SNOW ACCUMULATION AND SNOWMELT RUNOFF IN A SUBURBAN ENVIRONMENT

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ABSTRACT

Snowmelt and rain-on-snow events have been largely ignored in urban hydrology, despite the fact that they may result in severe flooding. Measurements of snow accumulation and snowmelt runoff during the spring of 1984 were made for the suburban and rural subcatchments of a small drainage basin in Peterborough, Ontario. In addition, daily and hourly melt rates were estimated based on the energy balance model. Urban development appears to have produced substantial increases in spring runoff yields from the study basin. A comparison of the general melt pattern for the two subcatchments shows that the suburban basin generated larger runoff response ratios than the rural basin as a result of the microclimatic, pedologic and hydraulic characteristics of urban areas. However, the dynamic nature of the runoff contributing area of the rural catchment resulted in a marked increase in its diurnal runoff output as melt progressed, while the daily suburban response declined over time. Therefore the runoff-producing mechanisms in urban areas must be considered when modelling urban snowmelt runoff.

Introduction

Studies of urban hydrology have concentrated on the response of urban catchments to rainfall events, and urban 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 urban areas. Yet in many cities in Canada, the United States and Scandinavia snowmelt runoff forms a significant portion of the annual discharge (Westerström, 1984), 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 the author is aware of work done in Sweden (Bengtsson, 1981a, b, 1983, 1984a, b; Westerström, 1984) and in Canada (Jolly, 1972, 1973; Waller and Coulter, 1974).

The study currently being undertaken by the author seeks to examine the snowmelt process in urban areas, the basic components of which are shown in Figure 1. Such studies would be of importance not only to our ability to forecast flooding in urban areas, but also to efforts to simulate the movement of contaminants such as chlorides from road salting into receiving water bodies. The present paper will restrict its attention to a comparison of patterns of snow accumulation in suburban and rural environments and the general runoff response to snowmelt and rain-on-snow from these two land uses.

Study Area Description and Method

The work is being conducted in the suburban area of Kawartha Heights in Peterborough, Ontario, which consists of a suburban catchment nested within a largely rural watershed that is currently undergoing urbanization (Figure 2). This urbanizing catchment will be referred to as the rural catchment. The entire basin has been undergoing intermittent suburban development since 1974, the hydrological impacts of which have been described by Taylor (1977; 1982) and Taylor and Roth (1979). It lies within the Peterborough drumlin field, with an altitudinal range of 26.3 m. The soils of the area are well-drained Otonabee loams and Bondhead sandy loams, and are underlain by sandy till, although a zone of kame deposits (sand, gravel, minor till) cuts diagonally across the basin from southwest to north-east (Gravenor, 1957). Total mean annual precipitation for the area is more than 760 mm, of which almost 80% falls as rain and just over 20% as snow. Precipitation is spread fairly evenly throughout the year, with the lowest mean monthly receipts occurring in March and the highest in August (Adams, 1985).

General characteristics of the entire drainage basin and the suburban and rural catchments are given in Table 1. The suburban catchment is drained by a storm sewer network (see Figure 9) which empties into a small spring-fed perennial stream. The rural catchment is drained by the downstream portion of this perennial stream as well as by ephemeral tributaries which flow at the wettest times of the year.

Table 1: General land use characteristics, Kawartha Heights

	Drainage area	open fields		forest		urbanized	
	(ha)	ha	%	ha	%	ha	%
Entire basin	96.9	54.6	56.3	6.6	6.8	35.7	36.9
Suburban catchment	33.5	6.1	18.3	2.2	6.4	25.2	75.3
Rural catchment	63.4	48.4	76.4	4.4	7.0	10.5	16.6

Information was collected on snow accumulation and distribution within the suburban and rural catchments prior to the 1984 spring melt. Within the rural catchment 50 and 90 water-equivalent measurements were made using an MSC snow sampler for open and wooded sites respectively. 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.

The energy balance approach (Anderson, 1968) was used to estimate hourly and daily snowmelt fluxes within the two catchments during the 1984 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 according to the procedure outlined by Price and Dunne (1976). Precipitation measurements throughout the melt period were made at the Trent Station and at the Peterborough Airport, 5 km south of the catchments.

Runoff was measured for the suburban catchment (site A - Figure 2) and for the entire basin (site B - Figure 2). The runoff response for the rural catchment was determined by lagging the suburban output by the travel time between sites A and B, and subtracting the suburban hydrograph from that for the entire basin to give the rural hydrograph.

Results

Patterns of snow accumulation

Man redistributes the snow that falls in urban areas, clearing it away from roads, driveways, sideways 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 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 pack evolution in Peterborough does 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 spring melt which consisted of two distinct melt periods, separated by a 15 day cold period with maximum daily temperatures ranging between 1.6°C and -13.2°C. Figure 3 shows the pattern of snow depth over the melt period measured at Peterborough Airport as well as the dates of snow surveys for the study area. Both surveys appear to have coincided with the peak water-equivalent depths over the study area. Table 2 presents a summary of the peak water-equivalent values for the component surface types while Figure 4 illustrates the variability in point values for both surveys.

Table 2: Summary of peak water-equivalent values

		Surface Type				
Survey		Open	Woods	Front Yards	Back Yards	Driveway Snowbanks
3/2/84	$\bar{x}$(cm)	11.96	10.93	11.31	12.28	24.05
	S.D.(cm)	3.56	2.56	3.05	2.82	6.02
	CV%	29.77	23.42	26.97	22.96	25.03
14/3/84	$\bar{x}$(cm)	5.46	8.27	2.18	2.38	5.47
	S.D.(cm)	4.27	3.31	1.24	1.55	1.92
	CV%	78.21	40.02	56.88	65.13	35.10

Prior to the first melt period, there were roughly equal water-equivalents on all the surface types except the driveway snowbanks. The variability of the point water-equivalents over a surface type was roughly similar, as indicated by the coefficient of variation values. 78% of the suburban catchment was snow covered while 77% of the rural catchment was covered by snow prior to melt. Weighted mean water-equivalents for the suburban and rural catchments were 11.06 cm and 9.29 cm respectively.

Spatial distribution of water-equivalents at the start of the second melt showed a marked contrast from those of the first survey. Greatest depths were found in the woods, as a result of residual snow remaining from the first melt period and intense drifting during early March following snow accumulation. In addition, the variability of the water-equivalent depths was much greater for some surface types than for others. The proportion of each catchment that was covered by snow prior to melt was the same as for the first melt period. However, the mean water-equivalent depth was greater for the rural catchment than for the suburban, being 4.38 cm and 3.87 cm respectively.

Snowmelt Runoff for the 1984 Spring Melt

The runoff response during the two melt periods for the suburban and rural catchments as well as the entire drainage basin is shown in Figure 5. The figure also indicates the type, amounts and duration of precipitation during the melt, as well as the hourly melt rates computed from the energy balance approach and meteorological observations made at the Trent University Weather Station. Due to loss of snow under the albedometer and net radiometer at the Weather Station following March 25 it was not possible to estimate surface snowmelt rates reliably after this date.

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 $.0055\ \ell\ s^{-1}\ ha^{-1}\ h^{-1}$. 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.

The effect of urban development upon seasonal runoff yield

Table 3 is adapted from Taylor (1982) and summarizes the spring, summer and fall quickflow responses for rainstorm, snowmelt and rain-on-snow events for the entire Kawartha Heights basin. The spring response for 1984 has also been included. The values for 1973 and 1974 were obtained prior to urban development of the catchment. While there is considerable evidence from the literature that suggests that urban development should lead to an increase in quickflow response in all seasons, such a change only appears to have occurred for the spring melt.

Table 3: Precipitation and quickflow summary for spring, summer and fall seasons in the Kawartha Heights watershed, 1973-1984.

Season	Peak Snowpack Water Equivalent (mm)	Rain & Snow During Period (mm)	Total Available Precip- itation (mm)	Total Quickflow (mm)	Quickflow Response Ratio (%)
SPRING 1974	69.0	41.2	110.2	6.5	5.9
SPRING 1977	81.4	48.4	129.8	28.6	22.0
SPRING 1978	159.2	31.8	191.0	32.0	16.8
*SPRING 1984	98.9	173.0	271.9	46.3	17.0
SUMMER 1974		132.8	132.8	6.6	5.0
SUMMER 1975		174.5	174.5	10.9	6.2
SUMMER 1976		188.0	188.0	8.7	4.6
SUMMER 1977		265.2	265.2	15.7	5.9
FALL 1973		147.5	147.5	10.5	7.1
FALL 1975		70.1	70.1	3.4	4.9
FALL 1976		107.5	107.5	3.0	2.8
FALL 1977		158.7	158.7	10.4	6.6

Taylor (1982) noted that soils of areas that underwent construction between 1975 and 1978 suffered substantial reductions in their infiltration capacities. While these areas failed to generate runoff under all but the most intense rainfalls, the large volumes of water released by snowmelt served to raise water table levels, saturate these disturbed soils, and integrate them into the active channel network allowing them to generate increased quickflow volumes from relatively low-intensity snowmelt and rain-on-snow events. The 1984 results demonstrate that the influence of urbanization upon increasing spring quickflow yields extends into the fully developed phase following construction.

Runoff production in suburban and rural environments

The differences between suburban and rural responses to snowmelt are further demonstrated by Figures 5 and 6 and Table 4, which summarizes the runoff response for the entire basin and the suburban and rural catchments for the entire spring and the first and second melt periods.

The suburban catchment has higher total runoff responses and quickflow runoff response ratios for both melt periods. However, this larger response is not consistent over time, as the hydrographs indicate that the increased suburban response to snowmelt and rain-on-snow events is most pronounced at the beginning of both melt periods. During the first melt period 50% of the total runoff generated occurred within the first 14% of the melt duration for the suburban catchment and within the first 40% of the melt duration for the rural catchment. For the second melt period, half of the total runoff left the suburban basin after 40% of the melt period had passed, while over 71% of the melt duration had passed before the rural catchment generated half of its total runoff yield.

Figure 6 shows the time lag between peak melt intensity and peak runoff for both catchments during the first melt period. Following the large rain-on-snow event on February 13, the time lag for the suburban catchment was quickly reduced, fluctuating between 0 and 2.5 hours for the remainder of the melt. The time lags for the suburban catchment were always less than those for the rural catchment, and were comparable to those observed for short hillside plots of varying slope angles and underlain by frozen ground

(Dunne et al., 1976).

Table 4: Precipitation, total runoff and quickflow summary for the entire basin and the suburban and rural catchments, Spring 1984.

	Total available precipitation (mm)	Total runoff (mm)	Total runoff response (%)	Quick-flow (mm)	Quickflow response ratio (%)
Spring 1984					
Entire catchment	271.9	101.5	37.3	46.3	17.0
Suburban catchment	280.3	159.9	57.1	68.7	24.5
Rural catchment	267.7	72.3	27.0	45.1	16.9
1st melt period (13/2/84-27/2/84)					
Entire catchment	147.7	41.5	28.1	19.6	13.3
Suburban catchment	159.4	76.5	48.0	37.9	23.8
Rural catchment	141.7	23.8	16.8	13.5	9.5
2nd melt period (14/3/84-9/4/84)					
Entire catchment	124.2	60.0	48.3	26.7	21.5
Suburban catchment	120.9	83.4	69.0	30.8	25.5
Rural catchment	126.0	48.5	38.5	31.6	25.1

There are a number of factors which appear to account for the suburban catchment's response to snowmelt and rain-on-snow events. These can be resolved into the microclimatic, pedologic and hydraulic characteristics of urban areas.

Temperatures in urban areas tend to be higher than in surrounding rural areas (Oke, 1978). Buildings and snow-free areas in cities absorb incoming radiation and emit long-wave radiation, some of which is absorbed by snow covered surfaces, thus increasing their net radiation gain. These snow surfaces are dirtier and have lower albedos than in rural areas, and tend to absorb more solar radiation. 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. All these factors suggest that urban areas will experience higher melt rates. Bengtsson (1981b) estimated that snowmelt intensity in a city can be 20-30 mm d^{-1} higher than outside the city, although this increase would be much less pronounced at the urban-rural fringe.

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. Figure 7 shows the ranges in infiltration capacities for surface types in the Kawartha Heights basin, as well as the range in calculated melt rates based on the energy balance. For the open fields and wooded areas in the rural catchment, the rate of melt was less than the infiltration capacity, and such surfaces will not generate Hortonian overland flow. In the suburban catchment the rate of melt exceeded the infiltration capacities of some of the lawns, leading to the production of Hortonian runoff.

The third factor that contributes to the larger and quicker response of the suburban catchment is the greater hydraulic efficiency of urban basins relative to rural catchments. Assuming Darcian flow along the base of a snowpack, Bengtsson (1984b) estimated times of concentration for a 20 m and a 200 m slope with a 2% grade. Taking the hydraulic conductivity of the snow to be 0.1 m s^{-1}, he arrived at times of concentration of 2 and 20 hours respectively. Since the lawns in the suburban catchment are 10-30 m in length, any Hortonian overland flow generated by these surfaces quickly reaches adjacent roadside gutters, sidewalks and driveways. These surfaces rapidly translate this input to the storm sewer system, contributing to the short time lags between peak melt and peak runoff observed in Figure 6.

Returning to Table 4, it can be seen that whereas the quickflow response ratio for the suburban catchment greatly exceeds that from the rural catchment for the first melt period, the responses are equal for the second melt period. One possible reason for this increased rural response is the presence of concrete frost in the rural soils prior to the second melt. Saturated soils may have frozen during the period of low temperatures and thin snow cover that followed the first melt period. Since concrete frost leads to a great reduction in infiltration capacity (Dunne and Black, 1971), these soils would then generate Hortonian overland flow when melt commenced. However, this answer is not entirely satisfactory. As Figure 5 shows, the rural response to snowmelt is smaller than the suburban response at the beginning of each melt period. The daily discharge from the rural catchment equals and then exceeds the suburban response only towards the end of the melt, by which time higher temperatures and the latent heat released by refreezing meltwater may have thawed the soil.

A more plausible explanation relates to basic mechanisms of runoff production and touches on a central issue in hydrology - the contribution of groundwater flow to peak streamflow. Bengtsson (1982) addressed this question when he noted the different character 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 on 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 snowmelt runoff is largely generated by overland flow.

This overland flow can be produced by two distinct mechanisms. The first is that of Hortonian overland flow, where the delivery rate of meltwater to the base of the snowpack exceeds the infiltration capacity of the soil. As Figure 7 shows, peak melt rates are less than infiltration capacities for soils in the rural catchment, and the reduction of infiltration rates by concrete frost does not appear to be a significant factor. This suggests that little runoff in the rural catchment is generated as Hortonian overland flow.

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., 1978). Water falling on these saturated areas, combined with subsurface contributions ("return flow") has been termed "saturation overland flow."

Figure 8 shows the seasonal changes in the stream network geometry and the extent of saturated areas in the Kawartha Heights catchments. In late summer (Figure 8a) the rural network is at its most contracted, with a drainage density of 0.88 km km^{-2} and saturated areas occupying 0.6% of the rural catchment's area. At the end of spring melt the drainage network reaches its maximum extent, with drainage densities reaching 5.14 km km^{-2} and saturated areas covering up to 38% of the rural basin (Figure 8b). Many of these saturated areas coincide with portions of the rural catchment that were compacted by heavy machinery during the construction activity noted by Taylor (1982). The drainage system of gutters and sewers in the suburban catchment remains consistent in extent during and between the two melt periods. Some saturated areas develop in the woods in the suburban basin which might account for the increase in total runoff response between the two melt periods (Table 4). However, the greatly increased saturated area and expanded drainage network in the rural basin increases its hydraulic efficiency and accounts for the progressive decrease in time lag between peak melt and peak runoff during the first melt period (Figure 6), the increase in the size of the daily rural runoff response as melt proceeds, and the larger quickflow response ratio for the second melt period (Table 4).

The importance of overland flow to peak streamflow observed from the two catchments is highlighted by the rainfall event of April 4-7, in which 39.0 mm of rain fell at the end of the snowmelt period. The suburban catchment was bare of snow, and had a quickflow response ratio of 18.6%. Since impervious surfaces (roads, sidewalks and driveways) comprise only 13.2% of the suburban catchment, substantial runoff contributions from lawns must have occurred. This supports Westerström's (1984) contention that rain-on-snow and rainfall events during the period immediately following disappearance of the snow cover can produce more runoff than summer rainfalls, since the runoff contributing area can expand to include those saturated pervious areas that tend not to generate flow under summer storm conditions. The rural response, however, was dominated by the generation of saturation overland flow. 41.7% of the rainfall left as quickflow, which corresponds well with the maximum potential extent of saturation of 38% of the basin area.

Conclusions

An examination of snow accumulation and snowmelt runoff from a suburban and a rural catchment in Peterborough, Ontario, has shown that suburbanization may have significant effects on the snowmelt runoff process. Urban development was shown to increase spring runoff yields over those observed prior to construction activity in the basin, as a result of the saturation of disturbed soils by the large melt volumes generated and the production of runoff from relatively low intensity snowmelt and rain-on-snow events. However, construction activity in the basin did not appear to generate significant changes in the response to summer and fall rainstorms.

Distinct differences were detected in the runoff response from the suburban catchment relative to the pattern of flow from the rural basin. As a result of microclimatic, pedologic and hydraulic characteristics of urban areas, the suburban catchment produced a larger quickflow response ratio than that from the rural catchment for the 1984 melt, with a short (0-2.5 hour) time lag between the diurnal melt and runoff cycles. The runoff from the suburban basin was generated by Hortonian overland flow, as the observed melt intensities exceeded the infiltration capacities of some of the lawns in the basin. The total runoff response increased from the first to second melt periods, while the quickflow response ratios for the two melt periods were relatively constant. This implies that the spatially-fixed nature of the gutters and sewers of the suburban catchment dampens fluctuations in its quickflow response.

Conversely, the quickflow response for the rural catchment was observed to increase from the first to second melt periods, and the diurnal runoff output increased through the course of each melt period. Initial snowmelt was not translated into runoff, but served to recharge shallow aquifers and elevate water table levels which progressively saturated large areas of the catchment. These saturated areas, amounting to up to 38% of the catchment area, transformed meltwater to saturation overland flow, which was quickly removed from the catchment by the expanded drainage network, particularly during the second melt period.

Increasingly, flood forecasts for urban areas in northern environments will have to come to grips with the snowmelt process. The simple transposition of models intended for rural environments can only be a first approximation when simulating and predicting urban snowmelt runoff. As a result, any real progress must hinge on the recognition of the ways in which urban development affects a catchment's response to snowmelt and rain-on-snow events.

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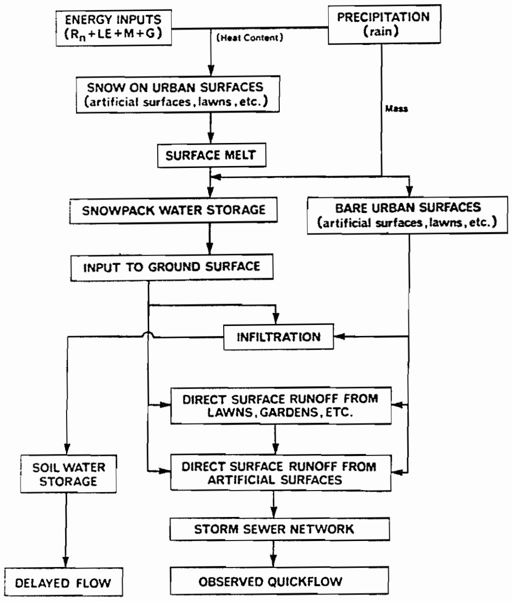


Figure 1: Snowmelt water pathways within urban areas

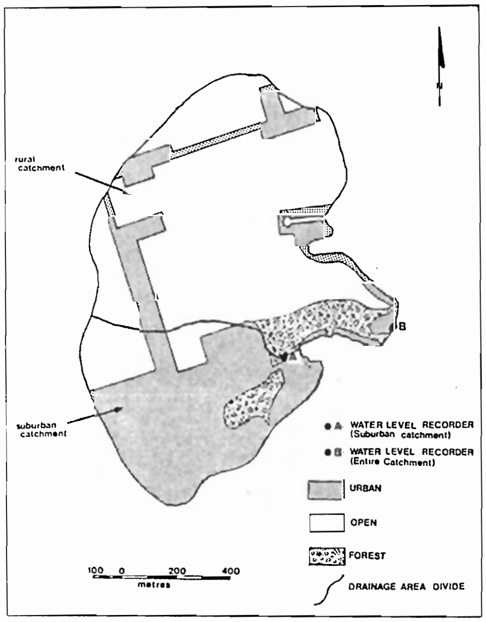


Figure 2: The Kawartha Heights watershed: land uses in the suburban and rural (urbanizing) catchments

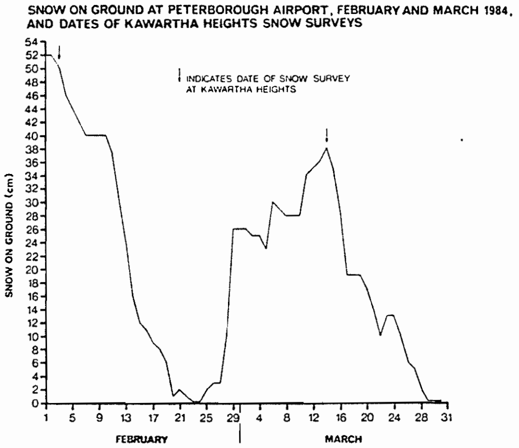
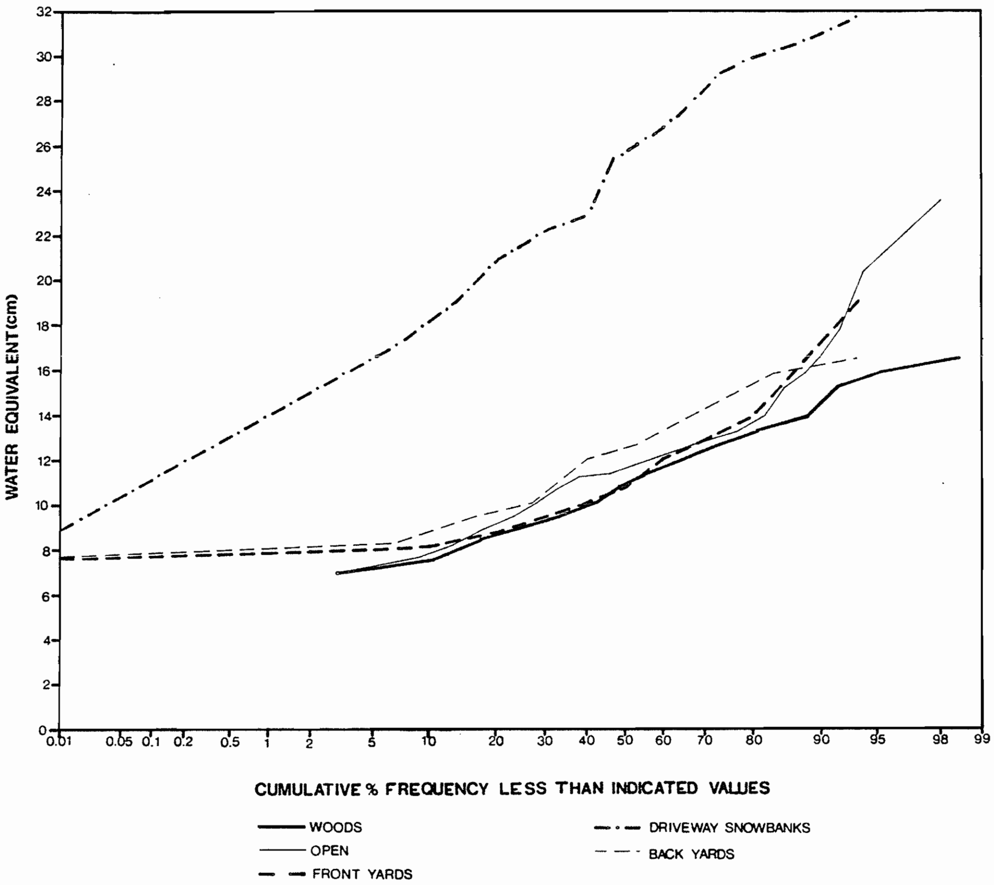


Figure 3: Depth of snow on ground, Peterborough Airport, Spring 1984, and dates of Kawartha Heights snow surveys

SNOW SURVEY 3/2/84



SNOW SURVEY 14/3/84

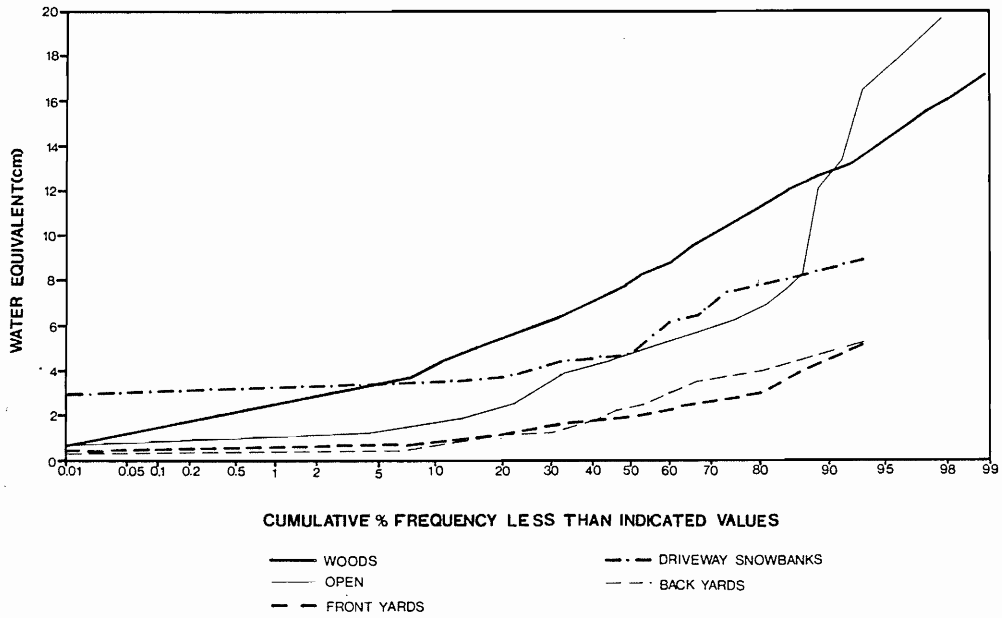


Figure 4: Cumulative frequency curves of water-equivalent depths for surface types in the Kawartha Heights watershed, Spring 1984.

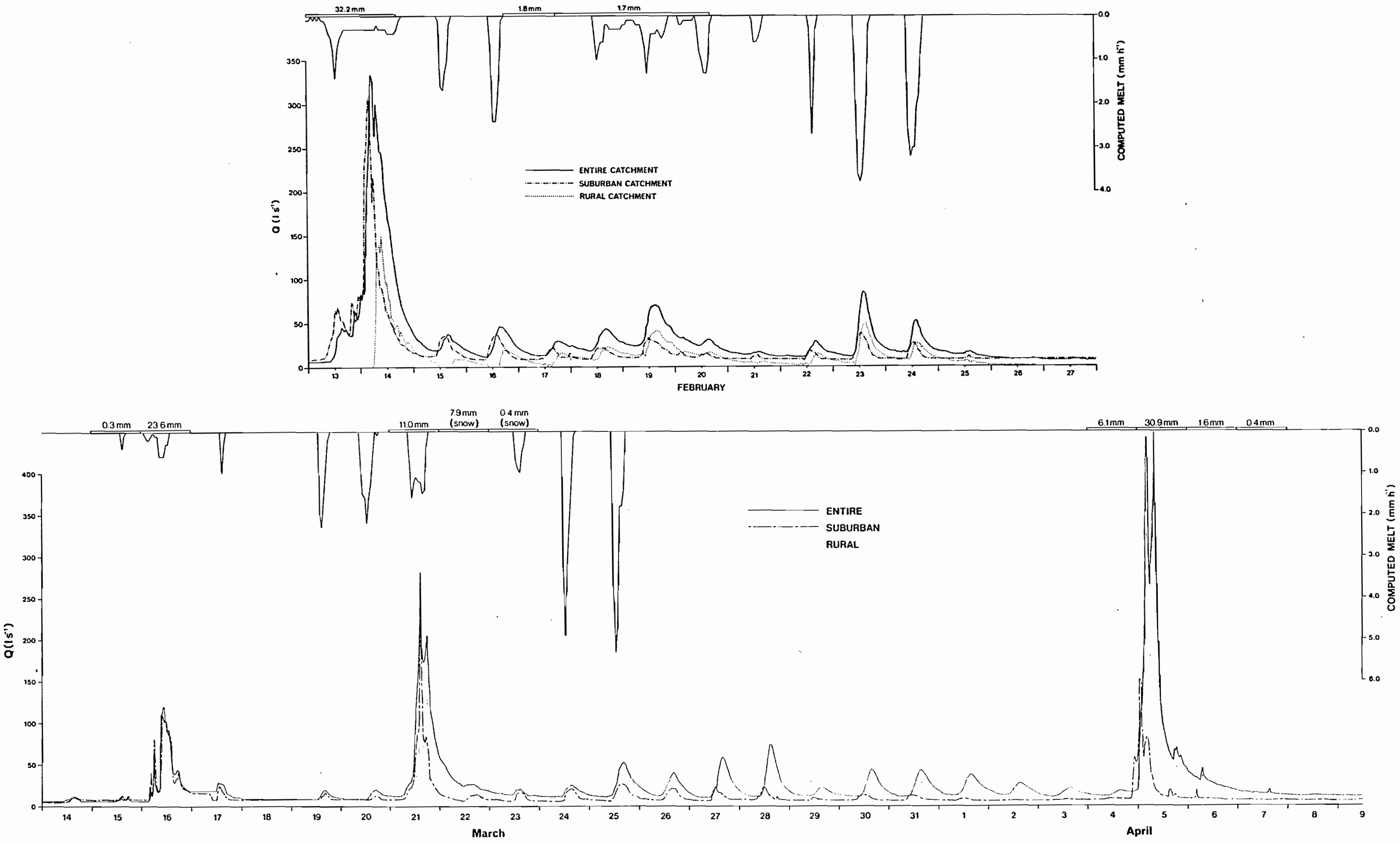


Figure 5: Precipitation, computed melt and runoff for the entire basin and suburban and rural catchments, Kawartha Heights, Spring 1984. Precipitation depths are given at the top of each hydrograph. All precipitation is as rainfall unless otherwise indicated. Duration of the precipitation event is indicated by the length of the bar.

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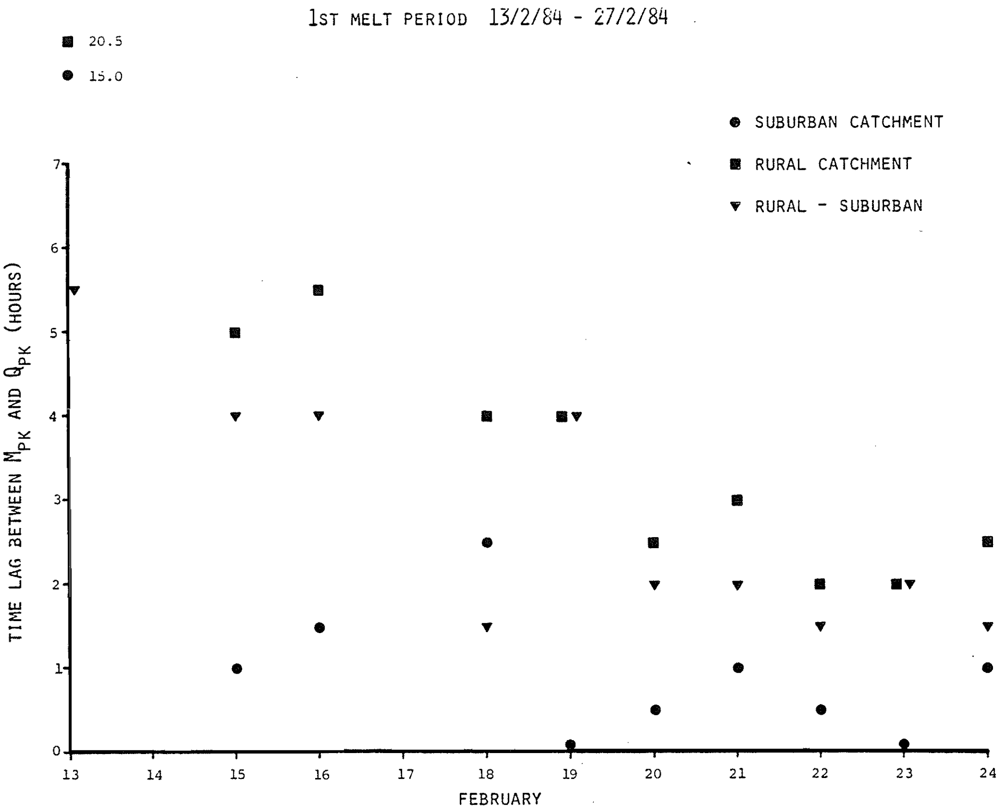

Figure 6: Time lag between peak melt intensity (Mpk) and peak discharge (Qpk) for the suburban and rural catchments, 1st melt period. The trend in the difference between the rural time lag and the suburban time lag is also shown.

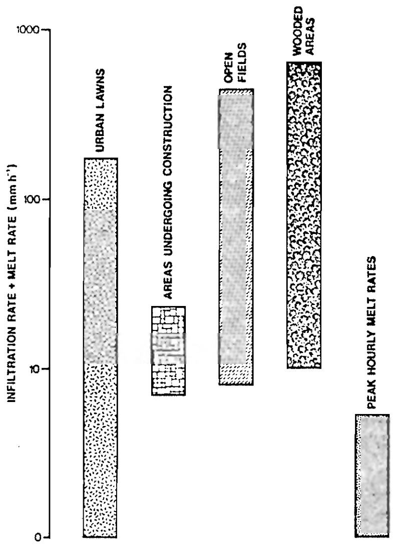

Figure 7: Ranges in infiltration capacities for surface types in the Kawartha Heights watershed, and the range in computed peak hourly melt rates, Spring 1984.

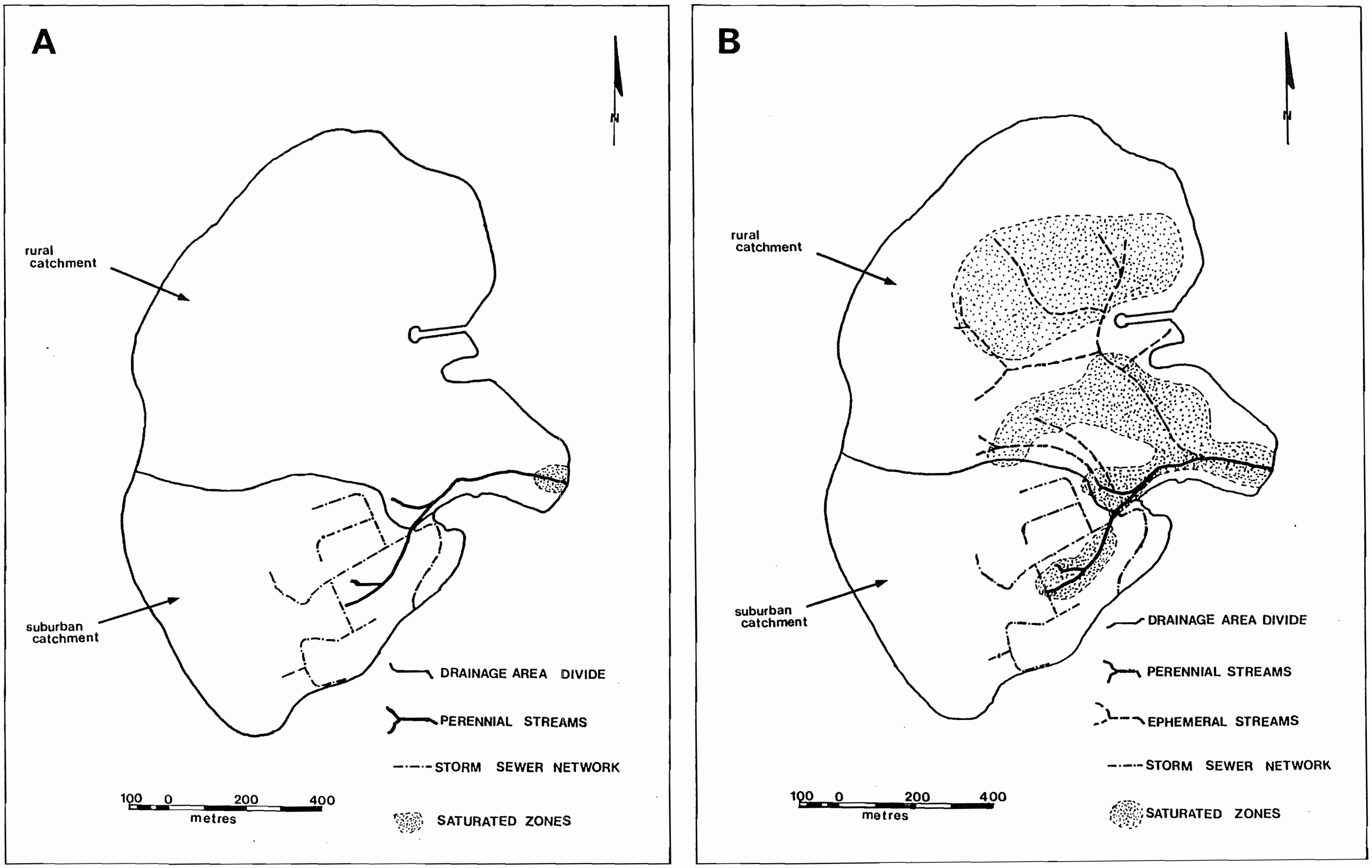

Figure 8: Stream network geometry and potential runoff contributing areas in the Kawartha Heights watershed: (a) Summer, (b) Spring.