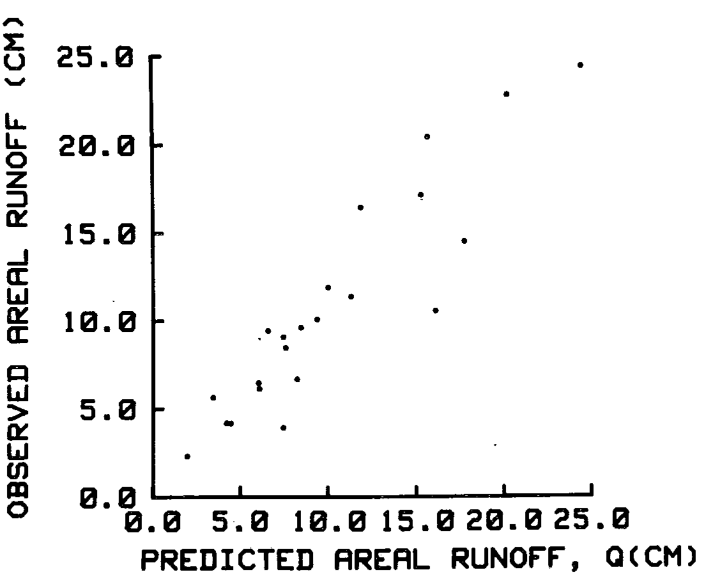

Figure 5. Observed areal runoff versus predicted areal runoff based on average snowpack water equivalent (S_{wc}) and previous August precipitation (P_a).

the outlet of the total basin. We also arbitrarily assumed that all runoff was generated from areas above 300 m. This reduces the basin area that contributes flow by 32 %. Elevations in excess of 1,500 m exist in this watershed. August precipitation was selected because snow starts to accumulate at the higher elevations in early September. In analyzing the streamflow, it was very difficult to separate out snowmelt runoff from rain-generated runoff. We deleted the data for years with excessive rain on snow. Although numerous snow survey gages exist at higher elevations in the watershed to estimate snowpack volume, rainfall data are from the lowest point in the watershed.

Despite the limitations of the above data, it can still be seen that a relationship exists between the ratio and the antecedent precipitation. The major limitation of this approach is that the ablation season can vary substantially from year to year. All the data in the upper right hand corner of Figure 4 represent points where the onset of runoff in the watershed was delayed until late in the season. This condition produces fairly high ratios of runoff volume to snowpack volume.

Predicted areal runoff versus observed areal runoff are plotted in Figure 5. An estimate of areal runoff is made from the following regression type equation:

$$Q = -4.22 + 1.98\, S_{wc} + 1.35 P_c \qquad (1)$$

where

Q = volume of runoff in cm over the watershed area above 300 m,
S_{wc} = average snowpack water content in cm over watershed area above 300 m,
P_a = August precipitation in Fairbanks in cm.

This graph gives a fairly decent prediction of the volume of snowmelt runoff based only on the antecedent precipitation (which influences the soil condition) and the average snowpack water content in the basin.

5. *Conclusions*

The objective of this paper is to make a case for the need of upgrading existing snowmelt runoff models to include a component that considers soil conditions. Results from our plot studies showed that extreme runoff conditions can be observed depending upon what soil conditions exist. Soil moisture levels and precipitation, prior to the onset of seasonal frost, are critical in producing conditions favorable for either infiltration or runoff. Redistribution of soil water during the winter season can substantially alter infiltration. This is especially important in controlling infiltration rates when redistribution occurs near the surface. Whether or not an impermeable layer forms depends upon many factors such as: soil type, soil water content, snow cover, surface vegetative cover, and climate. We do not intend to downplay snowpack and ablation processes since they are critical to the prediction of runoff, particularly for peak flow estimates.

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