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SOIL-WATER FREEZING, SNOW ACCUMULATION AND ABLATION IN MARMOT CREEK EXPERIMENTAL WATERSHED, ALBERTA, CANADA [1]

By

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Introduction

The potential for regulation and augmentation of the primary water supply for domestic, industrial and agricultural uses in the Canadian prairies lies almost entirely on the eastern slopes of the Rocky Mountains in western Alberta. This area, although it includes only 12.6 per cent of the drainage area of the Saskatchewan River system - the most important drainage basin and source of water in the prairie region of Canada - produces 87 per cent of the total water yield in the river system (Redmond, 1964). In recognition of the importance of this area for water production, a comprehensive research program was initiated in the early 1960's to explore the interrelationships between vegetation, soil, climate, and water and to define the mechanisms by which these interrelationships manifest themselves in the hydrologic regime. As part of this program, investigations were conducted in the Marmot Creek Experimental Watershed to define the soil-water and soil-temperature conditions on the watershed as related to snow accumulation and ablation, vegetation, and slope orientation. The results from this study and their interpretation in terms of infiltration theory and runoff forecasting are the subjects of this paper.

Marmot Creek Experimental Watershed

Marmot Creek Experimental Watershed, situated in the Kananaskis River Valley approximately 50 miles west of Calgary, Alberta (latitude 50°56'N, longitude 115°08'W) is typical of much of the high-elevation spruce-fir forest on the eastern slopes of the Canadian Rockies. The 3.6 square mile experimental watershed is characterized by moderate to steeply sloping topography and prominent glacial features. The winters are long and cold. Storr (1967) estimates that 25 to 30 per cent of the annual precipitation occurs as rain whereas the remaining 70 to 75 per cent occurs as snow or a mixture of rain and snow. The mean annual precipitation is about 35 inches, ranging from 25 inches in the lower portion of the basin to 45 inches at the higher elevations. Approximately 55 per cent of the annual precipitation is returned as streamflow. The elevational range is from 5200 to 9200 feet MSL.

The forest vegetation is predominately immature lodgepole pine (*Pinus contorta* var. *latifolia*) in the lower portion of the basin and mature to over-mature spruce (*Picea engelmannii* and *Picea glauca*) and fir (*Abies lasiocarpa*) with an admixture of lodgepole pine and sub-alpine larch (*Larix lyallii*) in the upper reaches.

The Study

In 1963, six sites (Table 1) were selected within the Marmot Creek Experimental Watershed and instrumented with a single stack of ten Colman fiberglas electrical-resistance units emplaced at the humus-mineral soil interface and at the 3, 6, 12, 18, 24, 36, 48, 60, and 72-inch depths. Each site was situated in an area of moderately uniform soil and vegetation, and approximately at a mid-slope position. The soils were developed in calcareous glacial till and colluvium, and were generally coarse with a high boulder fraction, and moderately-well to well drained internally and on the surface. The location of these study plots and relevant meteorological, streamgauging, and snow measurement networks are shown in Figure 1.

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Table 1. Summary of plot characteristics.

Plot No.	Cover Condition	Aspect	Basal Area ft^2/acre	Mean d.b.h. inches	Stems/acre
1	Spruce-fir (uncut)	Northeast	105	3.7	802
2	Spruce-fir (cut-over)	Northeast	141	4.6	924
3	Lodgepole pine	East	64	1.7	3624
4	Spruce-fir (uncut)	South	235	5.3	1202
5	Spruce-fir (cut-over)	Southwest	109	5.9	453
6	Lodgepole pine	South	70	2.0	2927

Weekly measurement of soil-water storage and soil temperature were made for an approximate three-year period ending July, 1967. Supplemental to these measurements, periodic observations of snow depth and snow-water equivalent were made on ten point snow courses located in the proximity of each study plot under similar vegetation and topography. The Colman units were calibrated individually in the laboratory at the termination of the field study following the procedure of Colman and Hendrix (1949). _In situ_ calibration was precluded because of the rocky nature of the soil profiles.

Results of Investigation

The results are presented in chronological order beginning with the observation of soil-water freezing in the late fall. The discussion emphasizes the soil-water phenomena and the implications to runoff forecasting and snow management.

Depth and duration of soil-water freezing.

Soil-water freezing as indexed by the electrical resistivity response of Colman soil-moisture units (Colman and Hendrix, 1949) commenced in mid-November to late December and persisted into the snow-melt period. Soil temperatures as measured by the thermistors incorporated in the Colman units were found to be highly variable and unreliable in indexing whether or not the soil was frozen. The depth to which soil-water freezing occurred increased progressively to a maximum in late March or early April. No consistent differences in the date of soil-water freezing or thawing were found between northern and southern aspects beneath the same vegetation type. The soil profiles beneath uncut spruce-fir froze earlier and thawed later than those beneath cut-over spruce-fir. The latter was intermediate in both time and duration of freezing between uncut spruce-fir and immature lodgepole pine.

Thawing of the soil profile occurred both from above and from below. In the 1966 and 1967 snowmelt periods, thawing of the soil profile occurred prior to initiation of snowpack ablation; whereas during 1965, the soil remained frozen, at least in part, until after complete disappearance of the snowpack.

Snow ablation and soil-water recharge.

The relative timing of snowpack ablation followed the same trend as thawing of the soil profile. The snowpack was depleted most rapidly beneath immature lodgepole pine cover and was most persistent beneath uncut spruce-fir. The 1965 through 1967 three-year mean snow-water equivalents for each cover condition and aspect combination are shown with the three-year mean daily stream discharge for the confluence area in Figure 2. The maximum snow-water equivalent, occurring in mid-March, was not significantly different between vegetation types. Differential rates of snowpack ablation, however, resulted in widely differing snow-water equivalents between vegetation types during depletion of the snowpack.

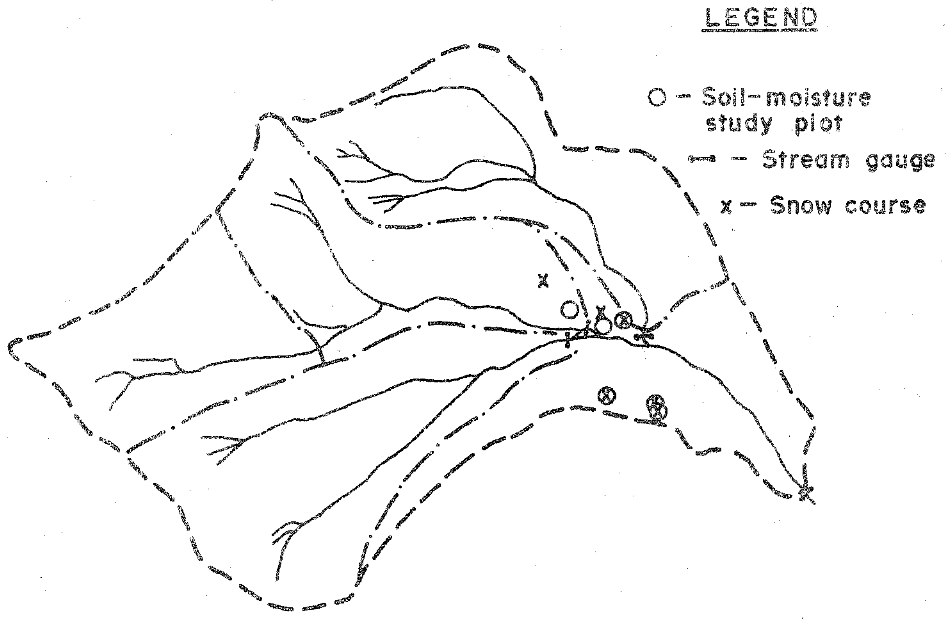

Figure 1. Instrumentation and soil-moisture study plot location map, Marmot Creek Experimental Watershed.

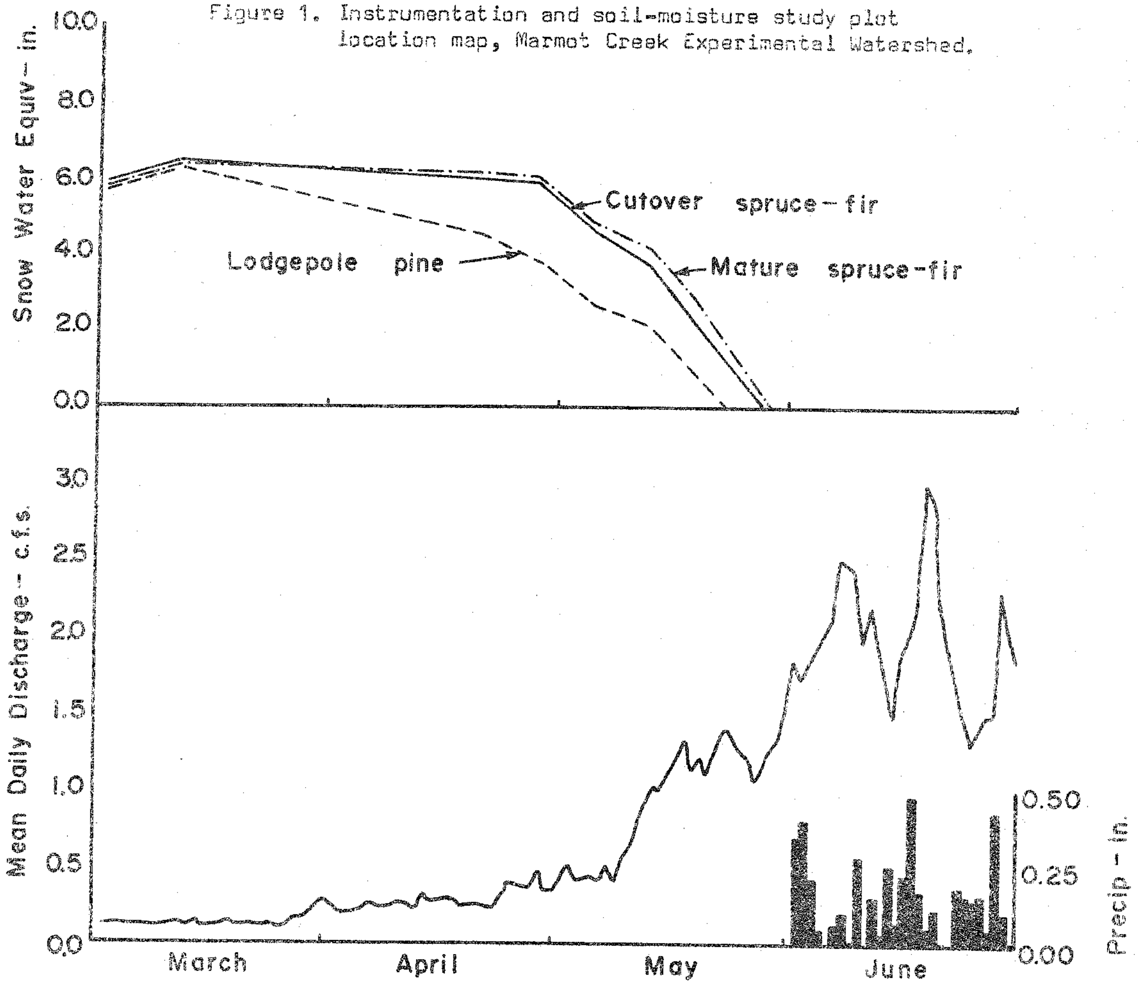

Figure 2. Mean streamflow hydrograph response as related to snow cover under three vegetative cover conditions.

Analysis of soil-water storage within the soil profiles showed that only a small percentage of the water in the snowpack can be accounted for in terms of increased soil-water storage during snowmelt. For example, of the maximum snowpack of approximately 6.3 inches water equivalent, only 0.4, 0.9, and 1.1 inches of water could be accounted for by increased soil-water storage under uncut spruce-fir, cut-over spruce-fir, and immature lodgepole pine, respectively. This sequence was inversely related to the moisture storage levels of the three vegetation types at the initiation of snowmelt. The soil profile beneath lodgepole pine was at the lowest initial moisture level, whereas the soil beneath virgin spruce-fir is at the highest moisture level although below moisture retention at 1/3 atmosphere tension. The major source of soil-water recharge was from spring rains subsequent to complete ablation of the snowpack. Hydrograph analysis (Figure 2) showed that although moderate increases in streamflow do occur during snowmelt, these steady and gradually increasing discharges are indicative of increased baseflow and not surface runoff. Since snowmelt appeared neither as soil-water recharge nor as overland flow, it is implicit that snowmelt contributed directly to groundwater except when melt precedes thawing of the soil profile and/or is lost to evaporation.

The inability to detect a large increase in soil-water storage during snowmelt is consistent with infiltration theory. Rubin and Steinhardt (1963) have shown analytically that where the rate at which water is added at the soil surface (i.e. rate of snowmelt) is less than or equal to the saturated hydraulic conductivity of the soil, soil-moisture contents at increasing depths tend to approach a constant level as infiltration proceeds. At this level, the hydraulic conductivity of the soil approximately equals the rate of supply at the surface. Thus the rate of snowmelt and hence the rate at which water is released by the snowpack governs the rate of infiltration into the soil and the resulting soil-moisture storage level. Consequently, if the initial soil-moisture storage conditions at the beginning of snowmelt are such that the unsaturated hydraulic conductivities are greater than or equal to the rate of snowmelt, then it is theoretically possible that little or no increase in soil-moisture storage will occur during snowmelt and that water released from the snowpack can be transmitted through the soil directly to the groundwater table.

The maximum rate of snowpack ablation was 0.03 inch water equivalent per hour during the period May 18 through May 26, 1967, on southern aspects. The minimum saturated hydraulic conductivity was in excess of 1.0 inch per hour. Thus transmission of snowmelt directly through the soil profile while the profile was in a condition less than field capacity is feasible from the standpoint of the physics of flow through porous media. Furthermore, since soil freezing was not observed at and near the surface horizons during snowmelt, there does not appear to have been any impedance to infiltration due to frozen soil except in the spring of 1965 when snowmelt preceded thawing.

Implications of Results to Runoff Forecasting

In the evolution of runoff forecasting, the methodology has been based upon systems analysis in which the interrelationships between observable hydrologic and meteorological parameters are described by explicit relationships. These relationships are then used in a model to predict or simulate the response of the system to given stimuli or input. The structure of the prediction model is such that the input is routed into alternative storage elements and transmission routes, connected in parallel and in series by a set of decision points. At each decision point, routing is accomplished on the basis of preassigned criteria, usually derived from empirical or statistical relationships which may or may not involve the flow rates into the decision point or the properties of the storage elements.

Since any realistic hydrologic response model must simulate on a continuous basis the important processes and relationships within the system that it represents, it must be physically relevant to the system and non-unique with respect to both time and space (Freeze and Harlan, in press). Consequently the runoff forecasting model must maintain in its controlling parameters and in its representation of the physical processes, some degree of similitude to reality and to the processes operative within the system. It becomes implicit, therefore, that the basis on which alternative routing decisions are accomplished must in fact represent the true physical nature of the system operation if it is to be representative and applicable to a range of conditions.

Commonly in systems hydrology, routing decisions are based upon the threshold concepts of infiltration capacity, field capacity, wilting point, or soil-moisture storage deficit. These concepts, however, are outdated and both fundamentally and practically inadequate in that they fail to represent the true physical system. It was shown from the analyses presented in this paper, for example, that the concept of field capacity as commonly used in hydrologic model building is without relevance to snowmelt infiltration and the resultant soil-water distribution. Snowmelt infiltration occurred without reference to some threshold value of soil-water storage, but was dependent upon: 1) the initial soil-water storage conditions and 2) the rate of snowmelt.

Although the results reported in this paper are from a study of limited scope, it is hoped that they will provide the incentive to re-examine the basis of much of our runoff forecasting methodology in terms of our current knowledge of the physics of the hydrologic system and the relevancy of the controlling parameters upon systems operation. The results are to be interpreted as indicative of the phenomena active within the hydrologic system and not as conclusive evidence in themselves.

Conclusions

If we are to forecast runoff on a scientific basis, we must re-examine the processes of snowmelt, flow through porous media, and streamflow generation and incorporate this knowledge in its physical and mathematical representation into our runoff forecasting or simulation methodology. Similarly, if the management of the snowpack for water production is to be optimized in terms of desired objectives, management prescriptions must be based upon and incorporate a thorough knowledge of the hydrologic processes. The rate of snowmelt, for example, has a regulatory effect on the resultant soil-water distribution at cessation of snowmelt. Hence, the rate of snowmelt as well as the spatial distribution of snow accumulation and melt with respect to the ground-water flow system becomes highly significant in terms of streamflow response. The management of even a single element of the hydrologic system, therefore, must be in full recognition of the continuity of the hydrologic cycle if the desired consequences are to be achieved.

From the observations in Marmot Creek Experimental Watershed, further research is needed to define:

1) the energy balance within the forest environment and its effects upon water movement within the soil-water-snow system, soil-water freezing, and snowpack ablation; and

2) the flow path of water from snowmelt to overland flow and into or through the soil profile, and the mechanism of ground-water recharge.

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