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Comparison of the Soil Water Cycle in Clear-Cut and Forested Sites[1]

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ABSTRACT

A study was undertaken to determine the importance of subsurface flow and drainage in a northern Saskatchewan forested basin, and to examine the effect of clear-cutting on the hydrologic cycle. Components of the soil water cycle were estimated for clear-cut and forested sites during the spring melt and growing season. Surface runoff was measured using interceptor troughs and tipping-bucket gauges. Soil water contents were measured using a neutron probe. Soil water fluxes were calculated using Darcy's Law and mass-balance equations. Creek flow was monitored using a water-level recorder and still well. Surface runoff was insignificant on all plots during the growing well. Surface runoff was insignificant on all plots during the growing season. Clear-cutting increased hillslope water yield fivefold during the snowmelt period and doubled drainage during the growing season, compared with the forested site. Stream hydrographs indicated the basin was dominated by subsurface flow. This was consistent with measurement made on the forested plots where calculated drainage values could account for almost all observed streamflow. Hydrograph separation was carried out using mass-balance calculations of Ca and Mg. The separation was used to identify sources of subsurface water contributing to streamflow.

Additional Index Words: **subsurface flow, drainage, snowmelt, hydrograph separation.**

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Demand for forest products is resulting in logging in the northern regions of Canada. This development can seriously affect streamflow regimes, and an understanding of hillslope flow is essential in predicting or remedying the effect of certain harvest practices. Subsurface runoff may be a major source of streamflow in forested basins (Hewlett and Hibbert, 1963; Whipkey, 1965; Dunne and Black, 1970). Subsurface runoff is likely when surface soil with a high saturated hydraulic conductivity is underlain by a layer with a hydraulic conductivity at least 10 times smaller (Whipkey and Kirkby, 1978). Usually the lower saturated hydraulic conductivity is caused by an increase in bulk density and/or clay content. Soil survey information indicates that many Canadian forest areas have conditions that favor subsurface runoff, but its importance has not been studied.

Surface and subsurface runoff of slope segments (or microwatersheds) can be measured using interceptor troughs (Dunne, 1970; Carson and Kirkby, 1972), while drainage can be estimated from mass-balance methods (Rose et al., 1965; Black et al., 1969; Ehlers and Van der Ploeg, 1976; Arya et al., 1975) or soil water-flux calculations (Freeze, 1978; Atkinson, 1978; Hewlett and Troendle, 1975). Alternatively, streamflow data can be analyzed to yield information on surface and subsurface runoff, and drainage. Either the shape of the hydrograph (e.g., Gray and Wigham, 1970) or the composition of the streamflow (e.g., Dincer, 1968) can be used. In the latter case runoff and deep drainage are separated with the equation:

$$C_t = rC_g + (1 - r)C_r, \qquad [1]$$

where

C_t = concentration of some specific ion in the stream,
C_g and C_r = concentration of that ion in the drainage and runoff water, respectively, and
r = fraction of total flow due to runoff.

Tritium has been used in many such studies (Dincer, 1968; Fritz et al., 1976), but theoretically any ion could be used. Wallis (1979) used tritium to separate the contributions of ground and surface water to streamflow, and then used this separation to predict Ca and Mg concentrations in the stream.

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Table 1—Physical characteristics of the experimental plots and the drainage basin.

Location	Area	Length	Slope
	m^2	m	%
Cutover area on deep till			
Top slope	155	29	8.6
Top slope	316	45	9.2
Mid slope	145	32	10.3
Mid slope	113	33	14.1
Lower slope	95	24	7.7
Lower slope	61	17	7.2
Cutover area on shallow till†			
Top slope	--	--	4.0
Mid slope	--	–	4.0
Lower slope	–	--	11.3
Forest on deep till			
Top slope	99	33	7.7
Top slope	102	34	7.7
Lower slope	159	21	9.1
Drainage basin	9.2×10^6	3.8×10^3‡	4.9§

† Plots instrumented with neutron-probe access tubes only.
§ Maximum length of travel for creek.
§ Average stream gradient.

MATERIALS AND METHODS

The study area was situated 160 km north of Prince Albert, Saskatchewan, Canada, in the West Montreal Lake Plain (54°N106°W). The area is gently rolling to undulating. Mixed stands of white spruce (*Picea glauca*) and jack pine (*Pinus banksianna*) are found in well-drained areas, and black spruce (*Picea mariana*) in imperfectly drained spots. The surface vegetation is dominated by feather mosses (*Pleurozeum schreber* Hylocomium sp). The soils of the area are formed on medium to moderately fine-textured, moderately calcareous glacial till overlain by medium to moderately coarse sand. The sand is of variable thickness, and where the sandlayer is thin (< 100 cm) secondary clay accumulation may occur at the surface of the till (Head et al., 1980).

All plots were located on a beach ridge that lies on the boundary of a small watershed drained by a seasonally active creek. The physical characteristics of the sites are given in Table 1. Nine sites were located on a portion of the ridge that had been clear-cut just before the study started. Six of these nine plots were in an area where the sand was > 130 cm thick, and these sites were matched by three sites that still had their original forest cover. Three plots in the clear-cut area had till within 70-100 cm of the surface. Data on texture, bulk density, saturated hydraulic conductivity, and exchangeable Ca and Mg of the major mineral soil horizons are given in Table 2.

Surface runoff from the nine plots with deep till was measured with troughs (Carson and Kirkby, 1972; Dunne, 1970). Galvanized steel troughs with an extended lip were placed in shallow trenches and the lip pushed into the face of the trench about 10-15 cm below the surface of the mineral soil. Water collecting in the troughs was measured with a modified tipping-bucket gauge (Chow, 1976). The capacity of the buckets ranged from 0.5 to 1.8 L/tip and was set prior to use and checked at regular intervals. Tips were registered on DC-operated event recorders; the chart speed of the recorders was varied as needed. The runoff area (Table 1) contributing to each trough system was determined from the general slope of the area (for the forested plots) or from a detailed topographic survey (in the cutover area). No troughs could be installed on the three cutover plots with the till near to the surface because of severe surface disturbance during the logging.

Table 2—Properties of the major mineral soil horizons found in the basin.

Horizon	Texture†	Bulk‡ density	Saturated‡ hydraulic conductivity	Exchangeable§ Ca	Exchangeable§ Mg
		g/cm^3	cm/h	meq/100 g	meq/100 g
A	LS	1.0-1.2	25-35	0.5-1.5	0.2-0.8
C	S	1.2-1.3	20-30	0.8-2.3	0.2-1.6
Till	SCL	1.7-1.9	0.001-0.01	6.0-21.3	1.6-4.9

† L = loam; S = sand; C = clay.
‡ Determined on undisturbed cores (7.6 cm diam by 7.6 cm high).
§ Adapted from Head et al., 1980.

Two neutron-probe access tubes were installed to a depth of 100 cm or more in each plot for measurement of soil water content below the 10 cm depth. Surface-soil water content was determined gravimetrically. Tensiometers were installed at regular intervals to 110 cm depth in the nine plots where the sane layer was at least 130 cm thick; one set of tensiometers was installed on each plot. No tensiometers could be installed in the three severely disturbed cutover plots. Soil water content and tension were measured every second week, and additional readings were taken immediately following snowmelt and major rains.

Rainfall was measured with a tipping-bucket rain gauge that was checked periodically against a standard rain gauge. Snow depth and density were determined prior to spring melt.

Runoff of the plots during the spring-melt period was also calculated using the mass balance equation:

$$R = W - \Delta S + P, \qquad [2]$$

where

R = surface runoff (cm),
W = water-equivalent of snowpack (cm),
P = precipitation during the melt period (cm), and
ΔS = change in soil water storage (including litter storage) between the previous fall, and the end of the melt period (cm).

The runoff calculated in this way includes water losses by deep drainage and evaporation between the end of the snowmelt period and the previous fall. During the growing season drainage was calculated with Darcy's Law using the tensiometer readings and values of the hydraulic conductivity (k_Θ) estimated from the k_Θ vs. water content curve. In situ estimates of k_Θ were obtained using the instantaneous-profile method (Ehlers and Van der Ploeg, 1976; Arya et al., 1975) on the clearcut plots. Undisturbed soil cores (7.6 by 7.6 cm) were used to obtain k_Θ at saturation and at low matric suctions. At the water contents where the two methods overlapped, agreement between them was good. These calculated drainage losses were compared with drainage estimates calculated from:

$$V_L = \int_{Z=L_o}^{Z=L} (\theta_{Z,t} - \theta_{z,t+\Delta t})\, dZ, \qquad [3]$$

where

V_L = drainage at depth L over time Δt (cm^3/cm^2);
θ = volumetric water content, cm^3/cm^3;
L = depth of deepest measured water content, cm;
L_o = depth of zero-flux plane (where the hydraulic gradient is zero); and
t = time, d.

Creek discharge was measured using a water-level recorder installed in a stilling well upstream from a culvert. Streamflow was calculated

Table 3—Surface runoff during the spring-melt period and growing season.

Area	Spring-melt period: Precipitation†	Spring-melt period: Surface runoff‡	Spring-melt period: Runoff§	Growing season: Precipitation	Growing season: Surface runoff‡
	cm	cm	cm	cm	cm
	14 April-3 May			3 May-10 October	
Cutover					
Deep till	20.0	6.1	6.2	25.5	0.1
Shallow till	12.5	--	5.3	25.5	–
	14 April-11 May			11 May-10 October	
Forest	15.3	0.0	1.2	25.5	0.1

† Includes snow cover at start of melt period.
‡ Measured with tipping buckets.
§ Calculated by mass balance; includes drainage and evaporation.

using the relationship between culvert discharge and hydraulic head given by Smith (1979). The hydrographs were analyzed for storm recession constants, time to peak flow, and subsurface storage, as outlined by Gray and Wigham (1970). Hydrograph separation was also carried out using Eq. [1] and the Ca and Mg concentrations in the streamflow. The concentrations of Ca and Mg were measured with a flame photometer.

RESULTS

Precipitation during the study year (October 1978–October 1979) consisted of 26.5 cm rain and 19.0 cm snow, which is quite similar to the long-term average for the area (Ellis and Clayton, 1969). Snowmelt started mid-April and was complete by early May; early in the melt period there was a 1.0 cm rainstorm.

At the six cutover sites where runoff was estimated using troughs and the mass-balance method (Eq. [2]), agreement between both approaches was excellent (slope = 1.02, intercept = 0.25 cm, r = 0.96). At the three forested sites the tipping-bucket system showed <0.05 cm runoff for all three sites, whereas the mass-balance method showed no water loss at two sites and 2.7 cm at the third. At this third site, the soil was saturated at the end of the melt period, and drainage could have accounted for most of the observed water loss. Because of the frozen subsoil, tensiometers could not be installed until late May and mid-June on the cutover and forested plots, respectively, and drainage and evaporation losses could not be separated before their installation. The results for all three sets of plots were averaged (Table 3) taking into account the size of the individual plots. Table 3 clearly illustrates the increased surface runoff on clear-cut sites during the spring-melt period. During the growing season surface runoff was negligible on all plots.

Estimates of surface runoff by the trough method were less than those of surface runoff, drainage, and evaporation by the mass-balance method (Table 2). Some drainage could have been in the form of interflow. During spring-melt total infiltration was similar on the cutover and forested sites on the deep sandy soil, and higher than on the shallow cutover site. It is worth noticing that snow cover was highest on the cutover with the deep till because this site was sheltered from prevailing winds, and least on the exposed cutover site in the area with the shallow till.

Once the tensiometers were installed, drainage rates on the cutover area with the deep sandy subsoil were calculated with Eq. [3] and with Darcy's Law. Calculations were made at least once every 2 weeks, and more frequently following snowmelt and significant rains. On two of the cutover plots, the absolute water contents differed significantly between the two neutron-probe access tubes, but changes in water content with time were similar. This would not affect drainage calculations with Eq. [3], but could cause an error when drainage was calculated with Darcy's Law using inferred values for k_Θ. The two methods of calculating drainage agreed well (r = 0.97, slope = 1.06, intercept = −0.03 cm/d), and the mean of the two methods is given in Table 4. The tensiometer readings indicated that the zero-flux plane remained between the 30- and 40-cm depths for most of the season. This depth corresponds to the approximate location of the B horizon. Darcy's law was used to estimate drainage of the forested site during the growing season, as root uptake of soil water prevented the use of Eq. [3]. The resulting water balances for the forested and cutover areas are given in Table 4. No drainage calculations were possible before the installation of tensiometers, and hence for most of May no drainage was calculated for the various plots. Deep drainage of the cutover area with the shallow till was calculated from the water balance assuming that surface runoff and evaporation of this area were similar to that of the deep cutover area. The drainage estimates in Table 4 were calculated with the implicit

Table 4—Water balance for the forest and cutover areas during the growing season (27 May–10 October).†

Area	Precipitation	Change in profile storage	Drainage	Evaporation, transpiration, and runoff
	cm			
Cutover				
Deep till	21.4	0.5	13.0	12.9
Shallow till‡	21.4	0.8	9.3	12.9‡
Forest	21.4	10.8	6.4	25.6

† Surface runoff was negligible (Table 3).

‡ It was assumed that evaporation and runoff were the same for the shallow till as for the deep till area; drainage was then calculated with the water-balance method.

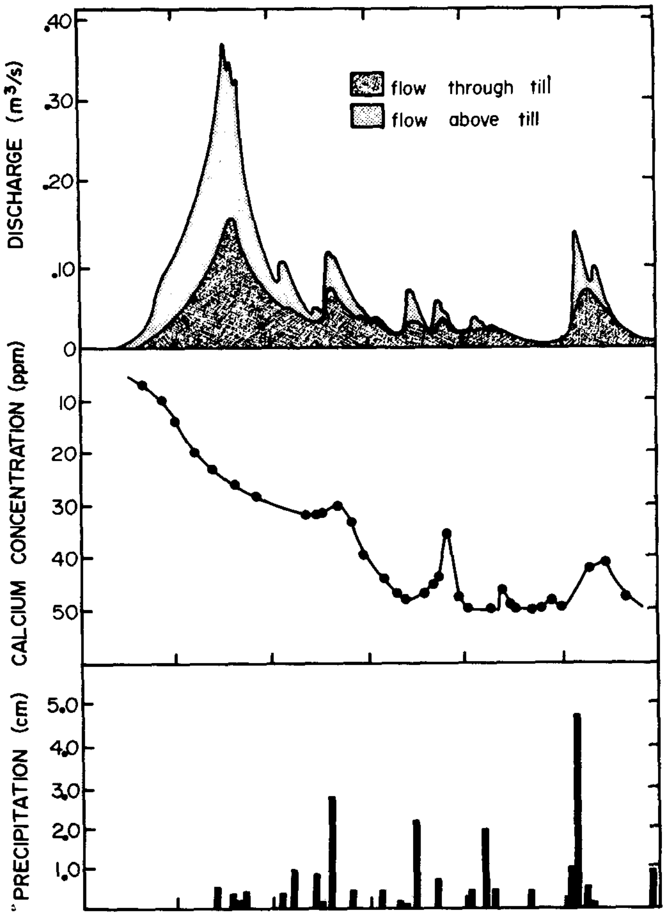

Fig. 1—Rainfall-discharge relationships, Ca concentrations, and the separation of creek flow above and within the till.

Table 5—Origin of creek flow according to season.

	Creek discharge		
	$m^3 \times 10^6$	cm/unit area	% of precipitation†
Snowmelt			
Through till	0.35	3.9	19
Over till	0.30	3.2	16
Total	0.65	7.1	35
Rain			
Through till	0.35	3.8	15
Over till	0.10	1.1	4
Total	0.45	4.9	19
Annual			
Through till	0.7	7.7	17
Over till	0.4	4.3	10
Total	1.1	12.0	26

† Includes snowpack for the smowmelt period.

assumption that water movement was only in the vertical direction; this assumption is probably valid where the till is deep. Significant lateral movement would occur where the till is shallow, as was indicated by the presence of a saturated layer above the shallow till immediately after a storm event.

The differences in exchangeable Ca and Mg levels between the sand and the till (Table 2) suggested that Ca and/or Mg levels in the creek water might be used to separate stream flow into ground-water flow through the till, and surface runoff plus interflow. The concentrations of Ca in the creek water are plotted in Fig. 1; Mg concentrations followed a similar pattern (r = 0.99). The concentration of Ca in the water flowing through the till was assumed to be 50 ppm (the values measured in the stream after several weeks of no rainfall, cf. Fig. 1), and that of rain or snowmelt (4 ± 1 ppm) was assumed to be characteristic of runoff and interflow. With these values and the measured values for Ca in the creek water, the hydrograph was separated into flow through the till and flow above the till. A similar calculation was done for Mg, and the separation shown in Fig. 1 is the average of the predictions based on Ca and Mg.

The growing-season hydrograph (Fig. 1) for the creek showed the high recession constants (0.994–0.966 h^{-1}) and long lag times (18–30 h) that are typical for basins dominated by subsurface flow (Dunne, 1978). On average about 20% of the precipitation of the major rainstorms entered subsurface storage. The extremely long lag time between disappearance of the snow cover on 3 May and peak flow on 18 May is probably due to frozen soil conditions, which would decrease k_Θ and subsurface flow rates.

Table 5 gives a breakdown of the creek discharge based on Fig. 1. The average drainage of the whole basin was 12 cm/year, or about 25% of the total precipitation, and more than half originated from snowmelt. During the spring-melt period about half of the streamflow was due to flow above the till and about half due to flow through the till. During the growing season flow above the till was much less important than flow through the till.

DISCUSSION

About 2% of the area of the small basin had been clear-cut, and its hydrograph is, therefore, essentially that of an undisturbed system. The hydrograph response indicated that the streamflow is dominated by subsurface flow with little or no surface runoff. This was consistent with the measurement made on the forested plots (Table 3).

During the snowmelt period the forest plots showed 1.2 cm of drainage loss (Table 3) and the hydrograph (Fig. 1) indicated the equivalent of 1.9 cm of streamflow. The presence of frozen subsoil during this period may possibly account for the large proportion of streamflow originating as lateral flow above the till. Streamflow after 27 May was equivalent to 5.8 cm (Fig. 1), which agreed well with drainage calculated for the small forest plots (Table 4). This indicates that about 25% of the summer rainstorms were lost from the root zone by drainage. About four-fifths of this loss occurred as deep drainage through the underlying till, while the other one-fifth moved laterally above the till (Table 5). The drainage calculations indicated that hill slope drainage can account for almost all observed streamflow. The portion of the streamflow that originated from flow above the till is equivalent to subsurface stormflow as defined by Hursch (1936), Whipkey (1965), and others, while the flow through the till is equivalent to ground-water flow.

Comparison between the clear-cut and forested plots gives an indication of the potential effects of clear-cutting on the hydrologic cycle. Clear-cutting increased hillslope water yield during the snowmelt period five-fold (Table 3) and doubled drainage during the growing season (Table 4). The increased water yield from the clear-cut plots during snowmelt occurred almost entirely as surface runoff. This would result in higher spring peak flows and shorter lag times, which may have significant effects on water quality. Clear-cutting would also affect streamflow during the growing season, but may not affect timing of the flow or quality of the water as severely as during the spring melt.

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