SOME FACTORS AFFECTING SPRING SNOWMELT WITHIN NARROWS MOUNTAIN BROOK BASIN, A FORESTED WATERSHED IN CENTRAL NEW BRUNSWICK

Andrew MacLean Gordon

Forest Soils Laboratory
University of Alaska
Fairbanks, Alaska

ABSTRACT

An analysis of the factors affecting snow accumulation, ablation and streamflow response to spring snowmelt is one aspect of the Nashwaak Experimental Watershed (NEW) Project in central New Brunswick. Five years of various climatic and runoff data from Narrows Mountain Brook were examined in order to establish a functional and practical relationship between observed snowmelt and thermodynamically-related causal factors. Daily contribution to streamflow of snowmelt was determined by recession analysis. Individual climatic parameters tested against snowmelt by regression were: on-site daily temperature and sum of hourly temperatures above 0°C, and off-site (Fredericton Canada Department of Agriculture Station) windspeed, maximum temperature, sunlight hours, and global solar radiation. Statistically significant, but not extremely strong relationships existed in all cases, except windspeed and sunlight hours, which were not significant. A multiple linear regression using the two on-site (NEW) factors as predictor variables for snowmelt gave a highly significant correlation coefficient of 0.69. The standard error of estimate was (±) 6.48 area-mm.

INTRODUCTION

In many areas of North America, the unbalanced seasonal distribution of streamflow may be attributed to the melting of snow and ice. Along the eastern seaboard, and in parts of the northeastern United States, for example, snowmelt is the principal source of water yield (Satterlund, 1972). In this region, more than one half of the annual runoff occurs during relatively short winter periods and in early spring (Satterlund and Eschner, 1965). In the Saint John River basin, New Brunswick, the annual streamflow regime shows little relationship to precipitation. This is primarily due to the spring release of precipitation accumulated in the basin snowpack as snow during the preceding winter (Inland Waters Directorate, 1973).

The Nashwaak Experimental Watershed (NEW) Project is a multi-institutional study concerned with the impact of certain forestry practices upon terrestrial and aquatic ecosystems, in terms of environmental quality and productivity. Under the auspices of the hydrometeorological section, Morrow (1977) has written on rainfall-runoff relationships for two selected basins on the Nashwaak watershed, and Dickison and Daugharty (1977) have discussed the effects of forest cover and topography upon snowcover in these same watersheds.

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In the same context, this report involves an analysis of some factors responsible for spring snowmelt in one of the basins of the NEW project.

THE STUDY AREA

Narrows Mountain Brook is a small tributary of the Nashwaak River, draining a minor watershed of 391 ha. The basin is of southeast aspect and ranges in elevation from 220 to 420 m above MSL. The basin is one of a pair of watersheds in a paired basin design, and is presently in the process of being clearcut. Hayden Brook, to the north, is the sister control.

The Nashwaak Experimental Watershed is located approximately 50 km north of Fredericton, N. B. and lies in a region of eastern Canada which receives 200 to 280 cm of snow annually. However, the maximum depth of snow during the snowcover season, November to April, is rarely above 90 cm. Forested areas may exhibit more.

METHODOLOGY

Initially, within any one year, the snowmelt "season" was set by the following criteria:

1. start of season: clear evidence of melt input, manifested in observable basin response during the preceding day, such that melt was not being stored in the pack
2. end of season: cessation of basin melt response to temperature inputs

Within this snowmelt season, individual recessions were designated by these further criteria:

1. total precipitation falling as rain in the previous 30 hours could not exceed 5 mm
2. precipitation falling as snow was allowed, as it would have no immediate effect upon melt and could also represent a contribution to future snowmelt volume on another day
3. on the temperature trace for any one day, the graphical representation of "melting degree-hours" had to exist as a distinct and well-defined entity (semi-circular area bounded by temperature trace and horizontal 0°C line). This spatial "amount" of heat was considered to be a primary driving force responsible for snowmelt.

Defining sample recessions in this manner resulted in 30 possible candidate recessions for the years 1972 to 1977, exclusive of 1975.

Using recession analysis as described by Garstka et al. (1958), daily volumes of snowmelt were calculated for all 30 recessions. In this type of analysis, each day's contribution to snowmelt is bounded by two sloping lines (Figure 1), which represent the theoretical natural decline of flow rate with time. Each hourly flow rate is a certain proportion of the previous hour's flow rate: this proportion is a constant, defined commonly as K.

If q_0 represents flow at the point at which snowmelt response for the next day begins to obscure the actual recession of the flow, then q_{-1} represents the flow at a point one hour previous to this, and so on. When averaged, the ratios q_0/q_{-1}, q_{-1}/q_{-2}, and q_{-2}/q_{-3} yielded the characteristic recession coefficient for each event. 36 events were averaged, and a K-value of 0.979 for the basin, established.[1]

Another method of calculating K averages only the ratio q_0/q_{-3} for all events.

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[1] 30 defined samples plus 6 valid recession limbs from other weakly-defined snowmelt events.

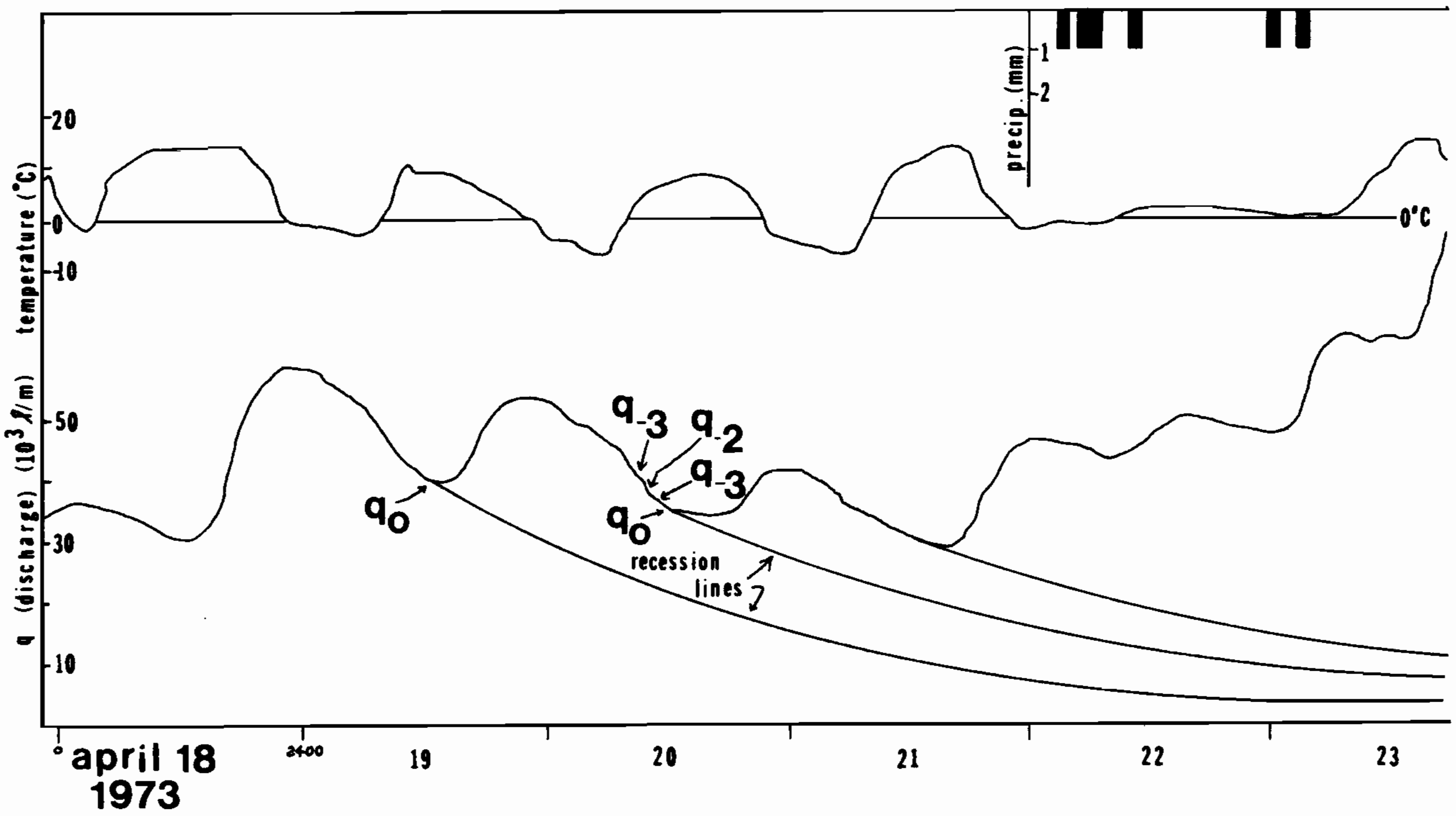

Figure 1. Daily runoff volumes, temperature and precipitation for the start of the 1973 snowmelt season.

The slope of the line in Figure 2 is also a K-value, 0.941, the result of such an averaging. However, it is not as sensitive to hourly changes in curve shape and hence its' use as a proportionality constant is not warranted.

The calculation of the recession volumes then proceeds by the solution of the following equation: (Figure 3)

$$M = Q - \Delta Q_a + \Delta Q_b - \Delta Q_c \qquad (1)$$

where M = daily contribution of snowmelt in ℓ/m-hours
Q = sum of hourly discharges for a 24-hour period, from the inflection point Q_o
ΔQ_a, Q_b, Q_c = volumes of melt water given by the determination of the area[1] under the recession lines in question

In Table 1, the 30 recessions are paired to form the boundaries of the snowmelt volumes. Dummy partners are provided in those cases where only single recession lines exist, in order to segregate boundable volumes. The lines recessing from these points were not included in the calculation of K; rather, K determined the rate at which the points recessed.

Once the recession volumes were determined, they were regressed on several independent variables. These were:

T_x (NEW) maximum daily on-site temperature (°C)

T_x (CDA) maximum daily (CDA) temperature (°C)

≤T (NEW) sum of hourly on-site temperatures above 0°C (°C)

$\bar{U}$ (CDA) daily average windspeed at 1.6 m (kph)

R_s (CDA) daily global solar radiation (langleys)

S (CDA) bright sunshine per day (hours)

A multiple linear regression equation was developed based upon maximum temperature, on-site, and the sum of hourly on-site temperatures above 0°C. Statistical testing followed Zar (1974). A degree-day factor (DDF) was developed for Narrows Mountain Brook according to the procedure outlined by Bruce and Clark (1969).[2]

RESULTS OF ANALYSES

The DDF for Narrows Mountain Brook was established at 1.3 mm/°C-day. This value is higher than the highest DDF for the Tobique River, N. B. (1.28) presented by Bray (1965), and indicates the predominance of events (used in calculating the DDF) taken from time periods in which the pack was ripe to overripe (ie. when active snowmelt was occurring).

The results of six simple linear regressions of snowmelt upon various independent variables are summarized in Table 2. Based on the two on-site variables, which were two of the strongest independent factors, the multiple linear regression equation is:

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[1] Barnes (1942) originally expressed the equation of the recession line in a simple exponential equation:

$$q_t = q_o K^t$$

where q_t = flow at time t
q_o = flow at time = 0, inflection point
K = K-value, recession coefficient

The integration of this equation is the volume below the recession line. The evaluation is:

$$Q = Q_o \left. \frac{K^t}{\ln K} \right|_{t_2}^{t_1}$$

[2] baseline 0°C

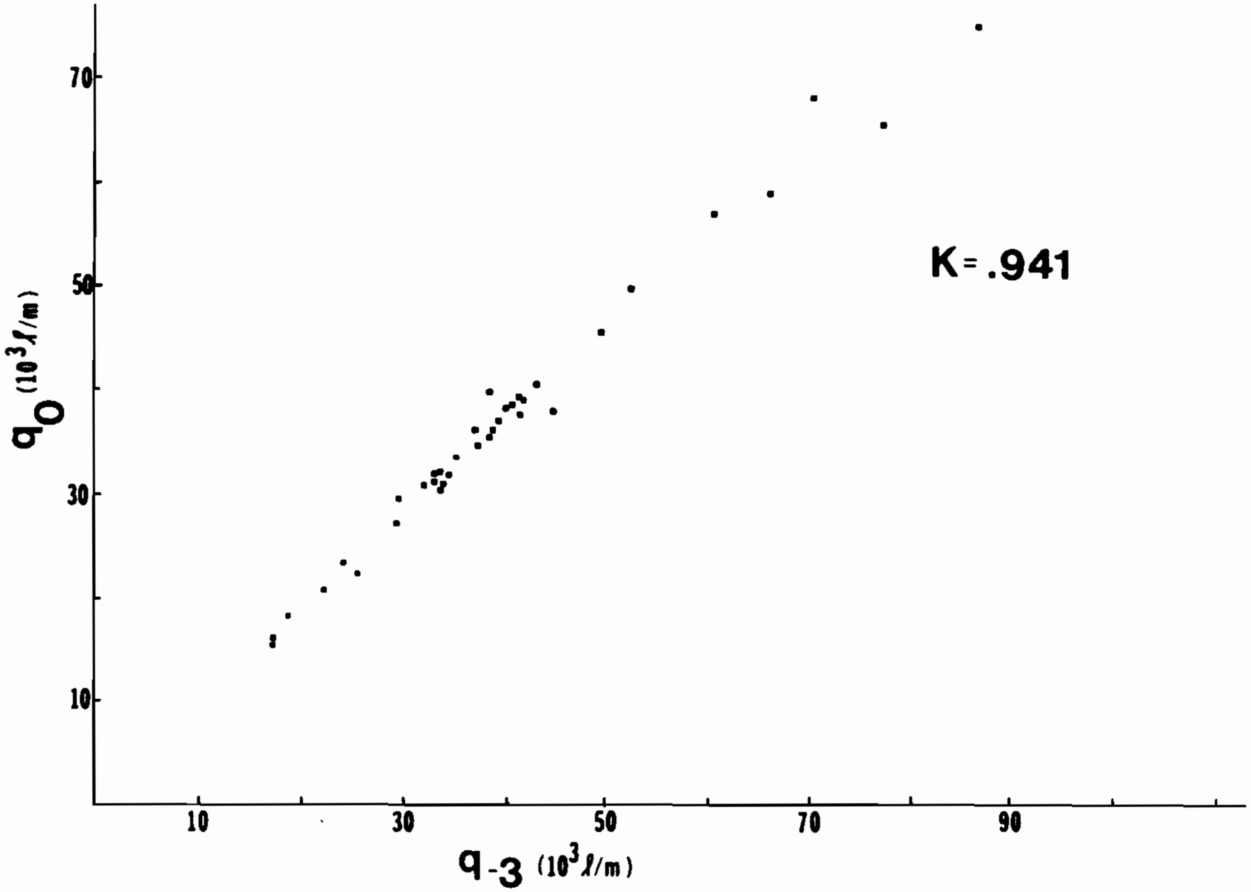

Figure 2. Flow at q_0 as a function of the flow three hours previous, q_{-3}. The slope of the best-fit line is K = .941.

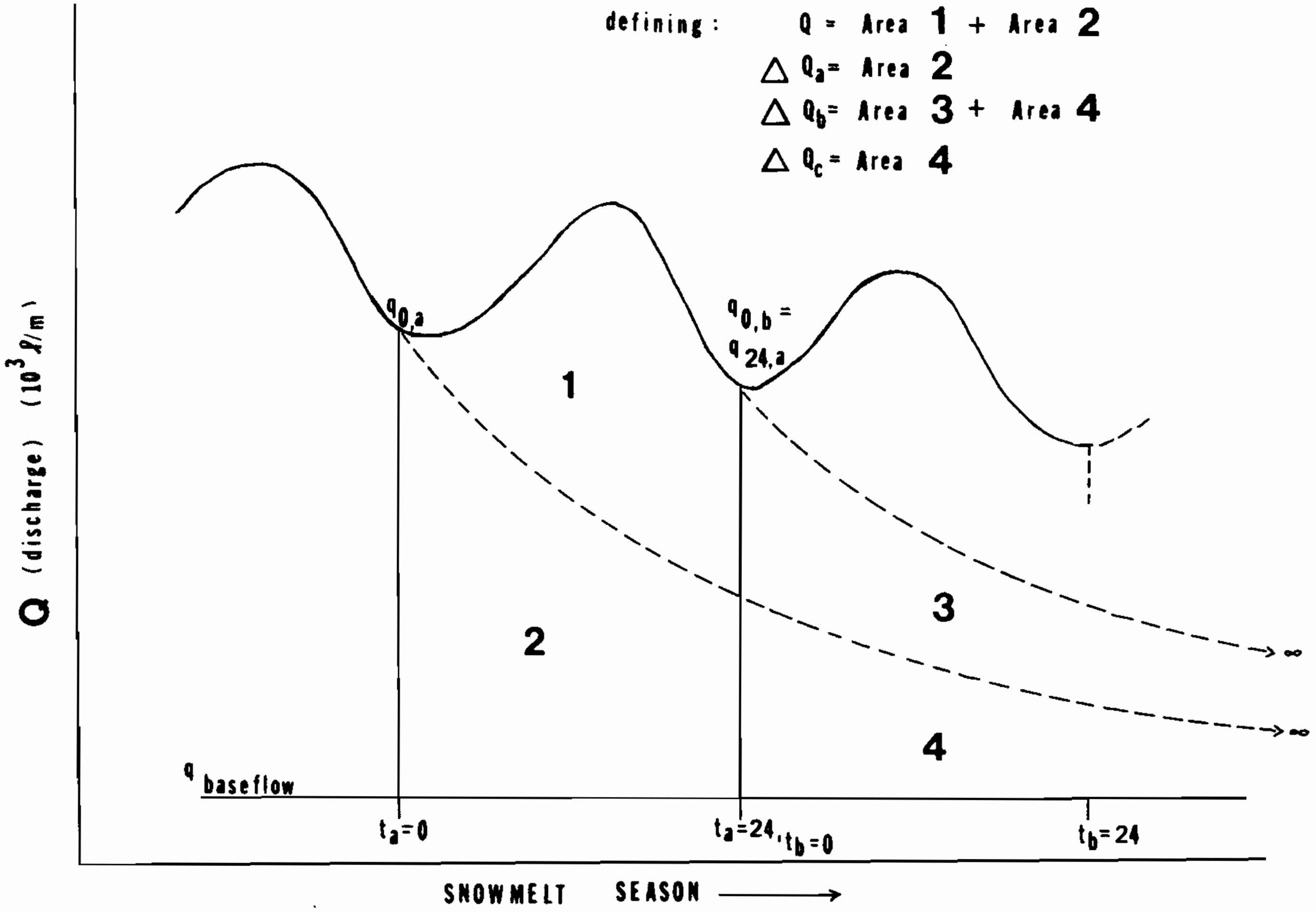

Figure 3. Segregation of snowmelt by day.

Table 1. Pairing of recession lines to give recession volumes.

No.	Recession Line Designation	Time (AST) and Date of inflection, q_0	Recession Volume No.	Date of Causal Parameters
1	72-1	1600, May 08, 1972	1	May 08, 1972
2	72-2	1800, May 09, 1972	2	May 09, 1972
3	72-3	1300, May 10, 1972		
	[a]X-1		3	May 13, 1972
4	72-4	1500, May 14, 1972		
	X-2		4	Apr. 17, 1973
5	73-1	1300, Apr. 18, 1973	5	Apr. 18, 1973
6	73-2	1400, Apr. 19, 1973	6	Apr. 19, 1973
7	73-3	1100, Apr. 20, 1973	7	Apr. 20, 1973
8	73-4	1300, Apr. 21, 1973		
9	73-5	1200, Apr. 24, 1973	8	Apr. 24, 1973
10	73-6	1300, Apr. 25, 1973	9	Apr. 25, 1973
11	73-7	1400, Apr. 26, 1973	10	Apr. 26, 1973
12	73-8	1700, Apr. 27, 1973		
	X-3		11	Apr. 26, 1974
13	74-4	0900, Apr. 27, 1974	12	
14	74-5	0900, Apr. 28, 1974	13	Apr. 28, 1974
15	74-6	1200, Apr. 29, 1974		
	X-4		14	May 03, 1974
16	74-7	1200, May 04, 1974		
	X-5		15	Apr. 19, 1976
17	76-1	1200, Apr. 20, 1976	16	Apr. 20, 1976
18	76-2	1300, Apr. 21, 1976	17	Apr. 21, 1976
19	76-3	2000, Apr. 22, 1976		
	X-6		18	Apr. 21, 1977
20	77-1	0900, Apr. 22, 1977	19	Apr. 22, 1977
21	77-2	0700, Apr. 23, 1977	20	Apr. 23, 1977
22	77-3	0600, Apr. 24, 1977	21	Apr. 24, 1977
23	77-4	0600, Apr. 25, 1977		
	X-7		22	Apr. 26, 1977
24	77-5	0700, Apr. 27, 1977	23	Apr. 27, 1977
25	77-6	0700, Apr. 28, 1977		
	X-8		24	Apr. 30, 1977
26	77-7	1000, May 01, 1977	25	May 01, 1977
27	77-8	0900, May 02, 1977		
	X-9		26	May 03, 1977
28	77-9	0600, May 04, 1977	27	May 04, 1977
29	77-10	1100, May 05, 1977	28	May 05, 1977
30	77-11	1200, May 06, 1977		

Table 1. (continued)

No.	Recession Line Designation	Time (AST) and Date of inflection, q_0	Recession Volume No.	Date of Causal Parameters
31	74-1[b]	1400, Apr. 18, 1974		
32	74-2	1400, Apr. 20, 1974		
33	74-3	1300, Apr. 26, 1974		
34	76-4	1900, Apr. 24, 1976		
35	76-5	1600, Apr. 25, 1976		
36	76-6	1400, Apr. 29, 1976		

[a] All X-values are dummy recession points and occur 24 hours prior to the q_0 value that they were paired with. In fact, due to the arbitrary setting of all q_0's to 1200 hours, all pairs occur 24 hours apart, regardless of their true date and time of inflection. The X-recessions were not included in the K-calculation.

[b] Recessions 31 to 36 were included in the calculation of K, but excluded from volume calculations.

Table 2. Statistics from linear regression of snowmelt upon various meteorological parameters.

Parameter	n	$a^{\dagger}$ (area-mm)	$b^{\dagger}$ $\left[\frac{\text{area-mm}}{\text{ind. var. units}}\right]$	r	r^2	Sy.x (area-mm)
ξT_x (NEW)	27	-2.28	1.46	$.67^{**}$	.45	6.52
T_x (CDA)	28	-4.05	1.29	$.70^{**}$	.49	6.16
ΣT (NEW)	27	2.87	0.11	$.68^{**}$	.46	6.46
$\bar{U}$ (CDA)	28	23.30	-0.83	$.23^{n.s.}$	.05	8.44
R_s (CDA)	23	31.15	-0.03	$.49^{*}$	.24	8.26
S (CDA)	28	22.65	-1.32	$.31^{n.s.}$	.10	8.23

† snowmelt = a + b (parameter) ± Sy.x

* significant at 0.05 level of probability
** significant at 0.01 level
n.s. not significant

ξT_x (NEW) = maximum on-site temperature (°C)

T_x (CDA) = maximum off-site temperature (°C)

ΣT (NEW) = sum of hourly on-site temperatures above 0°C (°C)

$\bar{U}$ (CDA) = windspeed at 1.6 m, off-site (kph)

R_s (CDA) = global solar radiation, off-site (ly)

S (CDA) = bright sunshine per day, off-site (hours)

$$M_p = -0.28 + 0.6856\ (T_x\ (\text{NEW})) + 0.0650\ (\ T(\text{NEW}))^{a} \qquad (2)$$

where $r^2 = .48_{**}$
$r = .69$
$S_{yx} = 6.48$ area-mm

A comparison of calculated and predicted M_p values, using Equation 2, is illustrated in Figure 4. Figure 5 shows the phenomenon by snowmelt season.

DISCUSSION

In choosing input variables for Narrows Mountain Brook, an attempt was made to limit the factors to meteorological parameters thermodynamically related to snowmelt, and readily obtained. As temperature was the only on-site parameter for which data were readily available, maximum daily temperature was a logical first choice. The summation of hourly on-site temperatures was also utilized as Jolly (1973) had used this temperature index with a high degree of success. Windspeed, global solar radiation, hours of bright sunshine, and maximum temperature were standard parameters that were readily available from the Canadian Department of Agriculture (CDA) station, 52 km off-site. The inference is that, should a working, practical relationship ever be established, even a forest manager with no special training could measure or obtain the necessary data inputs required to predict snowmelt floods, for example.

Windspeed and hours of bright sunshine, as expected, completely failed to predict snowmelt, both being off-site. The work of Weisman (1977) indicates that windspeed should be closely linked to the centre of the snowmpack in order to be a reliable predictor. The effect of sunshine hours 52 km away would be negated by any chance cloud cover over the watershed.

Global solar radiation was excluded from the MLR as it was only significant at the 0.05 level of probability. Although Jolly (1973) has shown that the incorporation of solar radiation into a multiple-linear regression that includes some index of temperature can give highly significant results, global solar radiation has a seasonally dependent relationship with net radiation, and for this reason is not entirely suitable as an input parameter.

As the snowmelt season progresses, air temperatures rise, and average albedos decline. In the early part of the winter, during the coldest months, cloudy days with low insolation result in relatively small net radiation losses. However, losses are high on days with high insolation. As the season progresses, though, the net radiation losses become smaller at high insolation, as albedo decreases, and finally the net gain is positive (Figure 6). Thus the amount of net radiation that is absorbed by a snowpack for any given amount of global radiation tends to increase. Global radiation is actually a poor estimator from this standpoint, and hence its exclusion here.

The relationship between net radiation and solar radiation has been given by Dunne and Price (1975) as:

$$Rn = a + b\ (Rs) \qquad (3)$$

where Rn = net radiation
Rs = solar radiation
a,b = regression coefficients

Generally, an inverse relationship exists between Rn and Rs. However, as previously stated, the regression slope tends to become more positive as the season progresses and Rn increases with increases in Rs. The time of the slope switch differs from one year

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[a] originally, T_x (CDA) was included in the equation, but removed when it was found that it did not add significantly to the relationship.

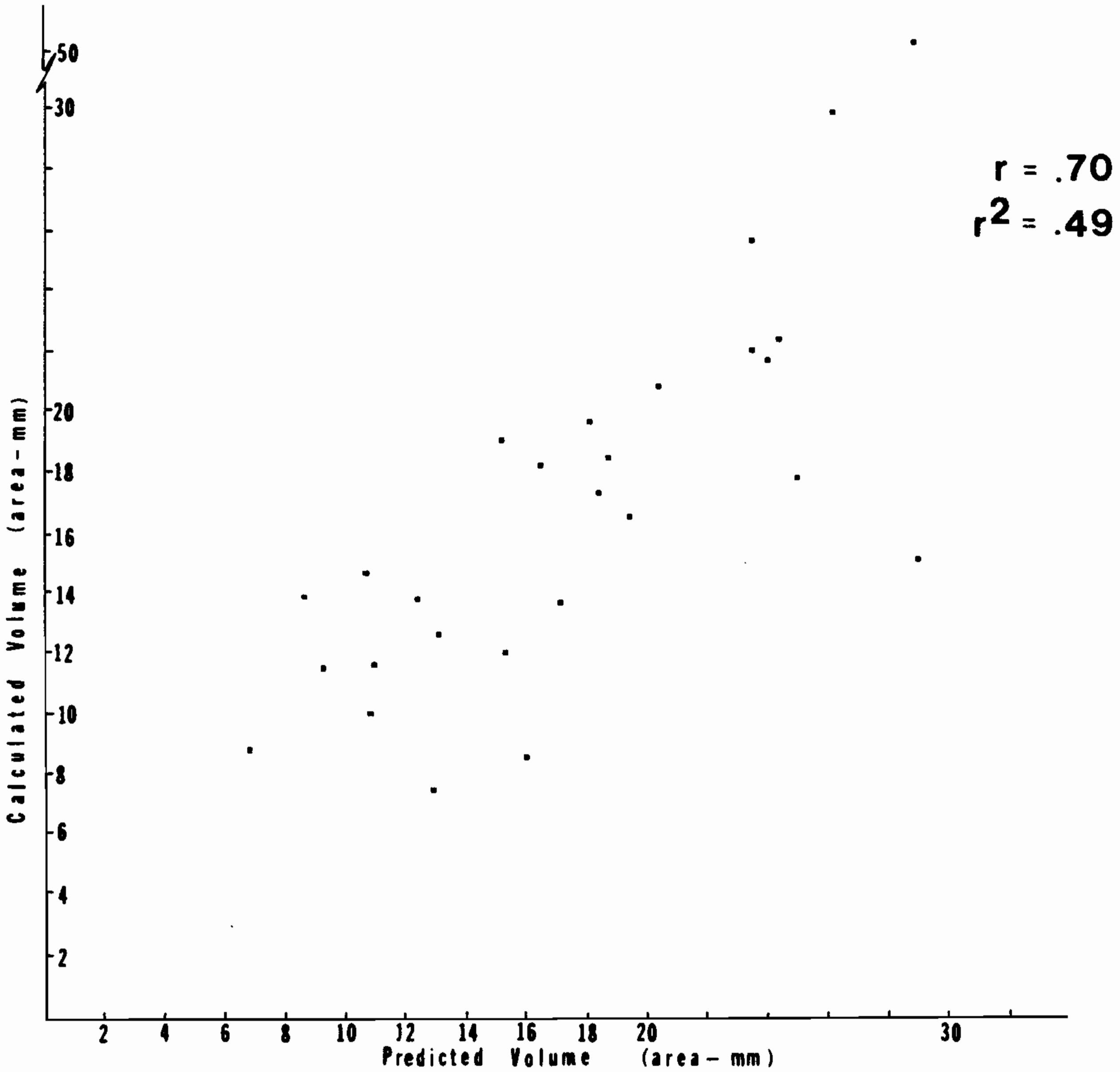

Figure 4. Relationship between calculated and predicted Mp values.

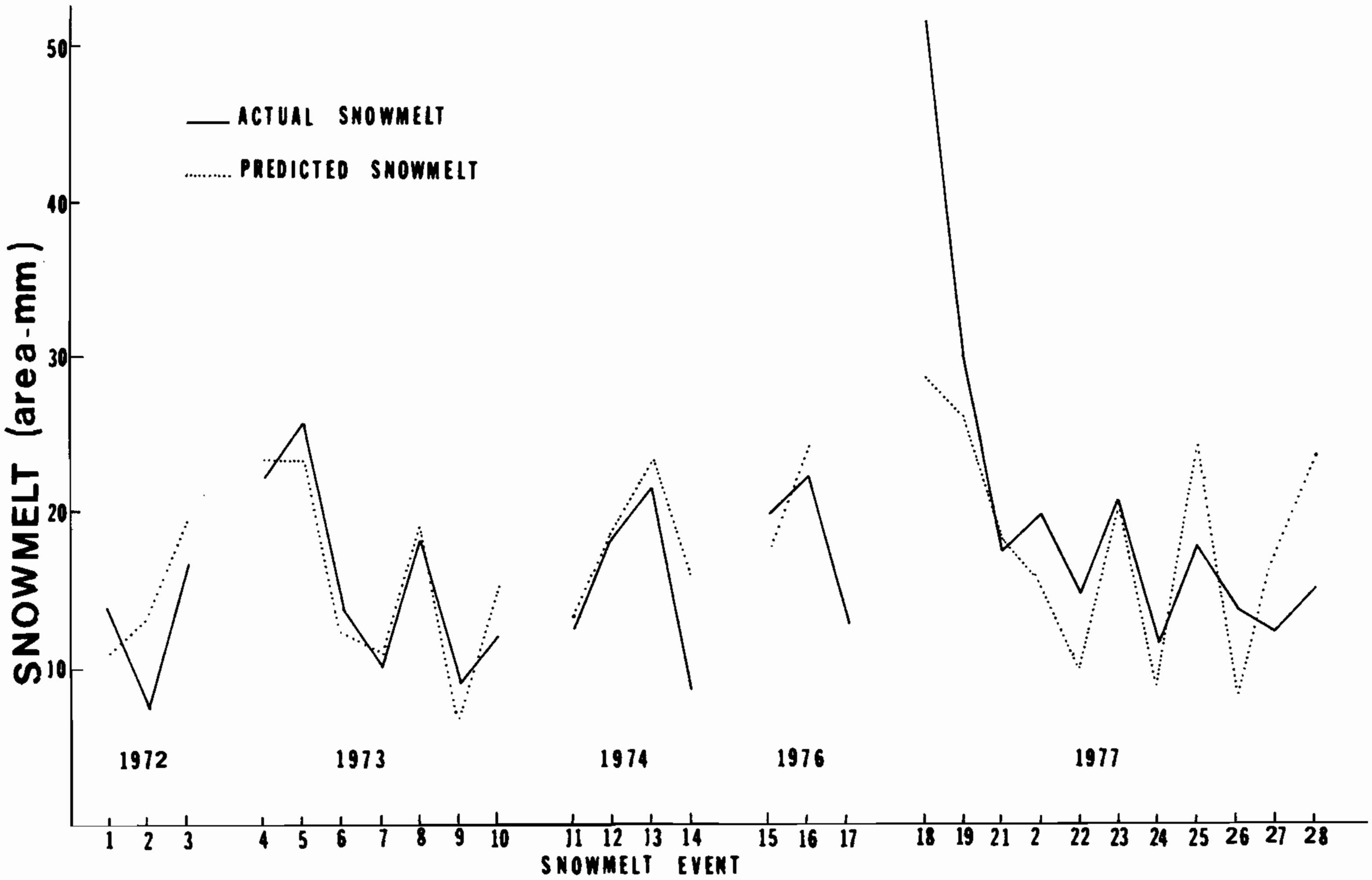

Figure 5. Actual and predicted snowmelt by season. The extent of the Sy.x, 6 area-mm, is not shown.

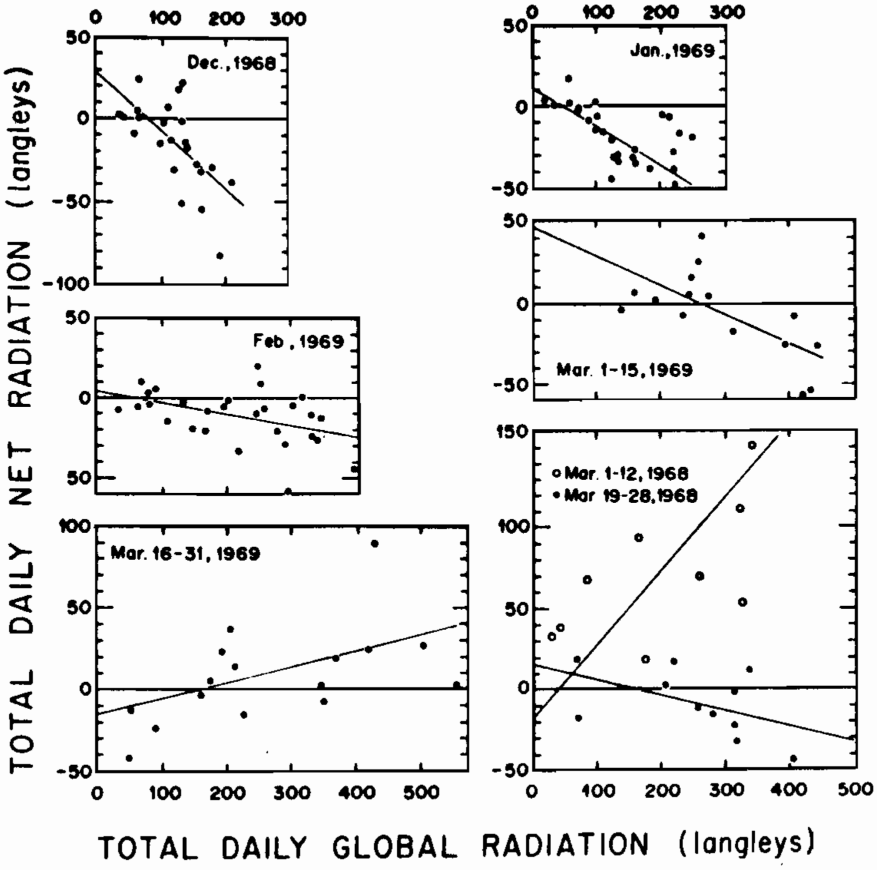

Figure 6. Relationship of net radiation to global solar radiation in Vermont, U.S.A., for various months. (From Dunne and Price, 1975)

to another. This could well explain the failure of CDA global radiation to successfully model Narrows Mountain Brook snowmelt, especially as data were not separated by year. There is no reason to expect global radiation to accurately predict snowmelt when its net effect is continually changing through the season, and at different rates each year.

The snowmelt model developed in this paper is interesting in that the derivation of the dependent variable (recession volume) is itself the result of the application of a model (reverse exponential decay). The closeness of the actual and predicted values, then, simply reflects the ability of the two models (recession volume model, for "actual" values, and multiple linear regression model, for "predicted" values) to predict equally, snowmelt for any given day. Considering that the error obtained stems from two possible sources, the results obtained are actually fairly reasonable.

The multiple-linear regression equation (Equation 2) was highly significant, and while the correlation coefficient (r) was not extremely high, it was satisfactory. The standard error of estimate (Sy.x) is high: evidently there are some aspects of the snowmelt process that are not being explained by the equation. From Figures 4 and 5, it can be easily seen that the snowmelt model deviates widely from actual snowmelt produced, on many occasions.

It is possible that, within seasons, a relationship may exist between the K-value, runoff volume flows and/or position within the snowmelt season. Garstka et al. (1958)

have shown the desirability of using a low K-value for high flows (above 50,000 ℓ/m), and a high K-value for low flows (below 50,000 ℓ/m). This figure, which corresponds to roughly 0.78 area-mm per hour for Narrows Mountain Brook is naturally too high to apply to the Narrows Mountain situation. In any case, it appears likely that high flows recess faster (lower K). This would reflect the relative inability of the stream to cope with volumes of water far in excess of normal flow. In other words the stream is more efficient in its drive to return to equilibrium conditions as quickly as possible.

The model deviated from the true volume by an average of 3.61 area-mm per event in 1972, 1.89 in 1973, 4.00 in 1974, 1.69 in 1976, and 6.22 in 1977. Single factor analysis of variance indicated that this year to year difference was not significant (alpha 0.05) and thus did not exist. Although this is based upon a relatively small sample, it is probably safe to assume that year to year differences are not large enough to warrant separate analysis by year. It would be desirable, though, to aim for a more equal distribution of sample recession volumes in each year. In this study, n varied from 2 in 1976, to 11 in 1977.

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented the derivation of a simple snowmelt model for Narrows Mountain Brook, one of two paired basins in the Nashwaak Watershed.

Snowmelt can be statistically modelled by a multiple linear regression equation relating daily runoff volumes to maximum on-site daily temperature and the sum of hourly on-site temperatures above 0°C. Maximum off-site temperature did not add significantly to the original regression and was removed. Daily global solar radiation (CDA) estimated snowmelt with a lesser degree of accuracy. Windspeed and hours of bright sunshine from a site 50 km away showed no statistical relationship to snowmelt.

Despite statistical significance, the model often predicted snowmelt values which deviated widely from the actual observed values, as indicated by large standard errors of estimate. Some variation could be reduced through an increased sample size and the use of a K-value related to flow. The latter would involve the development of a new method to determine K at different flow classes.

It does not appear to be an advantage to separate snowmelt phenomena by year. However, the contribution of net radiation would doubtless be beneficial, as it relects to a greater degree than global solar radiation, the amount of energy available for melting the snowpack. Separation of radiation data by year and possibly by month would be a prerequisite to its use.

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