SOLAR AND NET RADIATION OVER MELTING SNOW IN SUB-ARCTIC WOODLANDS

by

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a) Introduction

Snow is obviously a very important element of the physical environment of Canada and northeastern United States, however, it seldom attracts adequate consideration in modern microclimatological research. To a climatologist, the snowmelt process is particularly an interesting one since one can see, in the form of running water and swollen rivers, the result of heat fluxes directed at a snow surface. From a practical viewpoint, the production of springtime snowmelt runoff is of vital concern to water management techniques.

The primary motivating factor of the suddenly increasing interest in sub-arctic snowmelt processes has been the recent developments of the Churchill Falls and James Bay hydroelectric projects. However, from a hydrometeorological point of view, there are some obvious problems with respect to snowmelt prediction in a sub-arctic area. The present paper deals with the effect that the unique sub-arctic landscape, especially the forest, can play in altering radiation snowmelt prediction techniques commonly employed at middle-latitude locations. To this end, a concurrent snowmelt hydrology - radiation climatology program has been instituted at the McGill University Sub-Arctic Research Laboratory at Schefferville, Quebec, on the periphery of the Churchill (Hamilton) River basin (see Figure 1), and has been operating on a continuing basis since 1971. The underlying philosophy of such a program is to investigate problems of this interdisciplinary research having both a scientific and practical nature. The research is involved in three orders of magnitude: first there is the macro-scale study of major sections of the Churchill River basin (approx. 35,000 square miles) which includes studies of radiation variations with distance and meltwater flood predictions; second is the meso-scale studies of flood routing and topographic variations of radiation within the Knob Lake basin (approx. 30 square miles) near Schefferville; and third concerns the micro-scale investigations of net radiation beneath woodland canopies and runoff generation from small slope segments.

Net radiation is only one element of the energy balance of a melting snowpack, but it is perhaps the most important source of heat energy to the snowpack, and is, as well, the most difficult to estimate accurately or measure directly. Empirical equations developed by the U.S. Army Corps of Engineers (1956) for both the long-wave and shortwave radiative contributions to the melt have been produced for both clear and cloudy days, and forested and open locations. Despite frequent simplifications of these equations, a rather complete set of meteorological parameters must be measured and this can be done only by a skilled technician. This type of equation has been widely used, not only for snowmelt estimation, in areas where radiation measurements were not available. Emphasis has recently switched to the linear estimation of net radiation by solar radiation since this method is simple yet accurate (Shaw, 1956; Monteith and Szeicz, 1961; and others). If the radiation balance of an open area on the earth's surface is given by

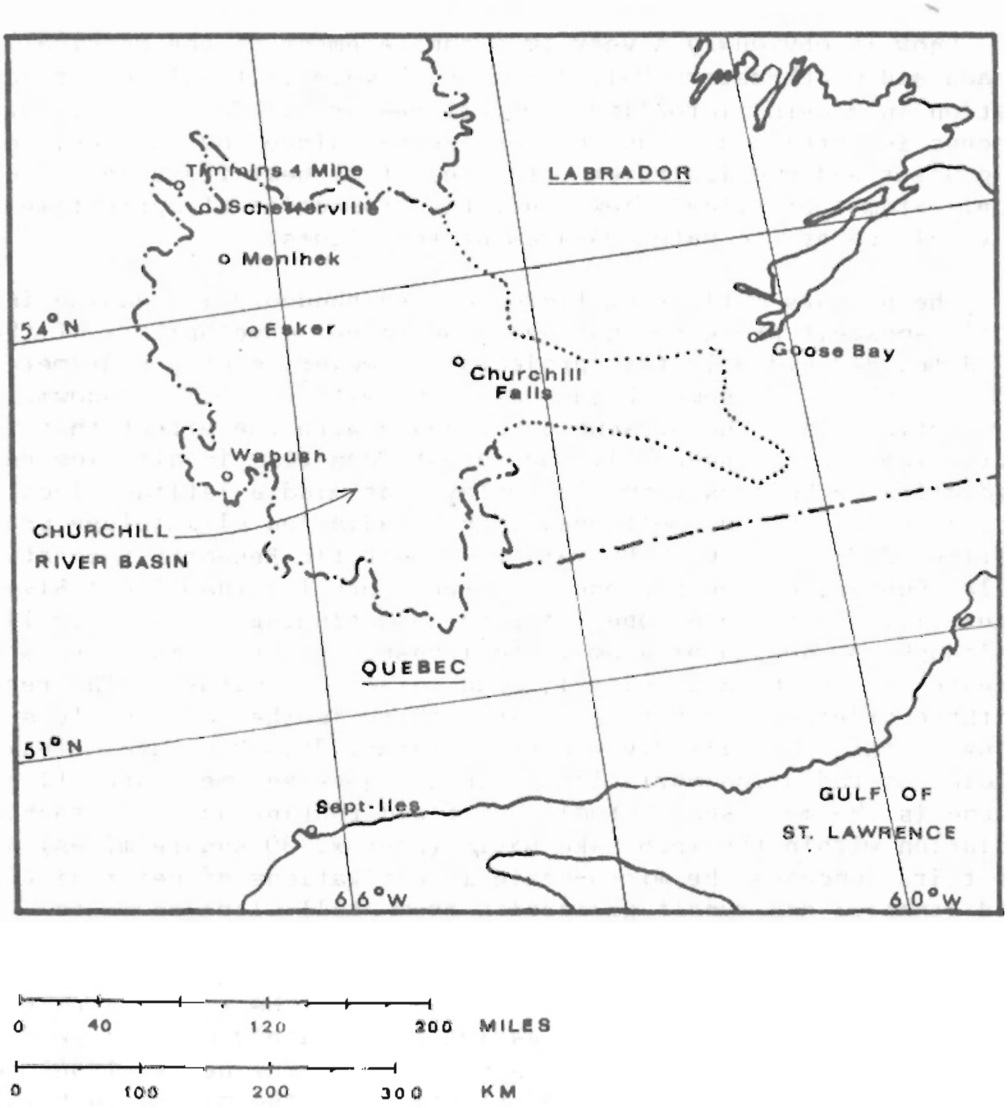

Figure 1. Location of the Churchill River basin.

$$Rn = (Q+q)(1-\alpha) + Ln, \quad (1)$$

where Rn = net radiation,
$(Q+q)$ = solar radiation, direct plus diffuse,
α = surface reflectivity or albedo,
and Ln = the net longwave balance at the surface,

the the following linear relation may be used as a good approximation:

$$Rn = a + b(Q+q), \quad (2)$$

where a and b are regression constants. The unit of radiant energy used here is the calorie per square centimeter per minute or, as it is more commonly known, langley per minute (ly min^{-1}). Until present the linear approach has been used almost exclusively for agricultural or naturally vegetated surfaces.

The radiation balance in a forest environment takes on a much more complex dimension than an open area. Much of the solar radiation incident upon the top of the forest is absorbed and reflected by the foliage and branches and in turn is dissipated as sensible heat in three ways: (1) by warming the canopy itself; (2) by evapotranspiration during the growing season; and (3) by re-radiation in the longwave spectrum. Thus, the downward flux of longwave radiation beneath the forest canopy may be increased in comparison to an open site if the canopy has a higher radiating temperature than the sky or clouds above. Hence, while the forest significantly reduces the shortwave radiant supply to the underlying snow, it augments the longwave radiation supply. The fact that the canopy temperatures are governed largely by solar radiative heating suggests a strong relationship between solar radiation, $(Q+q)_f$, and net radiation, Rn_f, beneath the forest canopy, and indeed between solar radiation in the open, $(Q+q)$, and Rn_f. This reasoning has given rise to a series of radiation studies beneath various sub-arctic woodland canopies spanning the snowmelt periods of 1972 and 1973 with the objective of producing results in the form

$$Rn_f = c + d(Q+q)_f \quad (3)$$

$$\text{and } Rn_f = g + h(Q+q). \quad (4)$$

b) Instrumentation of the experimental sites

Solar and net radiation beneath a forest canopy were measured at three sites, denoted by "Mary Jo" and "Wishart Sites D" and "F" in Figure 2, near Schefferville, Quebec during the 1972 and 1973 snowmelt seasons. The total incoming shortwave flux in an open area, (Q+q), was measured at a site denoted by "Lab" in 1972 (see Figure 2) which was moved, due to construction, to the site denoted by "vault".

The forests at each of the three woodland sites consist almost entirely of black spruce (<u>Picea mariana</u>) and are classified as open lichen woodland according to Hare (1959). The average densities, expressed as the ratio of maximum limb area to the total ground area in a sample space of 930 m^2, were

	Density:
Wishart Site D	0.162
Wishart Site F	0.163
Mary Jo Site	0.504

Pairs of Lintronic Dome Solarimeters and Fritschen net radiometers were mounted on wooden stands and distributed randomly through the forest to ensure proper aver-

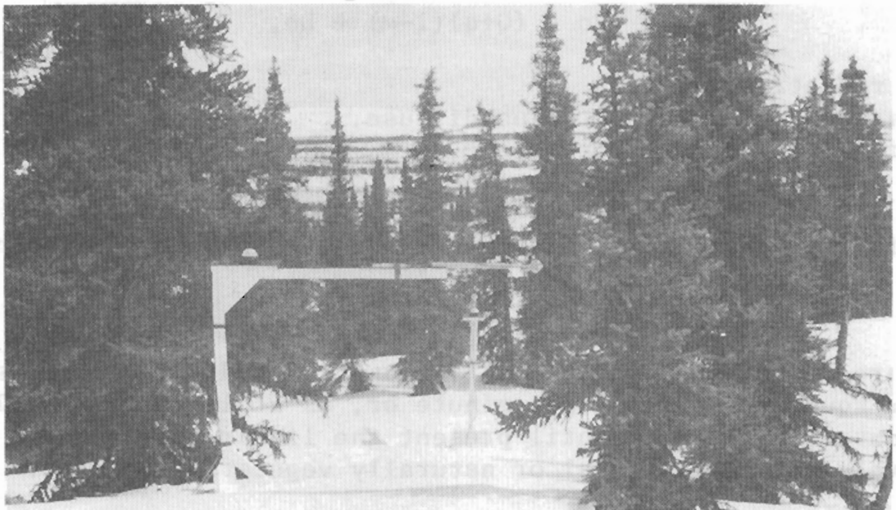

Figure 3. Instrument stand holding a solarimeter and net radiometer at Wishart Site D.

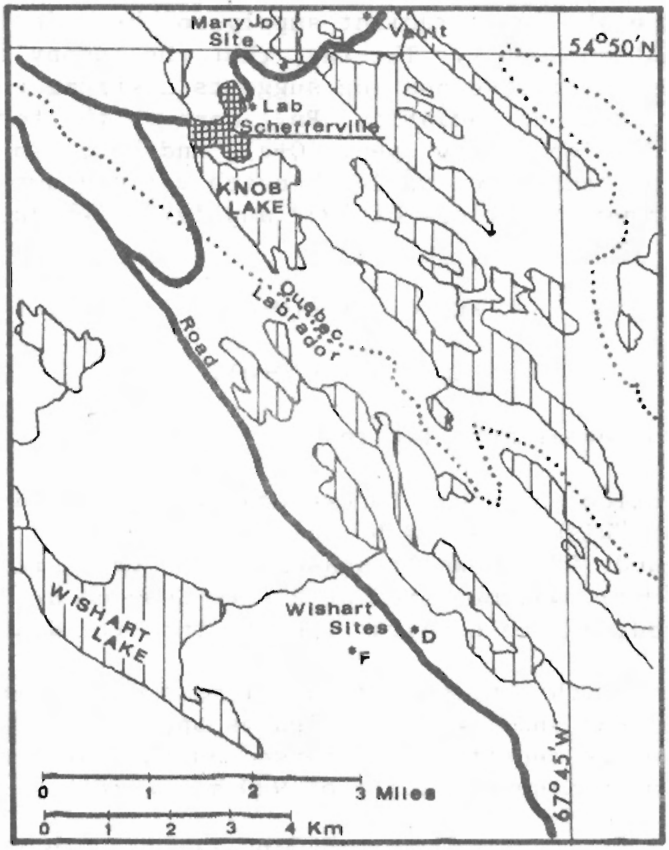

Figure 2. Forest radiation sites near Schefferville, Quebec.

aging. An example of an instrument stand and the forest at the Wishart Site D is shown in Figure 3. Five pairs of sensors were used at the Wishart sites and this number was increased to six at the denser Mary Jo Site. The solarimeters and net radiometers were separately connected in series and the resulting output was averaged on an hourly basis to produce a mean value of the radiative flux representative of the forest density at each site.

c) Net radiation prediction over snow in woodlands

Regression analysis of $(Q+q)_f$ and Rn_f collected at the three forest sites yield the following results on an hourly basis (units of ly min^{-1}):

Wishart Site D: $Rn_f = -0.026 + 0.291(Q+q)_f; \ r = 0.94,$ (5)

Wishart Site F: $Rn_f = -0.001 + 0.258(Q+q)_f; \ r = 0.94,$ (6)

Mary Jo Site: $Rn_f = +0.003 + 0.589(Q+q)_f; \ r = 0.91.$ (7)

The data and regression lines for each location are plotted in Figure 4 a, b, and c. It should be noted that two measurement errors may have contributed to the increased scatter at the dense Mary Jo Site. First is that the increased forest density at this site may not have been adequately compensated by the increased numbers of pairs of sensors in the network. Second, some scatter at each site can be attributed to the asymetric distribution of clumps of trees about the sensors.

The effect of the forest density is apparent in equations (4) to (6). The values of the intercept are similar although that for the Mary Jo Site represents a net radiative gain at sunrise and sunset which might be expected from such a dense forest. If night-time values of Rn_f and zero values of $(Q+q)_f$ were included in the regression, the forest effect on the value of the intercept would certainly be much more noticeable since the downward flux of longwave radiation would be augmented by a contribution from the forest canopy.

Of primary significance is the value of the slope of the regression line since it represents an indication of the amount of solar radiation penetrating the canopy that can be utilized as net radiation, the radiant energy available at the surface for the processes of melting snow, evaporation and so on. For the three sites considered here, the ratios of Rn_f to $(Q+q)_f$, at a value of $(Q+q)_f = 0.50$ ly min^{-1}, are:

	$Rn_f/(Q+q)_f$	Forest density
Wishart Site D	0.24	0.162
Wishart Site F	0.26	0.163
Mary Jo Site	0.60	0.504

Although it has been calculated that a greater amount of available solar radiation is used as net radiation at the greater forest density, smaller amounts of the shortwave flux incident on the top of the canopy are actually received at the surface below as density increases. The following regression equations express the relation between shortwave radiation in the open, $(Q+q)$, and $(Q+q)_f$, on an hourly basis (units of ly min^{-1}):

Wishart Site D $(Q+q)_f = -0.03 + 0.88(Q+q); \ r = 0.98,$ (8)

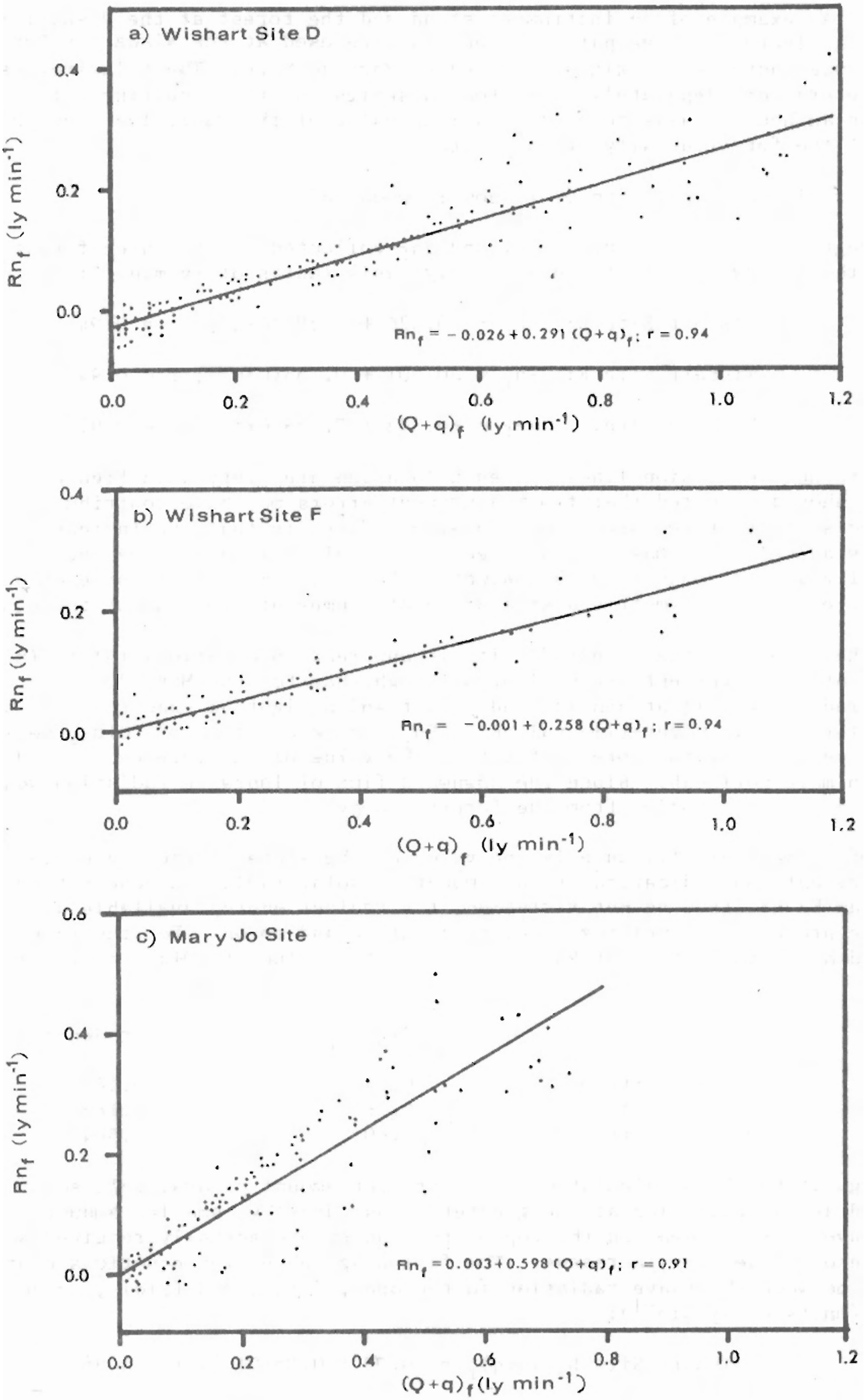

Figure 4. Data points and calculated regression lines for each forest location.

Wishart Site F $(Q+q)_f = -0.01 + 0.80(Q+q);\ r = 0.98,$ (9)

Mary Jo Site $(Q+q)_f = -0.01 + 0.51(Q+q);\ r = 0.91.$ (10)

Thus, the ratios of solar radiation beneath to that above the forest canopy, i.e., $\frac{(Q+q)_f}{(Q+q)}$, at a value of $(Q+q) = 1.0$ ly min^{-1}, are

Wishart Site D	0.85,
Wishart Site F	0.79,
Mary Jo Site	0.50.

These ratios would immediately indicate that Wishart Site F has a slightly greater forest density than Site D. Although silvicultural data used to compute this density at each site indicate almost exactly the same values at these two plots, the fact that the trees at Site F average 0.41 meters higher exerts a greater attenuating effect on incoming solar radiation at this site.

Thus, despite 60 percent of the available forest solar radiation being utilized as net radiation at the dense Mary Jo Site, the solar flux beneath the canopy amounts to only half that incident in the top of the forest. The effective amount of (Q+q) used beneath the canopy as net radiation at this site would be approximately 30 percent of (Q+q), and at the other two sites this ratio would be approximately 20 percent.

The preceding analysis indicates a rather close relationship between (Q+q) and Rn_f with minimal dependence on the forest density. With this in mind, regression equations between hourly values of Rn_f from each of the forested sites and (Q+q) from Schefferville (which is assumed to equal that incident on the top of the forest canopy) were calculated for each site and yielded the following (units of ly min^{-1}):

Wishart Site D: $Rn_f = -0.018 + 0.245(Q+q),\ r = 0.90;$ (11)

Wishart Site F: $Rn_f = -0.010 + 0.223(Q+q),\ r = 0.87;$ (12)

Mary Jo Site: $Rn_f = +0.009 + 0.279(Q+q),\ r = 0.89.$ (13)

These regressions produced standard errors in the Rn_f estimate of 0.046, 0.038 and 0.051 ly min^{-1} respectively. The resultant close agreement and accuracy of each relation, as shown graphically in Figure 5, led to the analysis of the combined data from all three sites which produced the following result (units of ly min^{-1}):

$$Rn_f = -0.010 + 0.255(Q+q);\ r = 0.88, \tag{14}$$

which exhibits a standard error of 0.051 ly min^{-1}. Thus, it is possible to relate forest net radiation to solar radiation in the open regardless of forest density while obtaining the same statistical accuracy as the relations for any particular forest density considered in this study.

d) Conclusions

The success of the application of modern microclimatological techniques to simplify accepted snowmelt estimation, in terms of net radiation, for the particular case of the sub-arctic woodland is quite evident. The full potential of the development of a single equation relating net radiation in woodlands of different densities to incoming solar radiation can be realized only after further testing. To this end, the radiation measurement program in forests of different struc-

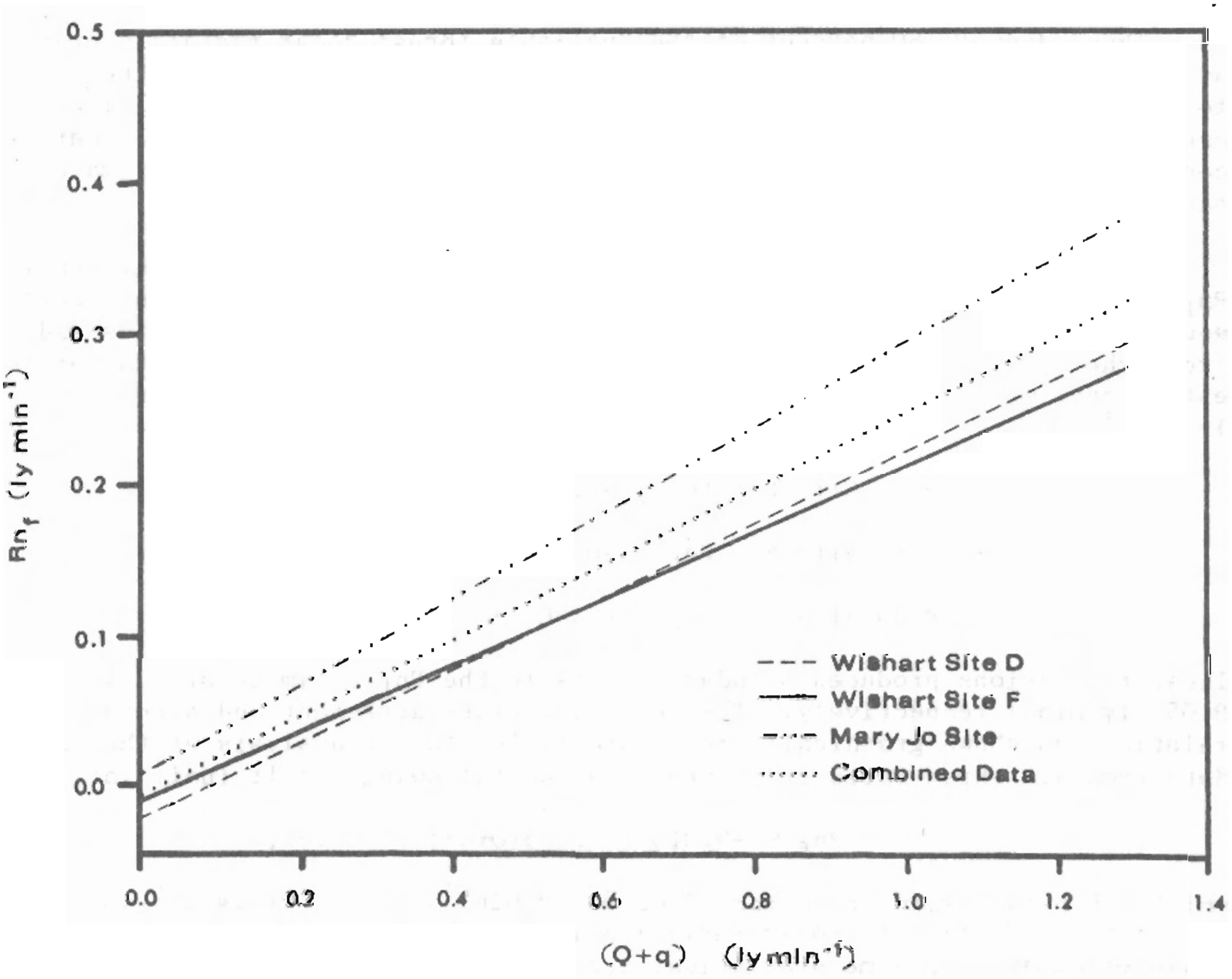

Figure 5. Computed relationships between Rn_f and (Q q) for the three forest sites and the combined data sets.

ture and density is continuing in the Schefferville area.

Similar research has been conducted to determine the relationships between net and solar radiation over snow in open, unforested locations. The results of this analysis show that a single equation was found to relate absorbed solar radiation to net radiation and that the accuracy was significantly improved if mean daily air temperature was incorporated into a multiple regression.

The implications of these results together with the results of the present paper are far reaching. It should now be possible to provide accurate information on the radiative balance of the entire Churchill River basin, and for that matter, most other sub-arctic areas with similar topographic and vegetative characteristics. The next step in utilizing this radiation knowledge is to incorporate it into a snowmelt prediction model, possibly with air temperature being the other major variable since the latter is a useful predictor of the sensible heat flux to a melting snowpack and has been shown to improve the prediction of net radiation in unforested areas.

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