Nordic Hydrology, 19, 1988, 19-40

Snowmelt Runoff in Suburban Environments

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While snowmelt and rain-on-snow events have received considerable attention in rural watersheds they have been largely ignored in urban hydrology, despite the fact that they may result in severe flooding. The runoff responses of two subcatchments of a small drainage basin in Peterborough, Ontario were investigated for the spring snowmelts of 1984 and 1985. One of the catchments has undergone substantial suburbanization, while the other is largely in rural land use. Measurements in each catchment included snowpack water-equivalent depths, snowmelt and precipitation, fluxes of net radiation over snowpacks, infiltration capacities of pervious surface types, and streamflow.

Suburban development appears to have produced substantial increases in spring quickflow yields from the entire basin. A comparison of the responses of the two subcatchments reveals that the suburban catchment reacts more rapidly to snowmelt and rain-on-snow inputs and generates larger initial quickflow response ratios than the rural basin as a result of the microclimatic, pedologic and hydraulic characteristics of built-up areas. However, the dynamic behaviour of the runoff contributing area of the rural catchment results in a marked increase in its quickflow yield as melt progresses. The results suggest that the distinct nature of the processes of snow accumulation, melt and runoff generation in built-up areas should be considered when modelling suburban snowmelt runoff.

Introduction

Studies of urban hydrology have concentrated on the response of urban catchments to rainfall events, and hydrological modellers have been preoccupied with the simulation of runoff response under high intensity rainfalls, as these are assumed to be the major flood-generating events in built-up areas. Yet in many cities in Canada, the United States and Scandinavia snowmelt runoff forms a significant portion of the annual discharge (Westerström 1986), and snowmelt and rain-on-snow events have been observed to cause flooding in urban environments (Bengtsson 1984b). Paradoxically, snowmelt has received relatively little attention in the urban hydrological literature, although we are aware of research in Sweden (Bengtsson 1981a, b, 1983, 1984a, b; Westerström 1986) and in Canada (Jolly, 1972, 1973; Waller and Coulter 1974) on this subject.

Snowmelt and Runoff in Rural and Urban Areas

Considerable work has been done on snowmelt and snowmelt runoff in rural environments, and a comparison of results with those from urban areas suggests that substantial differences exist in the nature and intensity of the processes involved. Studies of snowmelt in rural basins (*e.g.* Fitzgibbon and Dunne 1983) generally reveal that melt in open areas is the result of net radiative heat inputs to the snowpack as well as turbulent energy fluxes (sensible and latent heat), whereas in forests the effects of the turbulent fluxes are reduced and snowmelt is largely controlled by net radiation. The limited research on snowmelt in urban areas suggests that melt is dominated by net radiation fluxes (Westerström 1981), and Bengtsson (1981b) theoretically demonstrated that the higher air temperatures and lower snowpack albedos in built-up areas in Sweden can produce melt rates 20-30 mm d^{-1} greater than those at nearby rural sites. Water can also be delivered to the soil surface by rain-on-snow events, which may generate large volumes of water if the snowpack is ripe or none at all if the snow is dry and cold (Bengtsson 1983). Thus the runoff resulting from rain-on-snow events in rural basins can vary greatly in magnitude depending on snowpack conditions (Bengtsson 1985), while urban areas always produce some runoff from impervious surfaces which are kept snow-free throughout the winter.

In natural environments the meltwater that is produced can follow a variety of pathways in order to reach the stream channel. Areas undergoing a reduction in soil infiltration capacities as a result of ground freezing may contribute Horton overland flow to streams, whose hydrographs display pronounced diurnal fluctuations that mimic the daily melt pattern (*e.g.* Bengtsson 1985). Conversely, Horton overland flow may be completely absent where melt occurs over permeable unfrozen soils (*e.g.* Price *et al.* 1979). Under these conditions streamflow may originate mainly from groundwater contributions (Rodhe 1981), and the protracted nature of snowmelt often allows shallow water tables to intersect the soil surface (Bengtsson 1985). This leads to the production of runoff as saturation overland flow from areas that can fluctuate in extent during the course of the melt. In contrast, snowmelt runoff generation in urbanized catchments is dominated by Horton overland flow from paved surfaces as well as from normally-pervious areas rendered impermeable by ground freezing. The latter usually permit the infiltration of all meltwater during the initial stages of melt, but undergo a progressive reduction in infiltration capacity due to the filling of soil moisture storage and refreezing of meltwater in the soil (Bengtsson 1983). This expansion of the runoff contributing area appears to account for observed increases in the runoff/melt ratio during the melt period, and the combination of increased runoff volumes with the greater efficiency of urban drainage networks can result in peak discharges greatly in excess of those from rural catchments (Westerström 1986).

The present paper is an attempt to extend our understanding of urban snowmelt hydrology, based on field measurements of snow accumulation, snowmelt and runoff in suburban and rural areas. We feel that such a study is a necessary first step in improving flood forecasting for urbanized catchments that experience significant snowmelt runoff, and may assist efforts to simulate the movement of such contaminants as NaCl into receiving water bodies following winter road salting.

Study Area

Field studies were undertaken in the Kawartha Heights subdivision of Peterborough, Ontario (44°N, 78°W), which lies on the southwestern margin of the city (Fig. 1). The thirty year (1951-1980) mean annual temperature for Peterborough is 6-7°C and the mean annual precipitation is slightly in excess of 760 mm. This precipitation, 80% of which falls as rain and 20% as snow, is quite evenly distributed throughout the year. The site consists of a suburban catchment nested within a largely rural watershed that is currently undergoing urbanization. The entire basin (96.9 ha in area) 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).

The study area lies within the Peterborough drumlin field, and has a local relief of about 45 m with generally gentle slopes. The overall orientation of the suburban catchment is east-southeast, while the rural catchment has a south-southeast orientation. The soils of the area are well-drained Otonabee loams and Bondhead sandy loams, characterized by more than 50% sand and gravel. They are underlain by sandy till, although a zone of kame deposits (sand, gravel, minor till) cuts diagonally across the basin from southwest to northeast (Gravenor 1957).

General characteristics of the entire drainage basin and the suburban and rural catchments as of the end of 1985 are presented in Table 1. The vegetation of the open fields consists of scrub brush and grasses, while the woodland is a mixed forest composed largely of cedars. Prior to suburbanization the built-up area was mainly orchard, and the existing vegetation cover in this part of the basin is domi-

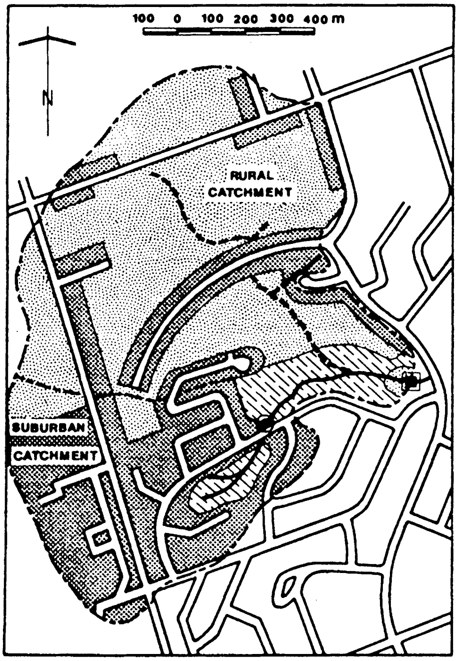


Fig. 1. The Kawartha Heights watershed: land uses in the suburban and rural catchments.

Table 1 - General land use characteristics, Kawartha Heights, 1985

		Entire Basin	Suburban Catchment	Rural Catchment
Drainage area	(ha)	96.9	33.3	63.6
Open Fields	(ha)	48.7	5.9	42.8
	(%)	50.3	17.7	67.3
Forest	(ha)	6.6	2.2	4.4
	(%)	6.8	6.6	6.9
Construction Areas	(ha)	4.7	0.0	4.7
	(%)	4.8	0.0	7.4
Urbanized	(ha)	36.9	25.2	11.7
	(%)	38.1	75.7	18.4

nated by urban lawns. Houses within the catchments are single family dwellings, with an average plan area of approximately 93 m^2. Storm sewers drain the suburban catchment and those sections of the rural catchment that have been recently developed. The sewers in the suburban catchment discharge into a small spring-fed perennial stream (Fig. 1). The rural catchment is drained by the downstream portion of this stream as well as by ephemeral tributaries which flow at the wettest times of the year.

Patterns of Snow Accumulation

Man redistributes the snow that falls in urban areas, clearing it away from roads, driveways, sidewalks and parking lots, and allowing it to accumulate on pervious surfaces such as lawns and gardens. Snow is often transported out of the downtown areas of cities (Bengtsson 1981b) or may be intentionally melted, although this did not occur in the Kawartha Heights area. Snow that falls on roofs often melts relatively quickly as a result of increased exposure to solar radiation and heat flux from the roofs themselves. As a result, roofs are generally snow-free when melt commences on other urban surfaces, as was the case in the study area.

As Adams (1976) notes, snow accumulation and snowpack evolution in Peterborough do not generally follow a unidirectional progression from initiation of snow cover to peak accumulation followed by melt. Instead, snowpack evolution is often accompanied by significant winter melting and rainfall. Such was the case with the 1984 (and to a lesser extent with the 1985) snowmelt, each spring melt consisting of distinct melt periods separated by an interval of freezing temperatures lasting several days. Surveys of peak water-equivalent were conducted immediately prior to each melt period during both study years.

Twice during the 1984 snowmelt, point measurements of water-equivalent were made in the open fields (50 samples) and wooded areas (90 samples) of the rural catchment using a Meteorological Service of Canada (MSC) snow sampler. 15 house lots were randomly selected in the suburban catchment and front yard, back yard and driveway snowbank source areas were identified and sampled. In addition, the geometries and water-equivalents of roadside snowbanks within the catchments were measured. Three intensive snow surveys were conducted in 1985, and during each survey 33 and 30 point measurements of water-equivalent were made in the open fields and the forest, respectively. Front yards, back yards and driveway snowbanks of 18 houses were sampled, along with two construction sites. Measurements of the geometries and water-equivalents of roadside snowbanks were repeated. The results for the component surface types in the basin are summarized in Table 2.

Despite differences in total snowfalls between the two years, similar patterns in the distributions of peak water-equivalent depths are apparent. Front yards possessed large water-equivalents due to contributions from shovelled driveways and walkways, while the high values in the forest during later melt periods were the result of residual snow from previous melts. 65% of the suburban catchment was snow-covered prior to each of the melt periods, while 85% of the rural catchment was snow-covered. Weighted mean water-equivalent depths in 1984 for the suburban and rural catchments were 11.1 cm and 9.3 cm prior to the first melt period, and 3.9 cm and 4.4 cm prior to the second melt. In 1985 the corresponding values were 6.9 cm and 6.5 cm at the commencement of spring melt, 10.1 cm and 10.2 cm at the start of the second melt period, and 8.1 cm and 7.0 cm prior to the third melt period.

Table 2 – Summary of peak water-equivalent values

		Surface Type			
Survey		Open Fields	Forest	Front Yards	Back Yards
3/2/84	mean depth (cm)	12.0	10.9	17.7	12.3
	standard (cm) deviation	3.6	2.6	4.0	2.8
	coefficient of (%) variation	29.8	23.4	22.7	23.0
14/3/84	mean depth (cm)	5.5	8.3	3.8	2.4
	standard (cm) deviation	4.3	3.3	1.2	1.6
	coefficient of (%) variation	78.2	40.0	31.6	65.1
7/2/85	mean depth (cm)	7.5	7.1	14.9	9.9
	standard (cm) deviation	1.8	1.3	3.3	4.1
	coefficient of (%) variation	24.4	18.7	21.9	41.4
18/2/85	mean depth (cm)	11.6	10.7	19.3	13.7
	standard (cm) deviation	4.2	1.8	4.5	3.9
	coefficient of (%) variation	36.4	17.7	23.3	28.5
10/3/85	mean depth (cm)	7.6	11.1	16.7	11.3
	standard (cm) deviation	3.2	2.7	4.3	5.0
	coefficient of (%) variation	41.4	24.1	25.8	44.4

Snowmelt Rates in the Suburban and Rural Catchments

The energy balance approach (Anderson 1968) was used to estimate hourly and daily snowmelt fluxes within the catchments for both years. Net radiation, air temperature, wind speed and relative humidity were recorded 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 according to the standard procedures outlined in Price and Dunne (1976). Precipitation throughout the melt periods was recorded at the Trent Station and at the Peterborough Airport, 4.5 km south of the catchments.

During the 1985 melt the energy balance measurements were augmented by results from a 1.38 × 1.38 m snowmelt lysimeter at the Trent Station. This permitted the continuous measurement of meltwater leaving the base of the snowpack. In addition, daily snow surveys were conducted from February 7 to April 11 in the three main land use types – open, forest and suburban. Measurements of water-equivalent were made at roughly the same time at the beginning of each survey day, with a minimum of 30 points being sampled during each survey. The number of measurements taken within each land use was proportional to that surface type's area.

The results of the daily snow survey were used to obtain an index of daily melt depth in both of the catchments for the 1985 field season (Fig. 2). The daily differences between the average water-equivalent values were assumed to represent either the mean melt depth within the land use units (positive values) or additions of water-equivalent due to precipitation events (negative values). It is important to bear in mind that there can be substantial variability about these mean depths due to spatial variations in energy fluxes over the snowpacks as well as errors associated with the snow sampling technique. Nevertheless, Fig. 2 indicates that the suburban area had the largest total melt over the period February 23 – 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 fields, and there are a number of possible reasons for this. The first is the potential for 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 southwest edge of Peterborough and experiences a prevailing westerly wind, so that any influence of the city's urban heat island upon the local microclimate is greatly reduced. Air temperature measurements made in the rural and suburban catchments during the 1985 field season failed to reveal significantly warmer conditions in the latter area. 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.

The second possibility is that urban snowpacks may possess lower albedos and therefore undergo greater melt. Bengtsson (1981b) 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 aspect, since the fields have the more southerly orientation and therefore should experience increased melt, all other factors being equal.

One aspect of a suburban area's microclimate that may differ significantly from that of its rural counterpart is in terms of the net radiative fluxes (Q^*) reaching the snowpack surface. Q^* is one of the most spatially variable components of the energy budget of a snowpack, since it is affected by changes in slope, aspect, shading and altitude, as well as by reflected radiation from surrounding surfaces

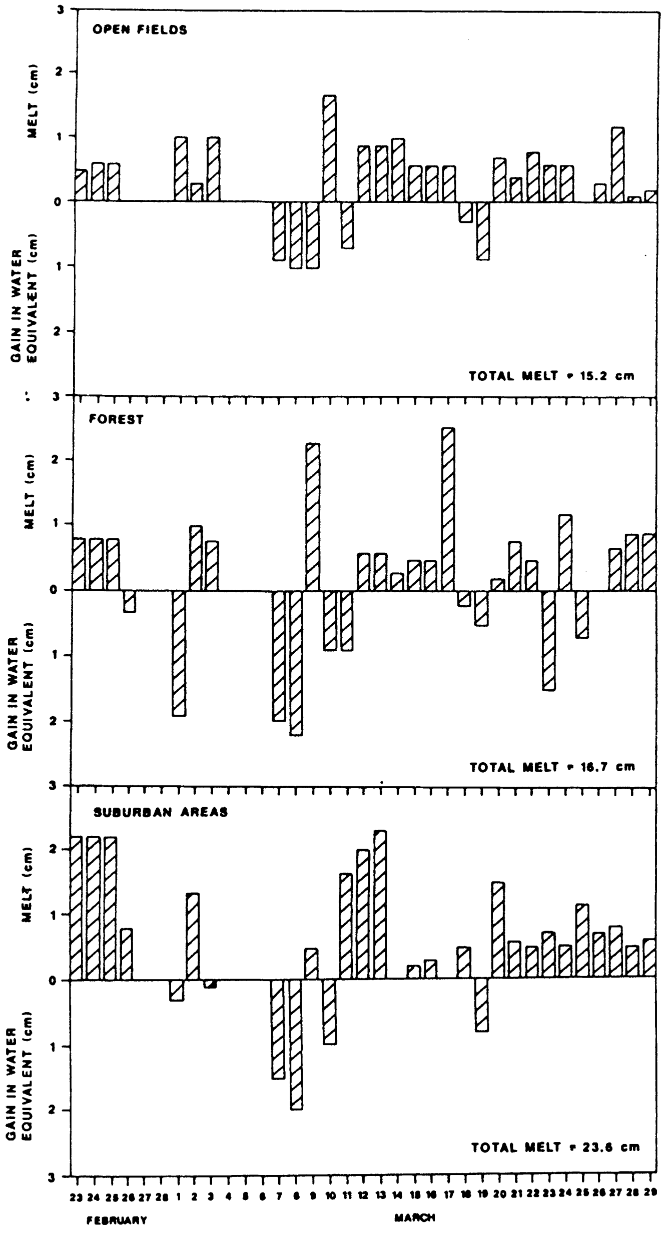


Fig. 2.
Average daily melt depths, February 23-March 29, 1985.

(Morris 1985). However, measurements of Q^* in built-up areas are comparatively rare, and the degree to which net radiative fluxes measured in open sites represent those in urban areas needs to be established (Xu and Buttle 1987). 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 over their surrounding

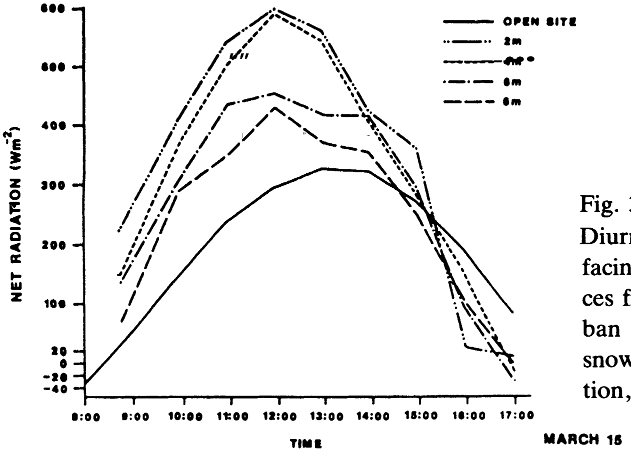


Fig. 3.
Diurnal trends of Q^* over a south-facing snowpack at varying distances from a house wall in the suburban catchment, and over an open snowpack at the Trent Weather Station, 1985.

snowpacks was measured during the 1985 melt using four custom-built net pyrradiometers. A network of ten sample points was established around each house, and hourly measurements of Q^* at a height of 1 m above the snowpack surface were taken on nine days between March 7 and April 4, 1985.

These observations were compared with Q^* fluxes over an open snowpack (assumed to be represented by the record of a Middleton CN-1 net pyrradiometer at the Trent Weather Station) for four days during the 1985 melt, and are discussed in detail in Xu and Buttle (1987). Fig. 3 shows the diurnal trends in Q^* for a south-facing snowpack in the suburban catchment along with net radiation fluxes recorded at the open site. There is a general tendency for Q^* over suburban snowpacks to increase with proximity to buildings, due to a diminished sky-view factor (Oke 1978) which reduces longwave radiative losses from the snowpack, as well as contributions of emitted longwave and reflected shortwave radiation from building walls. However, this pattern may be disrupted by the shadow effect of the buildings themselves, resulting in Q^* fluxes near houses that are lower than those observed in open areas. Fig. 3 also indicates that the diurnal peak in net radiation 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 the suburban daily snowmelt cycle may antecede that in open areas by as much as an hour.

The total radiative heat inputs to both suburban and open snowpacks for the measurement periods between March 7 and March 19 are summarized in Table 3. Due to the close spacing between the houses, only the receipts for the front and back yards of each house are considered. The influence of the houses upon Q^* over surrounding snowpacks was found to extend up to 8 m away from the house walls, and the measured Q^* fluxes were integrated over this distance in order to obtain the total net radiative input to the snowpack. The snowmelt depths given in the table are the water-equivalents corresponding to the net radiation energy supplied

Table 3 – Net radiative heat inputs and snowmelt depths, suburban and open snowpacks

Snowpack Aspect	Measurement Date	Time Period	Cloud Cover (tenths)	Q* Flux Suburban (kJ m^{-2})	Snowmelt Suburban (cm)	Q* Flux Open (kJ m^{-2})	Snowmelt Open (cm)	Melt suburban/ Melt open (%)
N	March 7	1200 – 1500	8	957	0.3	240	0.1	300
	March 15	0900 – 1600	0	4269	1.3	6342	2.0	65
E	March 13	0900 – 1600	5	4683	1.5	4172	1.3	115
	March 19	0800 – 1600	4	4671	1.5	5662	1.8	83
S	March 7	1000 – 1500	8	1816	0.6	417	0.1	600
	March 15	0800 – 1600	0	9914	3.1	6795	2.1	148
W	March 13	0900 – 1600	5	4309	1.4	4172	1.3	108
	March 19	0800 – 1600	4	4458	1.4	5662	1.8	78

to the snowpack.

It is apparent that the influence of the buildings' walls upon net radiation and resultant snowmelt varies from day to day. On cloudy days, the relative importance of radiative contributions from the buildings to the Q^* flux around the houses increases, and melt near the house may exceed that in open areas. In contrast, on sunnier days the shadow effect reduces Q^* over some snowpacks. This should result in a reduction of snowmelt in these areas relative to open sites except for south-facing snowpacks, where contributions of reflected shortwave from exposed walls result in higher H_m and greater snowmelt.

It is estimated that Q^* receipts for approximately 21 % of the snow-covered area of the suburban catchment (excluding roof tops) are influenced by the presence of the houses. During the 1985 melt period a cloud cover of 5/10ths or more was observed on 22 days out of 36, and the limited net radiation data suggest that the increase in radiative heat input to suburban snowpacks over that recorded for open snowcover is most pronounced on such days. Therefore it is possible that a significant proportion of the suburban snowpacks experienced a higher melt than was recorded in open areas during these conditions, assuming that latent and sensible heat transfers did not vary from one land use to the other. The potential for higher rates of snowmelt in suburban areas due to increased Q^* inputs is supported by such visual evidence as the appearance of »moats« of bare ground that developed around the houses in the later stages of melt.

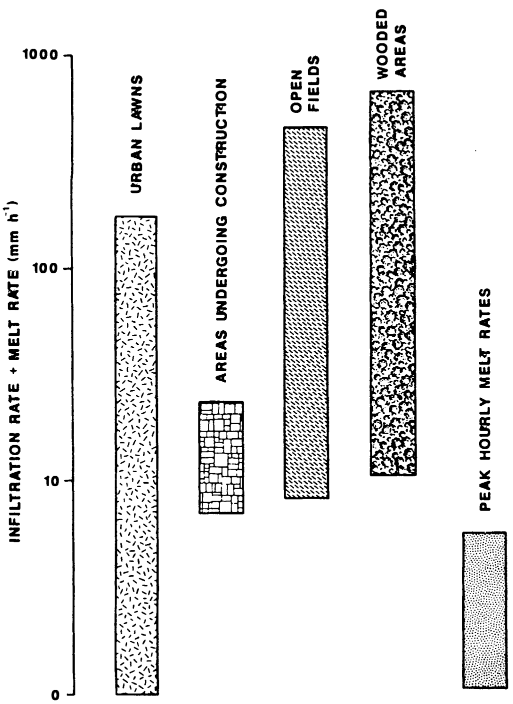


Fig. 4.
Ranges in infiltration capacities for surface types in the Kawartha Heights watershed, and the range in computed peak hourly melt rates, 1985.

Infiltration Rates in the Suburban and Rural Catchments

As well as experiencing higher melt rates, snow-covered lawns and gardens in suburbs tend to have lower infiltration rates than agricultural and forest soils. Urban soils suffer compaction by heavy machinery and foot traffic, as well as profile stratification caused by the addition of fill or the spreading of subsoil material over the original soil profile during basement construction (Kelling and Peterson 1975). The overall effect is a reduction in the soil's infiltration capacity.

Infiltration rates for the four pervious surface types within the Kawartha Heights basin (open fields, construction sites, urban lawns and forest soils) were measured during the later stages of snowmelt in 1985 using a double-ring infiltrometer with a constant head device. Between March 14 and April 23, 42 infiltration tests were conducted – ten each for urban lawns and construction sites, and eleven each for the open fields and the soils in the forest. Fig. 4 shows the ranges in infiltration capacities determined for these surfaces along with the range in peak melt rates estimated using the energy balance approach. For the open fields and forested areas in the rural catchment the rate of melt was less than the infiltration capacity, and such surfaces will not generate Horton overland flow. In the suburban catchment the peak rate of melt appears to have exceeded the infiltration capacities of some of the lawns, leading to the production of Hortonian runoff.

This runoff makes a rapid contribution to discharge from the suburban catchment, due to the greater hydraulic efficiency of built-up areas. Assuming Darcian flow along the base of a snowpack, Bengtsson (1984b) estimated snowmelt runoff hydrographs which corresponded well with observed outputs from an impermeable study plot. Time of concentration from the plot was determined as

$$t_c = \frac{n\,L}{k\,I} \tag{1}$$

where

t_c – time of concentration (s)
n – porosity of the basal layer of the snowpack
L – length of the runoff area (m)
k – saturated hydraulic conductivity of the basal layer (m s^{-1})
I – ground surface slope

Taking a range of ground surface slopes for lawns in the suburban catchment of 1-10%, and assuming $n = 0.7$, $k = 0.1$ m s^{-1} (Bengtsson 1984b), and an average surface length of 10 m, estimated times of concentration for the suburban lawns using Eq. (1) were found to vary from 2 hours to 12 minutes. Thus any Horton overland flow generated by these surfaces quickly reaches adjacent roadside gutters, sidewalks and driveways, which rapidly translate this input to the storm sewer system.

The Effect of Suburban Development upon Spring Runoff Yield

Runoff was measured for the suburban catchment and for the entire basin (Fig. 1) using water level recorders and stage-discharge relationships. The runoff response for the rural catchment was determined by lagging the suburban output by the travel time between the two gauging sites, and by subtracting the suburban hydrograph from that for the entire basin to obtain the rural hydrograph. Measurements for both years commenced at the beginning of snowmelt and continued well into April, by which time the runoff response of the catchments was due solely to rainfall inputs. The runoff hydrographs were separated into quickflow and delayed flow for all three basins using the Hewlett and Hibbert (1967) method with a separation line of 0.0055 1 s^{-1} ha^{-1} h^{-1}. This separation technique was employed because it distinguishes flow components on the basis of the speed with which water enters the channel, rather than on the basis of often-contentious assumptions concerning the source of the water. Quickflow response ratios, calculated by expressing quickflow depth as a percentage of precipitation input (snowmelt and/or rainfall), are used as indices of the catchments' runoff response.

Table 4 incorporates data presented by Taylor (1982) and summarizes the spring quickflow responses for snowmelt and rain-on-snow events for the entire Kawartha

Table 4 – Snowmelt, precipitation and quickflow summary, Kawartha Heights watershed, 1974-1985

Year	1974	1977	1978	1984	1985
Peak Snowpack (mm) Water-Equivalent	69.0	81.4	159.2	98.9	78.7
Rain and Snow (mm) During Period	41.2	48.4	31.8	173.0	84.3
Total Available (mm) Precipitation	110.2	129.8	191.0	271.9	163.0
# Degree-Days < 0°C Prior To Initiation Of Continuous Snowcover	31.9	68.5	8.0	32.9	118.9
30 Day Antecedent Precipitation Prior (mm) To Initiation Of Continuous Snowcover	72.0	28.1	91.2	92.7	67.5
Total Snowmelt (d) Duration	33	30	31	38	32
# Degree-Days > 0°C During Snowmelt	43.3	26.9	15.8	39.1	30.2
Total Quickflow (mm)	6.5	28.6	32.0	46.3	38.2
Quickflow Response (%) Ratio	5.9	22.0	16.8	17.0	23.5

Heights basin, along with various measures of the nature of the snowmelt period for each of the years indicated. The values for 1974 were obtained prior to suburban development of the catchment, while the data for the springs of 1977 and 1978 were obtained while the basin was undergoing large-scale construction activity. Taylor (1982) noted that soils of areas that underwent construction between 1975 and 1978 suffered substantial reductions in their infiltration capacities, generating increased quickflow volumes from relatively low-intensity snowmelt and rain-on-snow events and accounting for the increase in quickflow response ratios for these years over that observed for the pre-development stage. The results from 1984 and 1985 demonstrate that the influence of suburbanization upon increasing spring quickflow yields extends into the fully developed phase following construction.

One question that should be addressed concerns the reasons for the variations in quickflow response following development of the basin. Research into the runoff response of urban catchments has demonstrated that runoff/rainfall ratios may change in response to variations in the depth, duration and intensity of the rainfall inputs (Buttle 1984), and the same factors were analyzed for each of the years in Table 4. It was assumed that the intensity of the snowmelt could be represented by the accumulated number of degree-days > 0°C during the melt period, where one degree-day is a departure of one degree between the freezing point and the mean daily temperature, based on temperature measurement made at the Peterborough Airport. Despite the small number of observations, it does not appear that the nature of the snowmelt itself exerts a strong control upon the total quickflow yield from the basin.

Another source of the observed variations in the quickflow response ratio pertains to the condition of the basin prior to snowmelt. One factor which may dominate the snowmelt runoff response is the presence of »concrete frost«, the hydrological effects of which have been described by Dunne and Black (1971). Under some conditions frozen soil may act as an impervious surface, and the extent of concrete frost may partly govern the amounts of surface runoff generated by snowmelt and rain-on-snow events (Taylor 1982). Prolonged sub-zero air temperatures prior to snowpack development increase the potential for ground freezing, and there is a greater chance of concrete frost development if the soil is at or near saturation prior to freezing (Kane and Stein 1984). The presence and spatial extent of concrete frost was not measured during each of the springs listed in Table 4, and the potential for freezing air temperatures and saturated soils was estimated using two surrogates – accumulated number of degree-days < 0°C and 30 day antecedent precipitation prior to the initiation of a continuous snowcover in the basin.

The antecedent wetness of the catchment may also affect runoff response through its influence on groundwater storage in the catchment. Substantial rainfall inputs prior to winter freeze-up serve to recharge groundwater bodies, and a greater input in one fall season relative to another may mean that a smaller input of meltwater is required in the following spring to cause the water table to intersect the soil surface in low-lying areas. Thus a larger proportion of the available meltwater and rainfall may be able to run off as saturation overland flow.

Of these two indices, it appears that the accumulated number of degree-days < 0°C prior to the initiation of continuous snowcover accounts for some of the observed variation in quickflow response ratios during and following suburbanization of the catchment (Table 4). While this suggests that concrete frost may have played a role in some of the years of record, this cannot be substantiated at present.

Runoff Production in Suburban and Rural Environments

Additional information concerning suburban and rural responses to snowmelt is provided by the catchments' runoff hydrographs. Table 5 summarizes precipitation, total runoff and quickflow for the entire basin and the suburban and rural catchments for the snowmelt periods of 1984 and 1985. These data can be examined on an annual, intraseasonal and event-by-event basis.

Table 5 – Precipitation, total runoff and quickflow summary for the entire basin and the suburban and rural catchments, 1984 and 1985

	Total Available Precipitation (mm)	Total Runoff (mm)	Total Runoff Response (%)	Quickflow (mm)	Quickflow Response Ratio (%)
Spring 1984					
Entire Catchment	272	102	37.5	46	16.9
Suburban Catchment	280	160	57.1	69	24.6
Rural Catchment	268	72	26.9	45	16.8
1st Melt Period (13/2/84-27/2/84)					
Entire Catchment	148	42	28.4	20	13.5
Suburban Catchment	159	77	48.4	38	23.9
Rural Catchment	142	24	16.9	14	9.9
2nd Melt Period (14/3/84-9/4/84)					
Entire Catchment	124	60	48.4	27	21.7
Suburban Catchment	121	83	68.6	31	25.6
Rural Catchment	126	49	38.9	32	25.4
Spring 1985*					
Entire Catchment	163	88	54.0	38	23.3
Suburban Catchment	165	113	68.5	38	23.0
Rural Catchment	162	74	45.7	37	22.8
1st Melt Period (20/2/85-9/3/85)					
Suburban Catchment	141	64	45.4	26	18.4
2nd Melt Period (9/3/85-17/3/85)					
Entire Catchment	78	29	37.2	18	23.1
Suburban Catchment	79	39	49.4	19	24.1
Rural Catchment	78	23	29.5	15	19.2
3rd Melt Period (22/3/85-22/4/85)					
Entire Catchment	78	59	75.6	20	25.6
Suburban Catchment	78	73	93.6	18	23.1
Rural Catchment	78	51	65.4	29	37.2

* underestimate due to missing data prior to 9/3/85 and between 18/3/85 and 21/3/85.

Annual differences in basin runoff response may be due to variations in the degree of ground freezing, as discussed above. However, the seasonal quickflow response ratios for the suburban catchment for 1984 and 1985 are roughly equal, suggesting a fairly consistent hydrologic behaviour for this catchment on a year-to-year basis. Both the suburban and rural catchments exhibit marked variations in

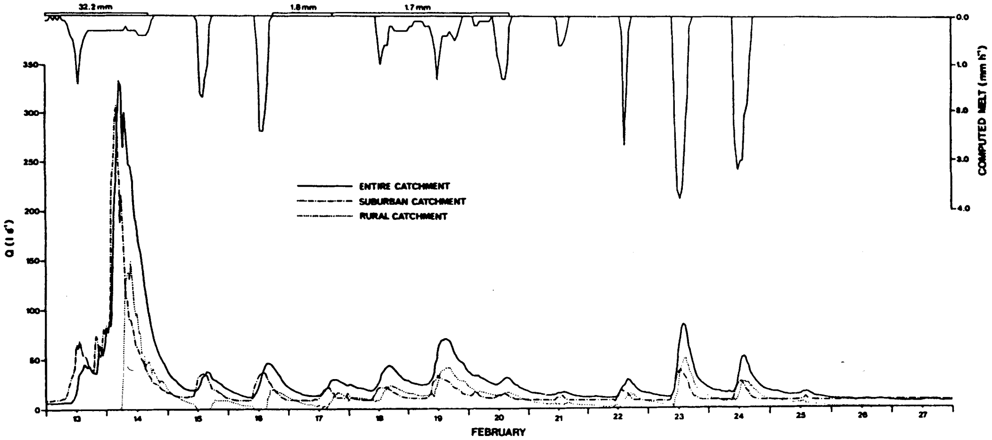
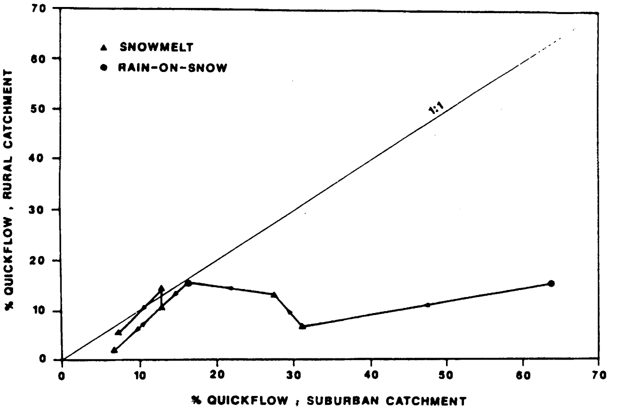


Fig. 5. Precipitation, computed snowmelt and runoff for the entire basin and suburban and rural catchments, first melt period, 1984. All precipitation is as rainfall, and the duration of the precipitation event is indicated by the length of bar at the top of the figure. It is worth noting that the hydrographs are not adjusted for differences in basin area – if they were, the differences in the discharge from the suburban and rural catchments would become even more pronounced.

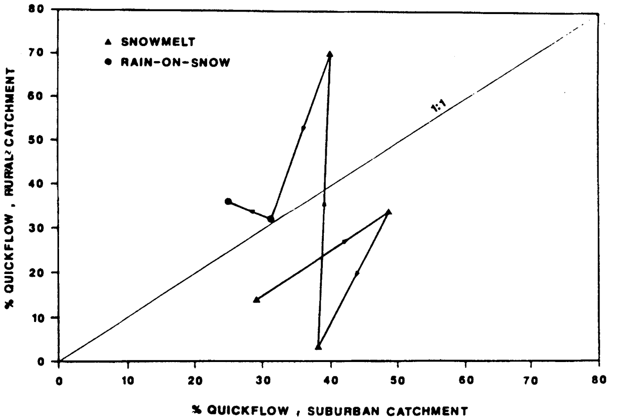
runoff response when individual melt periods are compared within a given year. During initial melt periods the suburban catchment's total runoff and quickflow responses exceeded those of the rural catchment. However, during the later stages of melt the total quickflow response from the rural catchment equalled or exceeded that of the suburban basin.

Comparisons of runoff from the catchments during individual melt periods (Fig. 5) reveal that the suburban catchment made large and rapid initial responses to snowmelt and rain-on-snow events, while runoff from the rural catchment tended to increase as the melt period progressed. This pattern was repeated for all of the melt periods indicated in Table 5. Fig. 6 shows changes in the catchments' quickflow response ratios for individual melt and rain-on-snow events for two melt periods. At the beginning of each period the quickflow response of the suburban catchment was greater than that of the rural basin, but as the melt proceeded the quickflow response of the rural catchment began to equal and in some cases exceed the suburban output.

The behaviour of the suburban catchment appears to be the result of the accelerated melt in suburban areas, combined with the generation of Horton overland flow on some suburban lawns and the rapid conveyance of this water to the stream via roadside gutters and the storm sewer network. The available water-equivalent of the suburban snowpack is quickly depleted, causing the suburban runoff response to snowmelt to decline while that for the rural basin is still increasing.



(A) First melt period, 1984.



(B) Third melt period, 1985.

Fig. 6. Trends in quickflow response ratios for individual snowmelt and rain-on-snow events for the suburban and rural catchments.

Although the relatively constant total quickflow response ratios between the various melt periods (Table 5) suggest that the suburban catchment behaves in a fairly consistent fashion during spring melt, these ratios mask considerable variability in quickflow response on an event-by-event basis (Fig. 6). This may be the result of daily changes in peak snowmelt intensity as well as the occurrence of rain-on-snow events; the latter are particularly important in that surfaces that do not generally produce runoff during snowmelt (roads, driveways, roofs) become the main runoff contributing areas during rainfall.

Any explanation of the runoff behaviour of the rural catchment during snowmelt must be made in light of the spectrum of processes that can generate streamflow. Bengtsson (1982) addressed this question when he noted the different characteristics of streamflow hydrographs when flow originates from groundwater and from overland flow. Streamflow originating from subsurface contributions reacts to daily snowmelt fluctuations, but the fluctuations are small and are superimposed upon an increase in mean daily flow during the snowmelt period. For a basin generating runoff by overland flow, streamflow is dominated by the diurnal snowmelt fluctuations. The form of the hydrographs from the rural catchment, with their pronounced daily peaks and relatively consistent baseflow levels, suggests that the quickflow from the basin is largely generated by overland flow.

This overland flow can be produced by two distinct mechanisms. The first is that of Horton overland flow, where the delivery rate of meltwater to the soil surface exceeds the infiltration capacity of the soil. As Fig. 4 shows, peak melt rates are generally lower than infiltration capacities for soils in the rural catchment. Although field observations during the 1985 melt revealed areas of frozen soil in the rural basin, we feel that Horton overland flow was a minor runoff-producing mechanism here.

The second manner in which overland flow may be produced is as saturation overland flow. The infiltration of meltwater serves to recharge groundwater bodies and increase water table elevations. Should the groundwater table intersect the ground surface, this produces saturated areas that are effectively impermeable to meltwater and rainfall (Dunne and Black 1970) and which may expand in size as melt proceeds (Price *et al.* 1979). Saturation overland flow consists of water falling on these saturated areas, combined with subsurface contributions (»return flow«).

Field mapping of surficial saturated areas in the Kawartha Heights basin was conducted throughout the 1985 melt using the procedure outlined in Dunne *et al.* (1975). There was a rapid expansion of the saturated areas in the rural catchment in response to a large rain-on-snow event beginning on March 11, 1985. These zones reached their maximum spatial extent in mid-March and comprised 32% of the basin area, after which they shrank gradually throughout April. This expansion coincided with an extension of the drainage network in the rural catchment, as the drainage density increased from its late-summer value of 0.88 km km^{-2} to a maximum value of 5.14 km km^{-2} on March 24. The greater volumes of saturation overland flow generated by these areas and the increased hydraulic efficiency produced by the expanded drainage network accounts for the increase in the size of the daily rural runoff response as melt proceeds, and the larger quickflow response ratio for the later melt periods (Table 5, Fig. 6).

This point is reinforced when the time lag between peak melt intensity and peak runoff is examined. The timing of peak melt intensity was determined from the energy balance measurements and, for 1985, output from the snowmelt lysimeter at the Trent Weather Station. A comparison of the energy balance and lysimeter data for 1985 revealed little difference in the estimated times of peak melt intensity, so that any time lag due to percolation through the snowpack was ignored. Fig. 7 illustrates the changes in time lag for the suburban and rural catchments for the first melt period of 1984. Following the rain-on-snow event of February 13, the suburban catchment displayed a short and consistent lag between peak melt and peak runoff as a result of its efficient but spatially-fixed drainage network. The

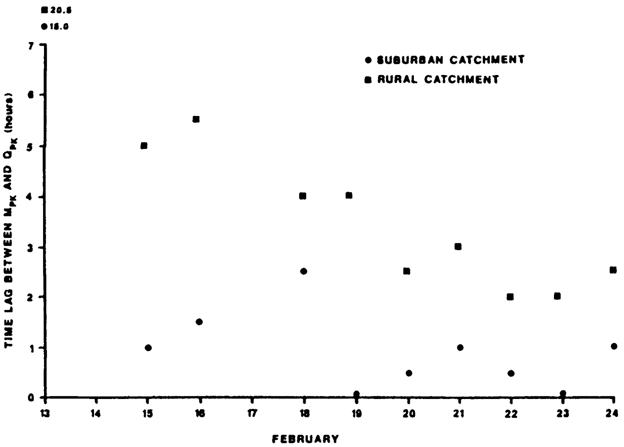


Fig. 7. Time lag between peak melt intensity (M_{pk}) and peak discharge (Q_{pk}), for the suburban and rural catchments, first melt period, 1984.

time lag for the rural basin shows a progressive decrease over time due to the enhanced hydraulic efficiency of the rural catchment associated with the expansion of the runoff-contributing areas. When the mean time lags for the suburban and rural catchments were compared for the second melt period of 1984 and the latter part of the 1985 melt, there was no statistically significant difference between the two values although the lag for the suburban basin tended to be slightly lower.

Conclusions

An examination of snow accumulation and snowmelt runoff from a suburban and a largely rural catchment has demonstrated that suburbanization may have significant effects on the snowmelt runoff process. In general, suburban development was shown to increase spring quickflow yields over those observed prior to construction activity in the basin, as the disturbance of soils during construction and the creation of extensive areas of impervious surfaces magnified the catchment's response to relatively low intensity snowmelt and rain-on-snow events.

When a more detailed comparison of snowmelt rates and runoff responses is made for the suburban and rural catchments, distinct differences may be detected:

1) Suburban areas produced higher melt rates than open fields and forested areas. Measurements of net radiation fluxes over suburban and open snowpacks indicated increased radiative heat inputs and melt depths in the vicinity of houses, particularly on overcast days. The results suggest that radiation fluxes measured at open sites cannot simply be used as surrogates for Q^* in built-up areas, and that the influence of buildings upon Q^* must be considered when using the energy balance approach to estimate snowmelt in urban areas.

2) Runoff from the suburban basin was generated as Horton overland flow, as the observed melt intensities exceeded the infiltration capacities of some of the lawns in the basin. Impervious surfaces, which dominate runoff responses to rainfall in the suburban catchment, were largely snow-free, and most of the snowmelt runoff was produced by pervious surfaces that are not generally considered to be hydrologically active during rainfall events. Roads, driveways, walkways and roofs were incorporated into the runoff contributing area only during rain-on-snow events. Conversely, most of the quickflow from the rural basin was generated as saturation overland flow. Initial snowmelt was not translated into runoff due to the higher infiltration rates observed in the rural catchment. Instead, this water recharged shallow aquifers and elevated water table levels, leading to the progressive saturation of large areas of the catchment during the course of the snowmelt.
3) Impervious surfaces in the suburban catchment served to transfer meltwater rapidly to the storm sewer system, resulting in short and consistent time lags (0.5-2.5 h) between the diurnal melt and runoff cycles. The initial time lag between peak melt and peak runoff in the rural basin exceeded that in the suburban catchment; however, the expansion of the rural drainage network led to the increasingly rapid removal of meltwater and rain-on-snow inputs such that the hydraulic efficiency of the rural catchment approached that of the suburban basin near the end of melt.
4) Quickflow response ratios for the suburban catchment exceeded those of the rural basin at the beginning of the spring snowmelt as a result of the higher melt rates and more rapid runoff production experienced in built-up areas. As snowmelt proceeded, the rural catchment's quickflow response equalled and occasionally exceeded that of the suburban catchment, as progressively more of the rural catchment became hydrologically active.

These differences in the nature of the snowmelt runoff processes in suburban and rural environments suggest that the simple transposition of models intended for rural basins can only be a first approximation when simulating and predicting urban snowmelt runoff. Any real progress in modelling snowmelt runoff in built-up areas must hinge on a recognition of the ways in which urban development affects a catchment's response to snowmelt and rain-on-snow events.

Acknowledgements

We would like to thank Trent University for financial support of this work, and wish to acknowledge the cooperation of the Board of Park Management and the Public Works Department of the City of Peterborough. We would also like to thank M. Ecclestone, G. Ward and P. Lafleur for assistance in the field, S. Gardiner for producing the graphics, and C. H. Taylor and an anonymous reviewer for their comments on an earlier draft of this paper.

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First received: 7 September, 1987
Revised version received: 26 November, 1987

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