PATTERNS OF NET RADIATION OVER URBAN SNOWPACKS

F. Xu[a] and J.M. Buttle[b]

a. Watershed Ecosytems Program, Trent University, Peterborough, Ontario
b. Department of Geography, Trent University, Peterborough, Ontario

ABSTRACT

Net radiation represents the dominant and most spatially variable component of a snowpack's energy budget in many regions. Attempts to forecast snowmelt runoff in urban areas should consider the differences that may exist between net radiation fluxes in built-up areas and those recorded at open sites, as well as the implications of these differences for the snowmelt process. Results of a detailed examination of patterns of net radiation over snowpacks in a suburban catchment are presented and compared with fluxes observed at an open site. Suburban net radiation fluxes were found to decrease with distance from buildings, although this trend was complicated by the shadow effect. Net radiation heat inputs to suburban snowpacks could exceed such inputs in open areas, depending upon snowpack aspect and degree of cloud cover. The increased heat inputs appear to account for the higher melt rates observed in the suburban catchment relative to melt in a rural setting.

Introduction

Snowmelt and snowmelt runoff processes play an important hydrologic role in the northern hemisphere, as significant amounts of precipitation as snow are stored in snowpacks and are released during the snowmelt season. For many basins in southern Ontario, for example, the highest discharges usually occur during snowmelt, because the accumulated water as snow augments the contributions of spring rainstorms. In addition there is increasing evidence indicating that snowmelt plays a major role in the hydrology of urban basins in Canada (Buttle, 1986) and Scandinavia (e.g. Bengtsson, 1981; 1983; 1984a,b).

There is general agreement that the energy budget model provides the most accurate estimates of snowmelt at a point, and this has been demonstrated for a number of natural environments such as mountain regions, forests and open areas (e.g. Corps of Engineers, 1965; Anderson, 1968; Price and Dunne, 1976; Richardson and Molnau, 1982). However, when such point models are used to estimate snowmelt for an entire catchment, spatially-averaged values of the input variables must be employed. One of the most spatially variable components of the energy budget is net radiation (Q^*), the flux of which is affected by changes in slope, aspect, shading and altitude, as well as by reflected radiation from surrounding surfaces (Morris, 1985).

The difficulties inherent in obtaining spatially-averaged values of Q^* are particularly apparent in attempts to use the energy budget approach to simulate snowmelt in urban catchments. Measurements of Q^* in built-up areas are comparatively rare, and the hydrologist's only option may be to substitute radiation inputs measured at open sites outside the city. While research has been conducted on the urban-rural differences in net radiative fluxes (e.g. Aida and Yaji, 1979) and the detailed microclimate of urban areas (e.g. Nunez and Oke, 1977), there appears to be no information in the literature concerning the differences, if any, that might be expected to occur between the fluxes of net radiation over urban and rural snowpacks during melt and the hydrologic significance of such differences.

The present study represents part of a larger examination of snowmelt runoff mechanisms in suburban environments (Buttle, 1986). It describes the results of measurements of the spatial and temporal patterns of net radiation around buildings during snowmelt. These fluxes of net radiation in a built-up area are compared with those for an open site, and are used in conjunction with the energy budget model to explain observed variations in melt rates between suburban and rural land uses.

Study-Area Description and Method

The area selected for study is in the Kawartha Heights subdivision of Peterborough, Ontario (44°N, 78°W) which lies on the south-western margin of the city (Figure 1). The thirty year (1951-1980) mean annual temperature is 6-7° C and the mean annual precipitation is in excess of 760 mm. This precipitation, 80% of which falls as rain and 20% as snow, is quite evenly distributed throughout the year (Adams, 1985). The study area consists of a suburban catchment nested within a large rural watershed that is currently undergoing urbanization. The entire basin has been subject to intermittent suburban development since 1974, the hydrological impacts of which have been described by Taylor (1977; 1982) and Taylor and Roth (1979). Table 1 presents general land use characteristics of the study catchments as of the end of 1985. Houses within the catchments are single dwellings, with average plan dimensions of 12.8 m x 7.3 m, giving an average plan area of approximately 93 m^2 .

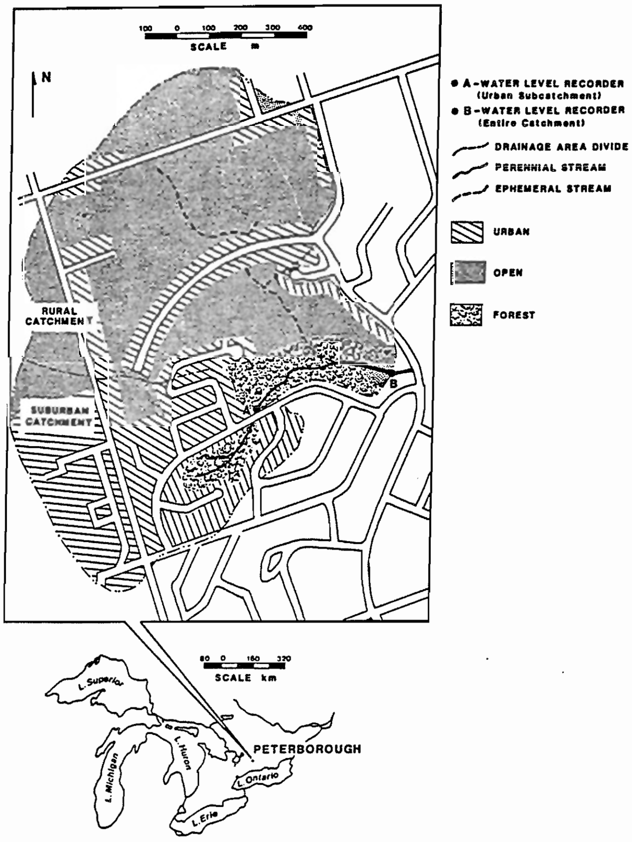

Figure 1: The Kawartha Heights watershed: land uses in the suburban and rural catchments

Table 1: General land use characteristics, Kawartha Heights

	Drainage area (ha)	Open (ha)	%	Forest (ha)	%	Urbanized (ha)	%	# of houses
Entire basin	96.9	48.7	50.3	6.6	6.8	41.6	42.9	337
Suburban catchment	33.3	5.9	17.7	2.2	6.6	25.2	75.7	258
Rural catchment	63.6	42.8	67.3	4.4	6.9	16.4	25.8	79

Two houses considered to be representative of house type and aspect within the suburban basin were selected, and the pattern of net all-wave radiation around them was measured using net pyrradiometers. The two house lots were north-south (N 17° 7'W) and east-west (N 72° E) in orientation. Four custom-built net pyrradiometers were employed in the study and their mV output was recorded using a Fluke 8060A multimeter. The pyrradiometers were calibrated against a Middleton CN-1 net pyrradiometer in order to translate their mV outputs into W m^{-2}. A network of 10 sample points was established around each house - four points in the front and back yards at 2 m intervals away from the house and one sample point between the study house and the adjacent house. The sample points 8 m away from the houses in the front yards (south- and east-facing snowpacks) were near the road edge. The pyrradiometers were set 1.0 m above the snowpack surface and hourly measurements of Q^* were usually taken at the sample points from 8:00h or 9:00h until 16:00h or 17:00h local time between March 7 and April 4, 1985. Measurements were taken on nine days during this period (see Table 2).

The energy balance approach (Anderson, 1968) was used to estimate hourly and daily snowmelt fluxes within the two subcatchments during the 1985 melt. Solar radiation, net radiation, albedo, air temperature, wind speed and relative humidity were measured at the Trent University Weather Station, 10 km northeast of the study area. The latter three meteorological variables were employed to calculate sensible and latent heat fluxes to the snowpack according to the procedure outlined by Price and Dunne (1976). Net radiation was measured using a Middleton CN-1 net pyrradiometer sited 1.0 m above the snowpack surface. Its output was registered on a Hewlett Packard strip chart recorder (model #7155B), thus providing a continuous record of net all-wave radiation that was considered to be representative of that in the open areas in the study basin. Precipitation was measured throughout the melt period at the Trent Station and at the Peterborough Airport, 5 km south of the basin.

An attempt was made to estimate daily snowmelt depths for the different land uses in the study area. These estimates were based on measurements of daily changes in snowpack water-equivalent using an M.S.C. (Meteorological Service of Canada) snow sampler. Daily snow surveys were conducted from February 7 to April 11, 1985 in the three main land use types - open, woods and suburban. The daily snow samples were collected at roughly the same time at the beginning of each survey day, with a minimum of 30 samples taken during each survey. The number of samples taken within each land use was roughly proportional to that surface type's area.

Table 2: Summary of cloud cover, % snow cover and average hourly fluxes of Q^*

Date of Measurement		Snowpack Orientation	Cloud Cover (tenths)	Snow Cover %	Q^*_s ($kJ\ m^{-2}\ h^{-1}$)	Q^*_o
Mar.						
7	1000-1500	S	8	100	363.2	83.4
	1200-1500	N	8	100	382.8	96.0
13	0900-1600	E	5	100	669.0	596.0
	0900-1600	W	5	100	615.6	596.0
14	1300-1400	S	5	60	1287.0	1069.0
		N	5	100		
15	0800-1600	S	0	100	1321.9	799.3
	0900-1600	N	0	100	609.0	906.0
19	0800-1600	E	4	100	583.9	707.8
	0800-1600	W	4	100	557.3	707.8
21	1100-1600	E	1	90	995.2	a
	1100-1600	W	1	90	997.0	
22	0900-1600	S	1	10	1155.7	
	0900-1600	N	1	90	856.0	
26	0800-1600	E	9	20	1162.5	
	0900-1600	W	9	90	1166.9	
April						
4	0800-1600	S	9	0	1133.3	
	0900-1600	N	9	0	913.3	

Q^*_s - average hourly flux of Q^* in suburban area

Q^*_o - average hourly flux of Q^* at open site (Trent Weather Station)

a - Snowcover disappeared beneath Trent Weather Station pyrradiometer on March 19.

Results and Discussion

The radiation measurements around the study houses on two measurement days are shown in Figure 2. These two days were selected for comparison because they experienced similar inputs of Q^* as measured at the Trent Weather Station (Q^* peak of 320 W m^{-2} for March 15 vs Q^* peak of 345 W m^{-2} for March 19 - see Figure 3). It can be seen that the pattern of net radiation around the houses is more or less circular in form, with the east-west oriented house possessing a more circular pattern than the north-south oriented house. This general pattern of decreasing Q^* with distance away from the houses was also observed on the other measurement days. Notwithstanding the fact that the results in Figure 2 are for two different days, it appears that the differences in the peak Q^* values between the south-facing front yard and the north-facing back yard are much larger than those observed for the east- and west-facing snowpacks (Table 2). This appears to be largely the result of the shadow effect upon measurements of Q^* at the 2 m sample point over the north-facing snowpack. Figure 3 shows the diurnal trends in Q^* around the houses for these measurement days, as well as the pattern of net radiation measured at the Trent Weather Station (open site). The pattern of net radiation in the vicinity of the houses tends to mirror changes in Q^* observed at the open site with two important qualifications. The first is the influence of the shadow effect, with radiometers in the shade recording much lower values of Q^* than those observed in the open and by adjacent exposed pyrradiometers. This disrupts the general tendency for Q^* to decrease with distance from the houses and usually the radiation flux values measured in shadow areas were the lowest values observed around the houses. The second qualification is that east- and south-facing snowpacks in urban areas may experience peak Q^* in advance of open level snowpacks. This was observed at all four sampling points over the south-facing snowpack and at the 2 m sampling point over the east-facing snowpack. The shift in the occurrence of peak net radiation appears to be due to the contribution of reflected incoming solar radiation from exposed walls in the suburban area when the sun's local angle is not yet at its maximum. This variation in the urban daily radiation pattern from that observed in open sites is similar to the findings of Nunez and Oke (1977) for the diurnal flux of Q^* for an east-facing wall in Vancouver, B.C. In their case, this phenomenon was attributed to the reflection of incoming radiation by the opposite (west-facing) wall of the urban canyon.

Based on the data obtained, the following regression model was formulated:

$$Q^* = 50.8 + 0.7Q^*_{open} + 0.7\text{Orien.} - 13.3\text{Dist.} \qquad (r=0.70)$$

where Q^* = net all-wave radiation at a point in the suburban area (W m^{-2})
Q^*open = net all-wave radiation measured at the open site (W m^{-2})
Orien. = orientation of the snowpack (N, E, S and W expressed as 0, 90, 180 and 90 respectively)
Dist. = distance from the building (2, 4, 6, and 8 m)

All of the regression coefficients were found to be significantly different from zero at the $\alpha = 0.05$ level. This equation provides a useful means of summarizing the general radiation patterns in suburban areas with respect to open level sites. There is a general decrease in Q^* with distance away from buildings, with snowpacks immediately adjacent to the house receiving heat energy released from building surfaces (reflected direct and diffused beam as well as reflected and emitted longwave radiation) in addition to incoming solar and environmental (longwave) radiation. However, the Q^* at any given distance from a house will not necessarily exceed that recorded over open (rural) snowpacks due to the complicating influence of snowpack aspect (Figure 4). On the sun-facing side of buildings (e.g. south-facing snowpacks), a radiometer would receive direct (S) and diffuse (D) beam shortwave radiation as well as incoming longwave ($L\downarrow$) radiation. Reflected and emitted radiation from building walls add to the net all-wave radiation total, producing a positive flux to the snowpack.

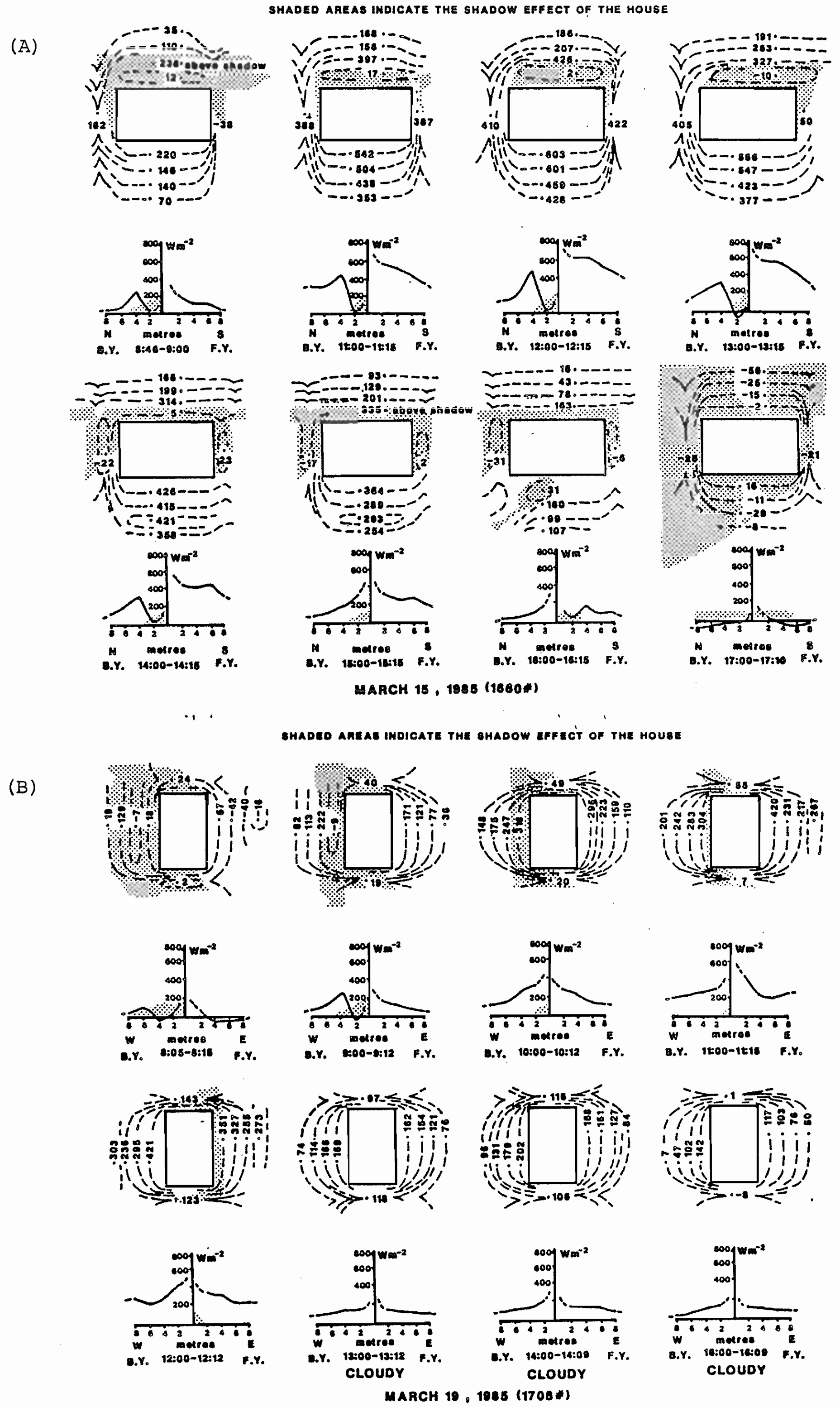

Figure 2: Patterns of Q^* around the north-south (A) and east-west (B) oriented houses, Kawartha Heights

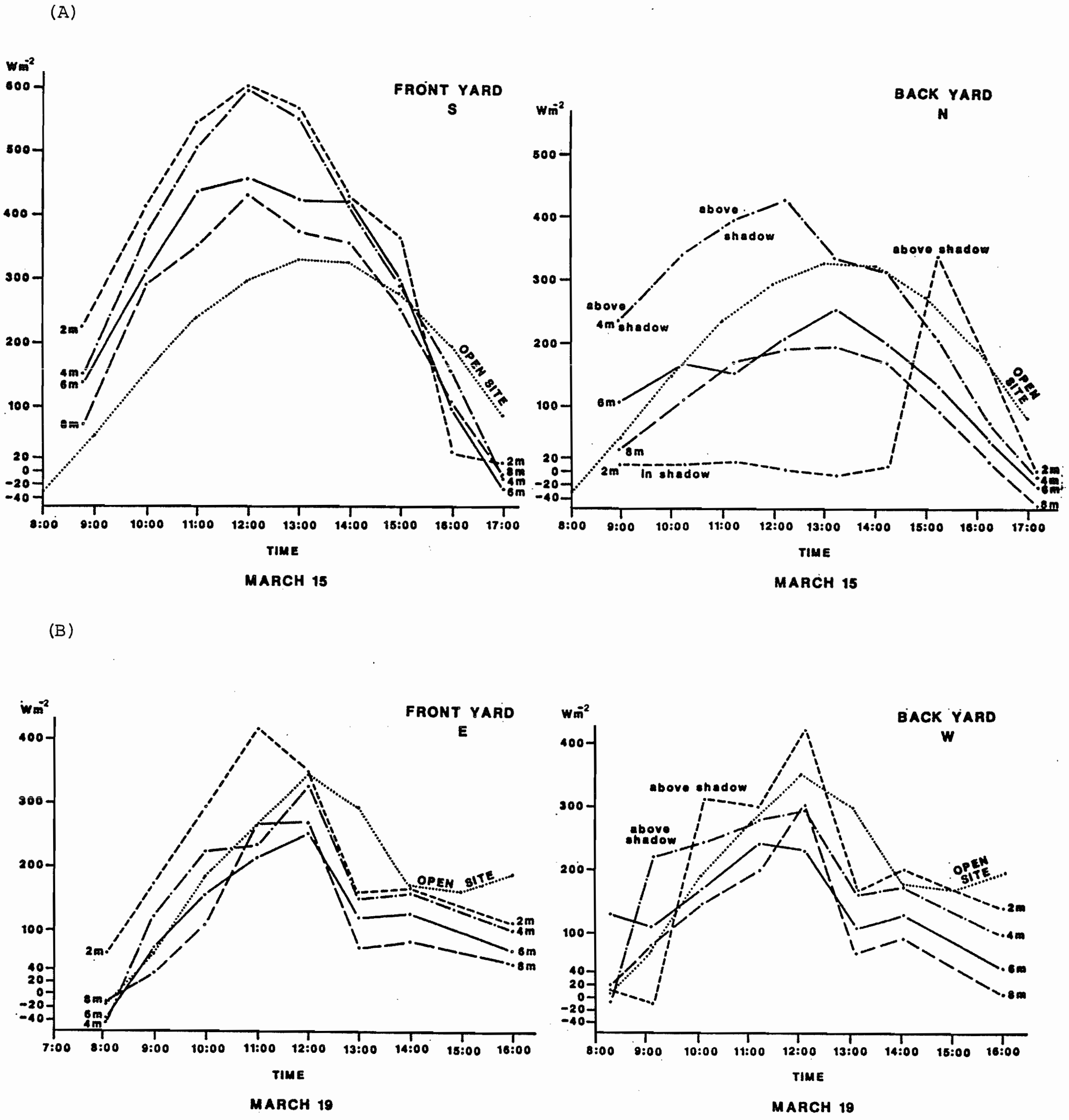

Figure 3: Diurnal trends of Q^* around the north-south (A) and east-west (B) oriented houses and at the open site (Trent Weather Station)

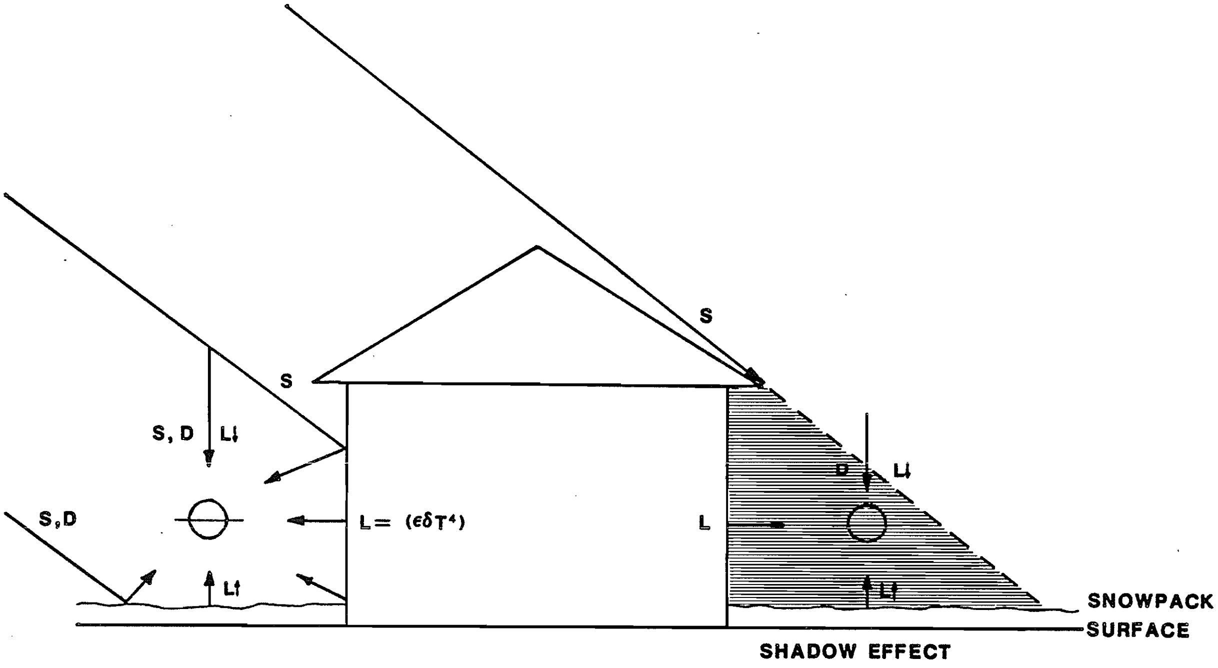

Figure 4: Sources of net radiation over a suburban snowpack (see text for explanation)

In contrast, areas in shadow (e.g.north-facing snowpacks) receive no direct beam radiation, and there is no reflected contribution of shortwave from the walls. The radiometer only receives diffused beam, L$\downarrow$, L$\uparrow$ and emitted longwave radiation from the wall. Since the shadowed wall does not experience warming as a result of shortwave inputs, its longwave contribution will probably be less than that of the sun-facing wall. It can be expected that lower values of Q^* will be observed in the shadow areas, thus reducing the energy available for snowmelt.

Table 2 presents the measured average hourly radiative heat fluxes to the snowpacks both around the study houses and at the Trent Weather Station (open) site, as well as data on cloud cover and snow cover in the suburban subcatchment. Snowcover disappeared at the Trent site following March 19. The total radiative heat inputs to both the suburban and open snowpacks for the measurement periods between March 7 and March 19 are summarized in Table 3. It is apparent that the influence of the buildings' walls upon net radiation varies from day to day. On cloudy days, the relative importance of radiative contributions from the buildings to the net all-wave radiation flux around the houses increases. For example, on March 7 the radiative heat fluxes available for snowmelt in the suburban area (Hm_S) were 399% and 435% of that for the open site (Hm_O) over the south- and north-facing snowpacks, respectively. These increased heat fluxes may accelerate snowmelt in the suburban area. In contrast, on sunnier days (March 15 and 19) the shadow effect actually reduces Q^* over some snowpacks (67%, 78% and 82% of the open site receipts on north-, west- and east-facing snowpacks, respectively). This should result in a reduction of snowmelt in these areas except for south-facing snowpacks, where continuously higher Q^* can be found: 146% of that at the open site on a sunny day (see Table 3). These results suggest that the melt rate in urban areas will be spatially variable when compared with that in an open field.

Table 3: Net radiative heat inputs to suburban and rural (open) snowpacks

Aspect	Measurement Date	Time Period	Hm_S (Suburban) ($kJ\ m^{-2}$)	Hm_O (Open) ($kJ\ m^{-2}$)	Cloud Cover (tenths)	Hm_S vs Hm_O %
N	March 7	1200-1500	957	240	8	399
	March 15	0900-1600	4269	6342	0	67
E	March 13	0900-1600	4683	4172	5	112
	March 19	0800-1600	4671	5662	4	82
S	March 7	1000-1500	1816	417	8	435
	March 15	0800-1600	9914	6795	0	146
W	March 13	0900-1600	4309	4172	5	103
	March 19	0800-1600	4458	5662	4	78

Although Q* contributions to suburban snowpacks may exceed those measured at an open site depending on aspect and cloudiness, do these increased heat inputs result in accelerated melt over suburban snowpacks? Table 4 shows the results of the daily snow surveys for the different land use types in the Kawartha Heights study area. The daily differences between the average water-equivalent values were assumed to represent either the mean melt depth within the land use units or additions of water-equivalent due to precipitation events. It is important to bear in mind that there can be substantial variability about these mean melt values due to spatial variations in energy fluxes over the snowpacks as well as errors associated with the snow sampling technique.

As Table 4 indicates, the suburban area had the largest total melt over the period February 22 to March 29, 1985. The increased melt in the suburban area compared with that in the woods is not surprising, since the tree canopy greatly reduces both incoming solar radiation and turbulent exchanges over the snowpack (Hendrie and Price, 1979). The total melt in the suburban area is also greatly in excess of that observed in the open areas, and there are a number of possible reasons for this. The first is the possibility of higher air temperatures in the built-up area, thus generating greater sensible heat fluxes to the snowpack. However, the study area is located on the south-west edge of Peterborough and experiences a prevailing westerly wind, so that any influence of Peterborough's urban heat island upon the local microclimate is greatly reduced. It is also unlikely that urban-rural differences in incoming longwave radiation of the type observed by Rouse et al. (1973) are a factor in the study area owing to the city's small size and its relatively clean atmosphere.

Table 4: Short-term melt depths for various land use types, Spring 1985, Kawartha Heights. + sign indicates gain of water-equivalent by the snowpack

Date	Mean W.E.(cm)			Difference between average water equivalent on successive surveys (cm)		
	Open N>4	Wood N>4	Suburban N=6	Open	Woods	Suburban
Feb.						
22	10.4	10.2	18.3			
25	8.7	7.9	11.7	1.7	2.3	6.6
26	8.7	8.2	10.9	0.0	+0.3	0.8
Mar.						
1	7.7	10.1	11.2	1.0	+1.9	+0.3
2	7.4	9.1	9.9	0.3	1.0	1.3
3	6.4	8.3	10.0	1.0	0.8	+0.1
8	8.3	12.5	13.5	+1.9	+4.2	+3.5
9	9.3	10.2	13.0	+1.0	2.3	0.5
10	7.6	11.1	14.0	1.7	+0.9	+1.0
11	8.3	12.0	12.4	+0.7	+0.9	1.6
13	6.5	10.8	8.1	1.8	1.2	4.3
14	5.5	10.5	8.1	1.0	0.3	0.0
16	4.3	9.5	7.6	1.2	1.0	0.5
17	3.7	6.9	7.6	0.6	2.6	0.0
18	4.0	7.1	7.1	+0.3	+0.2	0.5
19	4.9	7.6	7.9	+0.9	+0.5	+0.8
20	4.2	7.4	6.4	0.7	0.2	1.5
21	3.8	6.6	5.8	0.4	0.8	0.6
22	3.0	6.1	5.3	0.8	0.5	0.5
23	2.4	7.6	4.6	0.6	+1.5	0.7
24	1.8	6.4	4.1	0.6	1.2	0.5
25	1.8	7.1	3.0	0.0	+0.7	1.1
26	1.5	7.1	2.3	0.3	0.0	0.7
27	0.3	6.4	1.5	1.2	0.7	0.8
29	0	4.6	0.4	0.3	1.8	1.1
Σ of melt depths (cm)				15.2	16.7	23.6
30		4.6	0.5		0.0	+0.1
April						
2		4.3	0.1		0.3	0.4
4		4.1	0.0		0.2	0.1
7		1.5			2.6	0.0
8		1.5			0.0	
9		1.8			+0.3	
11		1.7			0.1	

There is a possibility that urban snowpacks may possess lower albedoes and therefore undergo greater melt. Bengtsson (1981) found the albedo of old snow in Luleå at the beginning of the melt period to be about 0.2 as opposed to an albedo of 0.6 for old snow in rural areas. However, in the Kawartha Heights area the "dirty" snow is restricted to the roadside snowbanks which comprise a small portion of the overall water-equivalent of the suburban area. The differences in total melt between suburban and open areas also cannot be explained in terms of their general aspect, since the open areas have the more southerly orientation and therefore should experience increased melt, all other factors being equal.

Thus it appears that the increased fluxes of Q* over suburban snowpacks may generate the larger melts observed in the suburban catchment. The data obtained do not permit a detailed determination of the proportion of urban snowpacks that may experience accelerated melt as a result of this increased net radiative input. Nevertheless, an approximation can be obtained if it is assumed that the snowpack area influenced by a typical house extends 6 m out into the front and back yards and halfway between the house and those adjacent to it (a distance of 1.1 m on either side of the house). Excluding the average roof top area of 93 m^2, this gives a snowpack area of roughly 197 m^2 per house that is affected by the presence of the building. The combined area of influenced snowcover (258 houses x 197 m^2= 50826 m^2) represents 15% of the total suburban area (Table 1) and roughly 21% of the snow-covered area of the suburban basin (excluding roof tops). As was noted earlier, the increase in radiative heat input to suburban snowpacks over that recorded for open snowcover is most pronounced on cloudy days when the shadow effect is minimized and longwave contributions from the building walls become significant. It is interesting to note that during the main spring melt period at Kawartha Heights (March 5 - March 18) a cloud cover of 5/10ths or more was observed on 9 days. Therefore it is possible that a significant proportion of the suburban snowpacks experienced a higher melt than was recorded in open areas on these days, assuming that latent and sensible heat transfers did not vary from one land use to the other.

Conclusions

Although the limited scope of this project did not permit a rigorous analysis of the influence of urban development upon the patterns of Q* and snowmelt for a variety of meteorological conditions, the results obtained permit several conclusions to be drawn.

1. There is a general tendency for the Q* over snowpacks to increase with proximity to buildings, although this pattern can be disrupted by the shadow effect.

2. The diurnal peak in Q* over some suburban snowpacks may precede that over open sites, due to the contribution of reflected incoming solar radiation from exposed walls in the suburban area. This suggests that daily snowmelt may begin earlier in built-up areas than at nearby open sites.

3. Net radiative heat inputs to suburban snowpacks can exceed such inputs in open areas on overcast days, due to the increased significance of longwave emissions from building walls. However, south-facing snowpacks consistently receive greater inputs due to the reflection from south-facing walls on sunny days. These results suggest that radiation data measured at open sites cannot simply be used as surrogates for Q* in built-up areas. The use of the energy budget approach to estimating snowmelt in urban areas requires a consideration of the influence of buildings upon Q* patterns over the snowpack.

4. The greater net radiative inputs manifest themselves in higher melt rates for suburban snowpacks. This was indicated by the results from the daily snow surveys plus such visual evidence as the appearance of "moats" of bare ground that develop around houses in the later stages of melt. This increased melt may assist in explaining the larger and quicker snowmelt runoff response of the suburban catchment in comparison with the largely rural basin (Buttle, 1986).

Acknowledgements

The authors would like to thank Trent University for financial support, H. Granberg and A. Nadeau for constructing the pyrradiometers, the Board of Park Management and the Public Works Department of the City of Peterborough for their cooperation, and the Geography Department of Guelph University for the loan of the Middleton pyrradiometer used in the study. We would also like to thank G. Ward and M. Dugas for assisting in the collection and analysis of the data, and S. Gardiner for help in producing the figures.

References

Adams W.P. (1985), The climate, past and present, in Adams, W.P. and C.H. Taylor (eds.), Peterborough and the Kawarthas, (Peterborough: Heritage Publications), 29-47.

Aida, M. and M. Yaji (1979), Observations of atmospheric downward radiation in the Tokyo area, Boundary Layer Meteorology 16, 453-465.

Anderson, E.A. (1968), Development and testing of snow pack energy balance equations, Wat. Resour. Res. 4, 19-37.

Bengtsson, L. (1981), Snowmelt generated runoff in urban areas, Proc. Second Int. Conf. Urban Storm Drainage, Urbana, Ill., 444-451.

----------- (1983), Snowmelt induced urban runoff in northern Sweden, Proc. Stormwater and Water Quality Model Group Meeting, Athens, Ga, 215-236.

----------- (1984a), An analytical approach for determining snowmelt induced runoff, Proc. Fifth Northern Res. Basins Symp., Vierumaki, Finland, 5.41 - 5.50.

---------- (1984b), Modelling snowmelt induced runoff with short time resolution, Proc. Third Int. Conf. Urban Storm Drainage, Goteborg, Sweden, 305-314.

Buttle, J.M. (1986), Snow accumulation and snowmelt runoff in a suburban environment, Proc. East. Snow Conf., v.30, 13pp.

Corps of Engineers (1965), Snow-Hydrology, Summary Report of the Snow Investigations, U.S. Army Corps of Engineers, North Pacific Division, Portland.

Hendrie, L.K. and A.G. Price (1979), Energy balance and snowmelt in a deciduous forest, in Colbeck, S.C. and M. Ray (eds.), Proc. Modeling of Snow Cover Runoff, (Hanover, N.H.: CRREL), 211-221.

Morris, E.M. (1985), Snow and ice, in Anderson, M.G. and T.P. Burt (eds.), Hydrological Forecasting, (Chichester: John Wiley & Sons), 153-182.

Nunez, M. and T.R. Oke (1977), The energy balance of an urban canyon, J. Appl. Meterology 16, 11-19.

Price, A.G. and T. Dunne (1976), Energy balance computations of snowmelt in a subarctic area, Wat. Resour. Res., 12, 686-694.

Richardson, C.W. and M.P. Molnau (1982), Precipitation, in Haan, C.T., H.P. Johnson and D.L. Brakensiek (eds.), Hydrological Modeling of Small Watersheds, ASAE monograph No. 5, 81-118.

Rouse, W. R., D. Noad and J. McCutcheon (1973), Radiation, temperature and atmospheric emissivities in a polluted urban atmosphere at Hamilton, Ontario, J. Appl. Meteorology 12, 789-807.

Taylor, C.H. (1977), Seasonal variations in the impact of suburban development on runoff response: Peterborough, Ontario, Wat. Resour. Res., 13, 464-468.

------------ (1982), The effect on storm runoff response of seasonal variations in contributing zones in small watersheds, Nordic Hyd., 13, 165-182.

Taylor, C.H. and D.M. Roth (1979), Effects of suburban construction on runoff contributing zones in a small southern Ontario drainage basin, Hyd. Sci. Bull., 24, 289-301.