**10989 SNOW COVER AND UPWARD MOVEMENT OF MOISTURE**

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ABSTRACT: The soil moisture in the ground beneath a snow cover in the north central United States has been observed to increase during the winter season. The maximum prethaw soil moisture frequently is observed immediately prior to the onset of the spring melt. A primary mechanism producing the increase is the upward movement of moisture in both liquid and vapor phase that which may occur with or without the presence of frozen conditions when induced by a temperature gradient. The importance of this phenomenon in relation to forecasting the snowmelt runoff during the critical spring period is examined.

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# Effect of Snow Cover on Upward Movement of Soil Moisture

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## Introduction

The purpose of this paper is to present a brief summary of some of the characteristics of soil moisture that have been observed under the late-winter snow cover and to indicate why soil moisture and temperature conditions may be an important factor in predicting the spring snowmelt runoff.

Several major factors are critical in predicting spring snowmelt runoff. One of these factors is the inability to assess the amount of water that is stored in the snow cover. The problem of nonrepresentativeness of point measurements was examined by Peck (8). Another factor is the inability of existing hydrologic modeling techniques to properly account for changes in soil moisture beneath snow cover or under frozen ground conditions. All catchment analysis procedures recognize that the amount of moisture already present in the soil is a critical variable in the function that expresses runoff components in terms of the amount of water newly deposited on the surface either as rain or snowmelt. In most such procedures, the moisture at one or more levels is computed continuously on the basis of moisture input (rain or snowmelt), meteorological evaporative factors, and mathematical representations of interception, infiltration, percolation, ground-water storage depletion, etc. Although it is generally recognized that the mechanics of these processes are not the same under winter conditions as they are in summer, no hydrologic model known to the writer makes this distinction in its soil moisture accounting.

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**Results of Field Surveys**

Just prior to the major snowmelt flood that developed in the north central plains area of the United States in the spring of 1969, the Office of Hydrology of the National Weather Service sent a team of hydrologists to survey the conditions in the Rock River Basin in extreme southwestern Minnesota above the stream gaging station at Rock Rapids, Iowa. The objective of this mission was to study the problems of assessing the flood potential, particularly those dealing with obtaining water equivalent measurements that would be representative of the areal conditions.

A continuous snow cover had existed over the Rock River Basin since about the middle of December, 1968. During the winter season and until March 22 no appreciable snowmelt or rainfall had occurred. Some rain, with very little runoff, occurred on March 22 with the rain changing to snow by that afternoon. From then until the first week in April, when the major snowmelt occurred, extremely cold weather persisted with no additional precipitation. During this interval extensive meteorological and hydrological measurements were made over the basin. Since the water equivalent of the snow cover remained approximately constant, an unusual amount of information on the basin conditions preceding snowmelt was obtained. On the basis of these measurements, the average water equivalent of the snow cover for the basin prior to the spring melt was estimated to be 6 in. (155 mm). This quantity of water et is sufficient to produce serious flooding in the Rock River Basin if the snowmelt occurs suddenly, even without additional precipitation.

During the spring of 1969 a large portion of the Rock River Basin was found to be frost-free and the remainder of the basin had frost depths generally less than 1/2 in. (12.5 mm). Only in a few locations where the snow had apparently been blown free during most of the winter were frost depths found to be greater. Normally, the ground under the snow cover just prior to the spring melt is frozen to considerable depth. The nonfrozen soil condition obviously presents a difficult problem when the National Weather Service forecasters are called upon to predict the snowmelt runoff. To help evaluate this problem, soil samples were obtained at 18 sampling stations that had been established in the basin for snow cover measurements. Prior to receiving the results of these analyses from the soil testing laboratory, an investigation was made to determine the maximum water retention (field capacity) for the types of soil found in the basin.

Considerable information on soil types and characteristics was furnished by the Agricultural Research Service, the Soil Conservation Service, and the University of Minnesota. A report by Holt, et al. (4) and the soil scientists interviewed indicated that the field capacity for the types of soil in the basin was approx 32% (weight of moisture over the oven dry weight of the soil).

The results of the laboratory analyses indicated that the average soil moisture for the 18 stations was 44% or approx 12% greater than their average field capacity, and the soil samples were found to be as pliable as modeling clay when first removed from the ground. When exposed to the warmth of a car, they became very "soupy." An unpublished report by the University of Minnesota had been prepared on the soil moisture conditions of the previous fall. Due to heavy fall rainfall, the soil moisture was exceptionally high. However, the thought at the time was that this should leave the soil moisture content near that of the field capacity or approx 32%. A later soil survey on April 25, 1969 showed that the soil moisture at 10 of the network's 18 stations had decreased from 48.9% prior to the snowmelt to 32.8% afterward.

### Movement and Retention of Soil Moisture

Subsequent to the 1969 experience, a review of the literature had revealed some possible reasons for the soil moisture conditions that were observed. Harlan (2) and Ferguson, et al. (1) have reported on the upward movement of moisture in the vapor phase when the surface layer of the soil is frozen, due to the difference in vapor pressure that exists over ice and water particles. Willis, et al. (14) have reported on the depth of frost in the northern plains area of the United States and the associated lowering of the free-water table indicating a decided upward movement of water during the winter period. Sartz (10) has reported on the effect of winter thaws on increasing the ground-water level.

In addition to the frozen ground effects, two other factors have been found to be of importance: (1) The field capacity of the soil is a function of temperature, i.e., decreases with increase in temperature (see Ref. 3); and (2) the layer of the soil near the surface can retain additional moisture above field capacity when subject to the temperature gradients that are observed under the winter snow cover (12). The studies by Taylor and Cary (12) have indicated that considerably more moisture moves upward than would be indicated by consideration of only the vapor movement resulting from frozen conditions. Their conclusion is that a large part of the movement of moisture is in the liquid phase, rather than the vapor phase. Taylor (11) also has stated that the force acting to move liquid water in the soil resulting from temperature gradients may be many times greater than that due to gravity.

As reported by Taylor (11) the direction of movement of soil moisture that is released when a temperature gradient is removed is controlled more by the microscale temperature gradients than by the force of gravity. It is the opinion of the writer that the released water may not necessarily move downwards, but may move laterally or at an angle to the vertical that would permit it to become intercepted or to move in the form of interflow. The observation of the formation of relatively large bodies of water in agricultural fields where only a small average water equivalent existed over the immediate drainage area the day before tends to support this theory.

Recent studies by Meiman, et al. (5) using deuterium, trituim, and oxygen-18 isotopes for determination of the origin of snowmelt runoff have indicated a significant intermixing of water derived from the snow cover with the water that was in the soil. This result supports the contention that some water may actually be released from the soil instead of all water percolating downwards to the water table.

Most of the Rock River Basin was found to be free of frost during the 1969 special survey. Therefore, the amount of water above normal field capacity had to move into the upper layer of the soil by some process other than that resulting from frost in the soil. A conceptual snowmelt model now under development by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (6) was applied to the Rock River Basin. The snowmelt indicated by this model showed that the yield from the snowpack should have been about 1/2 in. (12 mm) for the entire snow cover period prior to snowmelt. The additional water, even in only the upper 8 in. (200 mm) of the soil, would have been three to four times this amount. The soil moisture increase in the upper layer of the soil must have come from below rather than from above.

### Soil Moisture Measurement in Conjunction with Aerial Snow Surveys

Research on the use of the natural radioactivity of the soil as a means to measure the water equivalent of the snow cover has been conducted for several years in the Soviet Union and more recently by Peck, et al. (9) in the United States. Because soil moisture has a pronounced effect on radiometric snow measurements, its behavior prior to and during the snow season has been carefully recorded both in the Soviet Union and in the United States. Zotimov (15) of the Soviet Union reported on variations in the mean soil moisture content during a 6-yr period. He reported that the mean values in open fields between November and March increased from 2.7 in. (69 mm) to 3.7 in. (94 mm), or 36%, in the 0-in. to 8-in. (0-mm to 200-mm) soil layer and from 5.8 in. (148 mm) to 7.0 in. (179 mm), or 21%, in the -in. to 20-in. (0-mm to 500-mm) layer. In a forested area he found the mean soil moisture between November and March increased from 2.5 in. (64 mm) to 2.9 in. (74 mm), or 16%, for the 0-in. to 8-in. (0-mm to 200-mm) layer and from 5.9 in. (149 mm) to 6.2 in. (158 mm), or 6%, in the 0-in. to 20-in. (0-mm to 500-mm) layer.

Vershinina (13) gives similar data for soils of various types and for various geographical and climatological regions of the Soviet Union. Vershinina's studies indicated a general increase in the soil moisture underneath the snow (averaging approx 19% for all areas), but shows that the increase varies considerably for the different regions. The increase for most regions was reported as being fairly consistent from year to year with the exception of those regions where winter thaws and rainfall may frequently occur.

In the United States, a flight line in the Rock River Basin south of the city of Luverne, Minn. has been used for research on the use of aerial gamma radiation for measuring snow. The 8.4-mile (13.5-km) survey line is in an agricultural area typical of the plains area of the north central United States. Most of the land is cultivated in corn and hay.

Ground surveys of the soil moisture have been made since the fall of 1969 at established locations along the line near Luverne, Minn. concurrently with aerial gamma radiation surveys.

The soil moisture under the late winter snows in the Rock River Basin has been observed to increase from that during the fall, in agreement with the observations of Zotimov and Vershinina. Fig. 1 shows the variations in soil moisture conditions observed during the 1969–1970, 1970–1971, and 1971–1972 seasons. In each of these three diagrams the top set of data represents the soil moisture conditions found under the late season snow cover. The lower two sets of data are for relatively "wet" periods earlier in the winter or following disappearance of snow in the spring. In all three cases, frost was observed under the late season snow cover.

An aerial reconnaissance snow survey program also was conducted over the Lake Ontario Basin in New York state during 1972–1973 in conjunction with

Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, Minn., June, 1972.

8. Peck, E. L., "Review of Methods of Measuring Snow Cover, Snowmelt and Streamflow Under Winter Conditions," *Proceedings*, International Symposia on the Role of Snow and Ice in Hydrology, Banff, Canada, September 6–13, 1972.
9. Peck, E. L., et al., "Evaluation of Snow Water Equivalent by Airborne Measurement of Passive Terrestrial Gamma Radiation," *Water Resources Research*, Vol. 7, No. 5, Oct., 1971.
10. Sartz, R. S., "Winter Thaws Can Raise Ground Water Levels in Driftless Area," *Research Note NC-35*, U.S. Forest Service, St. Paul, Minn., Aug., 1967.
11. Taylor, S. A., "Irreversible Thermodynamics," presented at Utah State University, Logan, Utah, May, 1965.
12. Taylor, S. A., and Cary, J. W., "Soil-Water Movement in Vapour and Liquid Phases," *Proceedings of the Montpellier Symposium, Methodology of Plant Eco-physiology*, United Nations Educational, Social, and Cultural Organization, Paris, France, 1965.
13. Vershinina, L. K., "Assessment of the Accuracy in Determining Water Equivalent of Snow Cover, Determination of the Water Equivalent of Snow Cover, Methods and Equipment," *Trudy No. 178*, Leningrad, U.S.S.R., 1969, Israel Program for Scientific Translation, *TT70-50093*, Jerusalem, Israel, 1971.
14. Willis, W. O., et al., "Water Table Changes and Soil Moisture Loss Under Frozen Conditions," *Soil Science*, Vol. 98, No. 4, Oct., 1964.
15. Zotimov, N. V., "A Surface Method of Measuring the Water Equivalent of Snow by Means of Soil Radioactivity," *Soviet Hydrology: Selected Papers*, No. 6, 1965.



the International Field Year for the Great Lakes (IFYGL). Fig. 2 shows the soil moisture differences observed in this area between very wet nonsnow periods and February 28, 1973, just prior to loss of the snow cover. Frost was observed in the ground beneath the snow on February 28. During the previous month of January, three unseasonal thaws occurred, which had removed the entire

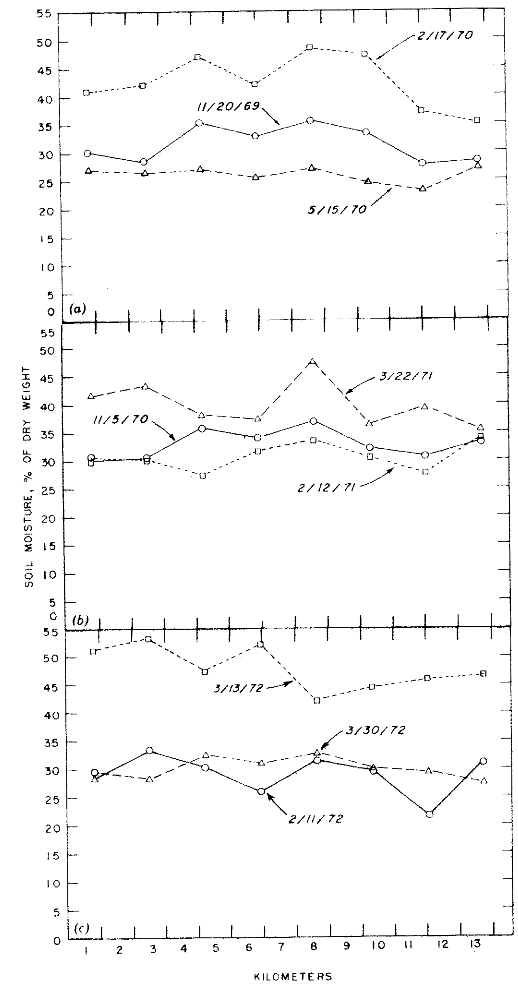


**FIG. 1.—Average Soil Moisture for 13.5-km Line near Luverne, Minn.: (*a*) 1969–1970 Season; (*b*) 1970–1971 Season; (*c*) 1971–1972 Season**

snow cover. The soil survey on June 15, 1972, was made only 12 hr after a very heavy rainstorm [2.5 in. (64 mm)] had occurred over the area. A survey on March 9, 1973, was taken shortly after the snow cover had completely melted.

The high soil moisture values on February 28, 1973, could have resulted from several processes, e.g., earlier melt water and by vapor or liquid transport,

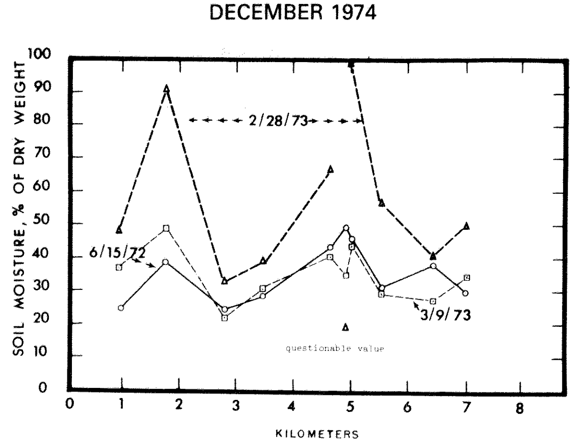


**FIG. 2.—Average Soil Moisture for 8-km Line near Fleming-Scipio Center, New York, 1972–1973 Season**

or both, from lower subsurface layers. Regardless of the origin of the excess moisture, the additional moisture was retained in the upper layer of the soil by virtue of the temperature gradients that existed.

### Other Influences

The availability of free water for increasing the soil moisture under the snow during the winter period is an important factor. The amount of additional soil moisture that may be derived from the free-water table probably depends upon the depth of the free-water table below the surface of the ground and the type of soils through which the water must be transported.

It is recognized that the increase in soil water may not be as large in forests and other heavily vegetated areas. Pabst, et al. (7) have analyzed snowmelt floods in basins with considerable forest cover and in other basins and found that flood magnitudes were considerably less than could have been expected because of loss by infiltration due to low soil moisture in the upper layer of the soil.

### Corroborative Observations

If we assume that soil moisture greater than field capacity is retained in the soil primarily by the temperature gradient (whether the soil is frozen or not), a removal of the temperature gradient therefore should result in a release of the excess moisture. Field experience of surveying during the spring melt season has given some indication that a critical change occurs in the characteristics of the soil at the time of the temperature gradient removal. Within a short period after the snow cover has been removed, walking in the cultivated fields is much more difficult due to the stickiness of the soil and the depth to which one penetrates. A few days later even with heavy rains adding to the moisture the conditions for walking are greatly improved.

A similar observation has been made by the author on the trafficability for



soils of clay or silt loam. Motor traffic has been observed to have little difficulty on dirt roads on days with heavy rain. However, during the 1-day period after the snow cover is removed, traffic has been observed to create especially deep ruts.

An additional subjective indication that the soil moisture is suddenly released at the time of final snow cover removal has been noticed by river forecasters in the northern and central part of the United States. These forecasters have reported that immediately following reports of the loss of the snow cover they frequently observe a sudden increase in the runoff that cannot be accounted for by snowmelt.

### Conclusions

The information presented in this brief paper is neither sufficient nor conclusive enough to demonstrate that soil moisture and temperature conditions under the late season snow cover are a critical factor in determining the magnitude of the snowmelt runoff. However, the evidence presented is sufficient to show that: (1) Soil moisture under the snow cover in selected areas usually does increase during the winter; and (2) the increase should be considered in predicting the spring runoff. Further research on the magnitude of the effects examined in this paper will probably indicate how conceptual watershed models can be modified to account for the unusual moisture movement.

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### Appendix.—References

1. Ferguson, H., Brown, P. L., and Dickey, D. D., "Water Movement and Loss Under Frozen Soil Conditions," *Proceedings*, Soil Science Society, 1964, pp. 700–703.
2. Harlan, R. L., "Grand Conditioning and the Groundwater Response to Surface Freezing," *Proceedings*, International Symposia on the Role of Snow and Ice in Hydrology, Banff, Canada, September 6-13, 1972.
3. Jensen, R. D., Harisasan, M., and Rahi, G. S., "The Effect of Temperature on Water Flow in Soils," Water Resources Research Institute, Mississippi State University, State College, Miss., June, 1970.
4. Holt, R. F., et al., "Soil Moisture of Some Representative Minnesota Soils," *ARS 41-48*, U.S. Department of Agriculture, Washington, D.C., Aug., 1961.
5. Meiman, J. R., Friedman, I., and Hardcastle, K., "Deuterium as a Tracer in Snow Hydrology," *Proceedings*, International Symposia on the Role of Snow and Ice in Hydrology, Banff, Canada, September 6-13, 1972.
6. "National Weather Service River Forecast System, Forecast Procedures," *Technical Memorandum* NWS HYDRO-*14*, National Oceanic and Atmospheric Adminstration, Silver Spring, Md., Dec., 1972.
7. Pabst, A. F., Bowers, C. E., and Baker, D. G., "Flood Forecasting in the Upper Midwest; Data Assembly and Preliminary Analysis," *Project Report No. 137*, St.