The Relationship Of Soil Freezing To Snowmelt Runoff

J. W. Bauder, L. J. Brun and T. H. Krueger

Surface runoff of spring snowmelt and early season precipitation from frozen ground may contribute significantly to high stream levels and water quality degradation. Studies are being initiated to evaluate the impact of agricultural management practices associated with irrigation or soil frost formation and surface runoff of snowmelt.

Water from irrigation and precipitation are inputs to one phase of the hydrologic cycle. Upon contact with the soil surface, the water may continue along one of several avenues of the cycle. Some of these are infiltration, surface runoff, evaporation and crop use. The latter two often are grouped together to make up evapotranspiration.

Water entering the soil is either returned to the atmosphere through evapotranspiration, stored in the soil as part of the soil moisture recharge requirement, or percolated through the soil to some subterranean drainage system. Water which becomes surface runoff is eventually discharged into a drainage system. As surface runoff, water may accumulate a considerable load of material in such forms as organic matter, suspended soil particles and dissolved nutrients and minerals. Such runoff water, laden with considerable amounts of organic and inorganic material, can contribute to the pollution of lakes and streams.

The contribution of melting snow and early spring rains to the amount of water entering our natural water bodies as surface runoff has not been thoroughly investigated. Melting snow over frozen soils may be one source of surface runoff during the spring. It is also quite possible that soils that are wet when frozen in the fall may behave differently than dry soils when considering the interaction of soil frost and surface runoff. The Department of Soils at NDSU initiated research in the fall of 1974 to investigate the interactions of soil water conditions and soil frost on the runoff of spring snowmelt water and rainfall. First year results are reported here.

History

In the course of soil freezing, various patterns of frost accumulation may occur. Patterns of frost accumulation have been studied in New Hampshire, Minnesota, Michigan, Montana, North Dakota and parts of Canada. Several researchers have studied frost formation in European and Asian countries. Frost and Driebelis (1943) studied soil freezing and frost penetration and their effects on soil water retention by woodland, pasture and cultivated land. They observed three types of frost being formed in the field: (1) concrete, (2) honey-comb, and (3) stalactite. Other workers, including Stoeckeler and Weitzman (1960) described a fourth type of soil frost as granular.

Researchers have shown that water infiltration and movement in the soil are characteristically reduced when soil freezes. Under many conditions of deep soil freezing, snowmelt and precipitation become potential sources of surface runoff because of reduced soil permeability. Stoeckeler and Weitzman (1960) indicated in northern Minnesota as much as 50 per cent of the total annual runoff may occur in a 2-month period in late winter and early spring. At this time rapid runoff is attributed to snow melting over frozen soils having reduced permeabilities.

Similarly, Trimble, et al (1958) stated, "Hard-frozen ground at times of heavy rain and quick-thawing snow often causes surface runoff with resultant increases in flood hazard and accompanying loss of potential ground water . . . ground freezing may have an important effect on streamflow and groundwater storage." The American Society of Civil Engineer's *Hydrology Handbook* states that "freezing of soils does not invariably result in an impermeable medium; soils of low moisture content often become granulated and more permeable; and very wet soils have a greatly reduced permeability."

Methods and Materials

Four study sites were selected in 1974 on coarse textured soils along the Maple river near Enderlin, North Dakota. The study areas had been mapped as Hecla soils, and mechanical analysis of samples collected indicated the soils were sandy loam in texture to a depth of six feet. Coarse textured soils were

---

This work was supported by funds from project ND 2537.

Dr. Bauder and Dr. Brun are assistant professors and Krueger is assistant, Department of Soils.

Figure 1. Field plots located at Enderlin, North Dakota. Top: pasture with $3\frac{2}{3}$ per cent slope; bottom: sunflower stubble with diked microplots.

desirable because of the possible interaction of irrigation, fall soil water conditions and frost formation. Late season irrigation of some soils could result in wet soils during the time of soil frost formation. With dryland farming practices, soils would usually be low in stored moisture during the time of soil freezing.

The study sites were selected to include a pasture and an area which had been cropped to sunflowers in 1974. Two small plots on sloping land (3 to 5% slope) were diked on all sides and equipped with soil moisture and temperature-measuring equipment (Figure 1). Runoff collecting tanks were constructed from 30-gallon garbage barrels and buried at the low end of each plot. Water level recorders were installed in each barrel to record the amount of runoff entering each tank (Figure 2). The dikes were built around each plot to channel any snowmelt or precipitation runoff from the plots into the catchment barrels. The dikes also prevented outside water from running onto the plots. Other equipment was installed to help determine the depth to which the soil froze on each plot.

In order to evaluate the effect of soil moisture conditions on frost formation and snowmelt runoff, one plot from each of the sites (pasture and sunflowers) was irrigated by hand in late October. An irrigation equivalent to a two-inch precipitation was applied to the plots. By doing this, it was possible to measure runoff from similar plots having two different soil moisture conditions at the time of soil freezing. Data were collected on each site from November 1, 1974 to April 30, 1975. During that time, the following information was collected on a regular basis at several soil depths: (a) soil temperature, (b) soil water content, and (c) soil frost presence. Other information collected included air temperature just above the soil surface, snow depth and quantity of runoff from each plot.

Results and Discussion

The 1974-1975 winter months were mild in comparison with other winters. Climatological data, collected by the National Climatic Center and supplied by Dr. J.M. Ramirez at NDSU, indicated that

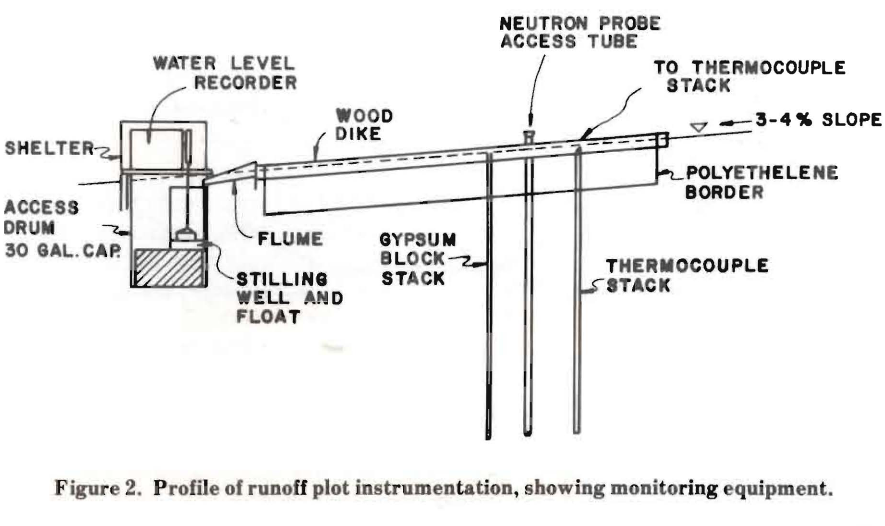

Figure 2. Profile of runoff plot instrumentation, showing monitoring equipment.

precipitation at Enderlin, only four miles from the study area, totalled 3.83 inches during the six months of the study period. The precipitation pattern is shown in Figure 3. Also included in Figure 3 is the average 6, 12 and 72 inches soil temperature for the four plots and the average cumulative soil moisture storage in the top 4 and 6 feet of soil.

The average measured soil temperatures at 6, 12 and 72 inches ranged from 53° to 15°F during the study period. As was expected, soil temperature decreased from November until about mid-March. Although the minimum temperature was experienced at six inches, the trends were the same at all depths measured. Warm weather in mid-March was responsible for an increase in soil temperature, followed by lower temperatures until early April.

The soil acts much like a reservoir, damping out the decreasing temperature with depth. Consequently, temperatures measured at the soil surface were colder than those at 72 inches. Although it is not illustrated here, the soil temperatures near the surface reflect quite well the ambient air temperatures. A second interesting observation is that soil temperatures at 72 inches were below 32°F on several occasions.

The soil moisture data in Figure 3 demonstrate that only during the months of November, March and April did the soil water content change. During these months the soil profile was partially thawed, allowing for surface infiltration of water from irrigation, precipitation and snowmelt. When this occured, the amount of water stored in the 72 inches of soil profile changed.

Soil temperatures do not always indicate the presence of frost in the soil. Figure 4 shows that the soil temperature may need to be below 32°F before frost forms. The natural salt in most soil-water systems acts somewhat like antifreeze, causing a freezing point depression with respect to soil water. At the same time, as soil water freezes, the existing salts are concentrated in the liquid water phase, creating an even greater freezing point depression. Because of this particular occurrence, it is difficult to quantify soil frost.

A method other than soil temperatures was used to indicate the presence of soil frost in this study. Porous blocks containing two electrodes (Bouyoucos and Mick, 1940) were buried at several depths in the soil after being saturated for a short period of time. By measuring the resistance to flow of electricity between the two electrodes in each block, some indication of the presence or absence of frost was attainable. When the water in the porous blocks was in the liquid phase, little resistance to flow was measured. However, when the blocks were frozen and water was in the solid or ice phase the resistance to the flow of electricity between the electrodes was infinitely large. Thus, when the block at a particular depth in the soil froze, the electrical resistance between electrodes increased greatly. As indicated in Figure 4, the depth of soil frost formation did not equal the 32°F depth, even though above that depth the soil temperature was less than 32°F.

Snowmelt runoff during the winter of 1974-1975 is summarized in Table 1. As indicated, the study areas were designated as irrigated and dryland, sunflower stubble and pasture. The data indicate that runoff did occur during the months of March and

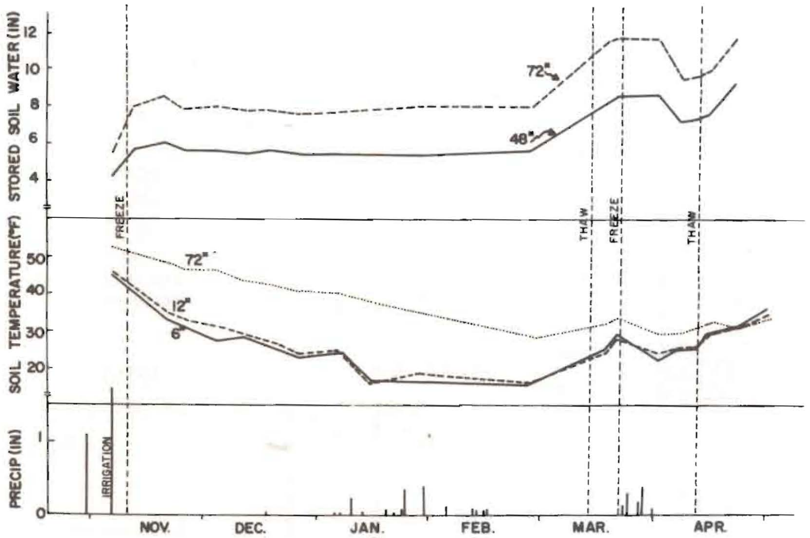

Figure 3. Seasonal soil moisture, soil temperature, and precipitation at the study sites, averaged for the four plots instrumented.

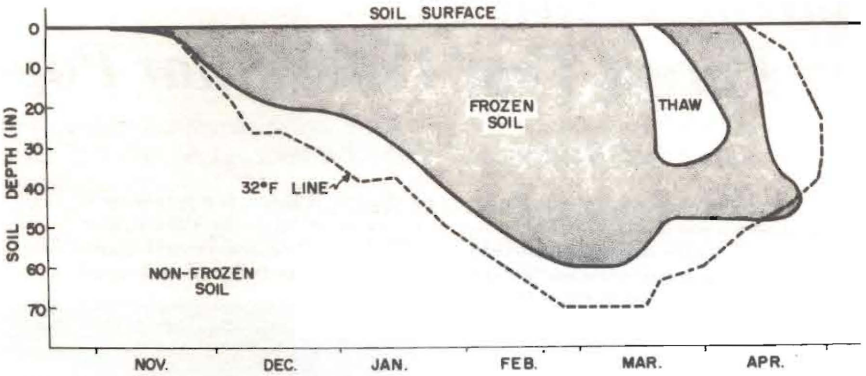

Figure 4. Pattern of soil frost and 32° F temperature boundary in the soil profile.

April. Between March 14 and 22 daytime air temperatures exceeded 32°F, contributing to the melting of all snow that was on the plots at that time. Although the soil temperature and frost curves indicate that the frost had left the soil during this period, snowmelt was rapid enough that all snow had melted and had run off as overland flow or infiltrated before significant thawing occurred. Although air temperatures did exceed 32°F on other days during the winter, most snowmelt water on these days was contained within the existing snowpacks. Additional snow was converted to the vapor phase and returned to the atmosphere through sublimation.

Table 1. Monthly runoff totals for irrigated and dryland plots in pasture and sunflower stubble.

	Cropping History			
	Sunflowers		Pasture	
Month	Dryland	Irrigated	Dryland	Irrigated
March	—	0.27"	0.82"	1.38"
April	0.43"[2]	0.56"	1.08"	1.78"
Total	0.43"	0.83"	1.90"	3.16"

[1]All runoff values are expressed on a unit area basis.
[2]Runoff measured was equivalent to that of a rainfall of equal magnitude.

The data in Table 1 also indicate that as much as 3.16 inches of water (that equivalent to a 3.16 inch rainstorm) was measured as surface runoff from one plot. This is equivalent to approximately 80 per cent of the measured precipitation. It was also observed that runoff occurred on all plots, regardless of the past cropping program and the fall soil water content. However, because of the limited number of plots and the small plot size, it was not possible to identify the contribution of either fall irrigation practices or past cropping practices to snowmelt infiltration and surface runoff from agricultural soils.

Based on a water balancing procedure, including runoff, drainage, soil water storage changes and precipitation, and ignoring evaporation, the data indicate that the total amount of water accounted for in farm drainage, runoff and storage changes exceeded precipitation. The precipitation value used here may not accurately reflect the amount of snow on the study plots. On several occasions drifts of snow were observed on the study sites. With such being the case, the actual precipitation to each plot was more than 3.83 inches recorded at Enderlin. The greater amount of runoff from the pasture plots was the result of a considerable amount of drifted snow on those plots in comparison to the sunflower plots.

Conclusions

First-year measurements of the quantities of snowmelt and precipitation runoff from some frozen soils demonstrate that runoff does occur. Coarse textured soils, suitable for irrigation, may become highly impermeable to water infiltration when frozen. Most likely the degree of impermeability is related to the amount of water held in the soil at the time of frost formation. Presently, only a limited amount of data is available, making it impractical to quantify the effects of cropping and tillage practices on soil frost formation and snowmelt runoff.

Literature Cited

Bouyoucos, G. J. and A. H. Mick. 1940 **An electrical resistance method for the continuous measurement of soil moisture under field conditions.** Michigan Agr. Exp. Sta. Tech. Bul. 172.

Post, F. A. and F. R. Dreibelbis. 1943. **Some influences of frost penetration and micro-climate on water relationships of woodland, pasture, and cultivated soils.** Soil Sci. Soc. Amer. Proc. 7:95-104.

Stoeckeler, J. H., and S. Weitzman. 1960. **Infiltration rates in frozen soils in northern Minnesota.** Soil Sci. Soc. Amer. Proc. 24:137-139.

Trimble, G. R., Jr., R. S. Sartz and R. S. Pierce. 1958. **How type of soil frost affects infiltration.** J. Soil and Water Conserv. 13:81-82.