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The Effect on Storm Runoff Response of Seasonal Variations in Contributing Zones in Small Watersheds

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Storm runoff production by saturation overland flow has been studied in two small watersheds in south-central Ontario. One is in rural land use and contains a wetland. The total saturated zone is at its maximum extent during spring snowmelt, when the overwhelming majority of total runoff and quickflow is produced. The stream seldom flows during the summer and winter seasons but does so occasionally in the fall if the wetland is recharged sufficiently. Simple calculations show that storm-to-storm variations in quickflow response are controlled by the extent of surface soil saturation (measured by field mapping and correlated with antecedent wetness variables) and precipitation amount. The other watershed has been undergoing suburban development since 1973. Quickflow response during summer and fall seasons has not changed noticeably since then, although 30% of the watershed surface has been disturbed. This is because in those seasons quickflow is still produced as saturation overland flow from the original contributing zones alongside the stream. In contrast, during spring snowmelt the very wet soil conditions and a high water table allow the disturbed surfaces with low infiltration capacities to be integrated into the contributing area via normally dry drainage lines. As a result spring quickflow has increased by three to four times over the original values.

Introduction

This paper reports results from the study of runoff processes in two small watersheds near Peterborough in south-central Ontario. In both, quickflow is produced primarily as saturation overland flow from contributing areas which fluctuate in size on a seasonal basis and between and within precipitation events, including snowmelt and rain-on-snow events as well as rainstorms. One watershed is in rural land use, the other has been partially affected by suburban development activity.

The mechanism of saturation overland flow, which has become accepted as the basic storm runoff model for many humid environments, has been well described by Dunne and Black (1970), Dunne et al. (1975), Dunne (1978) and Freeze (1974). Saturation overland flow consists largely of precipitation falling directly on to saturated surfaces in valley floors and on the lower parts of hillslopes. These saturated surfaces fluctuate in size in response to changes in water table elevations near the channels.

One of the study watersheds drains an ephemeral swamp, and in this respect is fairly typical of headwater drainage systems in the region. The effects of wetlands on storm runoff generation do not appear to have received a lot of attention in the literature. However, Bay (1967, 1969), Verry and Boelter (1975) and Boelter and Verry (1977) working on forested bog watersheds in northern Minnesota, O'Brien (1977) comparing two small wetland basins in eastern Massachusetts and Balek and Perry (1973) studying headwater swamps in tropical Africa, have all described the extreme seasonality of their runoff regimes. When water levels are high, considerable quickflow can be produced, but during the dry seasons when water levels are low, there may be no response at all. Although none of these authors looked at runoff response behaviour in detail, it seems probable that storm-to-storm variations in quickflow response of at least some wetlands can be explained using the variable-source-area saturation overland model as a framework.

The other study watershed has been undergoing suburban development. The effects of urban or suburban development on the runoff response of watersheds are well documented in the literature, as summarized by Leopold (1968) and Hollis (1975). The paving over of previously permeable surfaces and the replacement of natural channel systems by artificial sewers and ditches, generally causes substantial increases in runoff peaks and volumes and a decrease in lag times. The magnitude of these effects has been found to vary seasonally in some watersheds (James 1965, Gregory 1974, Hollis 1975, Taylor 1977, Taylor and Roth 1979). Taylor and Roth (1979) found that in the watershed described in this paper, quickflow volumes and peak discharges were much more strongly affected by the development under spring snowmelt conditions than at other times of the year. The reasons underlying this are explored further in this paper.

The Study Watersheds

The bedrock of the region is Ordovician limestone overlain by Pleistocene glacial till. The major landforms are drumlins, which are elongated hills up to 1.5 km in length and 30 m in height, composed of unconsolidated permeable sandy till, and

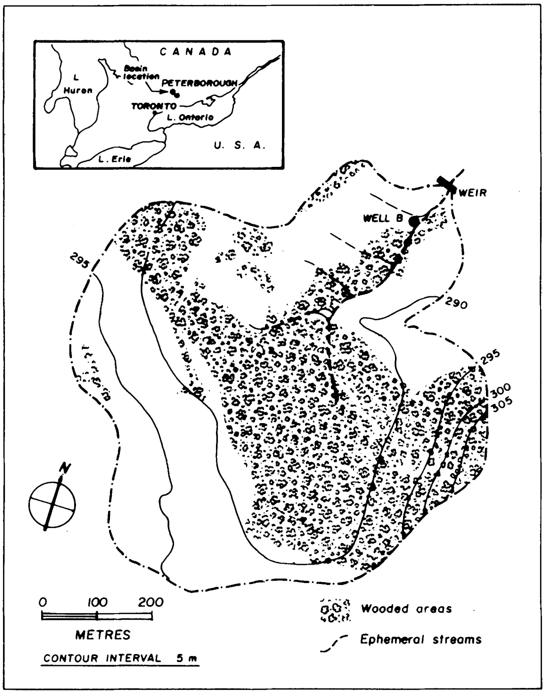


Fig. 1. The Telford Watershed.

separated by poorly drained inter-drumlin swales and former glacial lake beds and spillways. These low-lying areas are commonly occupied by wetlands which fluctuate in size in response to seasonal variations in precipitation types and amounts, temperatures and evapotranspiration rates. These wetlands supply most of the storm runoff (quickflow) to headwater streams. Mean annual precipitation in the region is 780 mm, fairly evenly distributed throughout the year. Snow lies on the ground from late November to early March, and the spring snowmelt period generally provides the highest flows of the year, particularly when rainstorms supplement the snowmelt. The mean annual temperature for Peterborough is 6°C, with a range in mean monthly temperature from 20°C in July to −10°C in January (Adams 1978).

The Telford Watershed

The Telford watershed (Fig. 1) is 0.47 km^2 in area and is in rural land use with 50% in forest (mainly white cedar and sugar maple, with some pine, oak, elm and ash), 35% in pasture, and 15% in cultivated fields. Slopes throughout the watershed are very gentle, averaging less than 3° except along a drumlin which forms the southern drainage divide, with a slope of approximately 8°. The central portion of the watershed is very flat, and is occupied by an ephemeral swamp, which is an example of the perched type described by Bay (1967). Bedrock is within 2 m of the surface in the lower parts of the watershed. Soils outside the swamp are Otonabee Loams (loams and sandy loams) with minimum infiltration capacities (measured with infiltration rings) ranging from 115 mm/hr in stony compacted pasture areas to 950 mm/hr nearer the swamp. Within the seasonally inundated swamp area the soils are largely organic muck and peat. When not under water these soils have infiltration capacities up to 400 mm/hr.

Outflow is measured at a 90° V notch weir equipped with a Belfort water level recorder. Rainfall is measured with a siphoning recording rain gauge and a network of manual gauges. Water equivalent in the snowpack is measured with a Mount Rose snow tube along a snow course previous to, and at intervals during, the melt period. Ground water levels are measured with a network of shallow wells, some equipped with recorders, and the spatial extent of the saturated zone has been measured by field mapping a number of times, using the techniques recommended by Dunne et al. (1975). This involves walking over the watershed marking the edge of the saturated zone on a large scale base map. This can be done quite rapidly by pacing distances relative to reference points shown on the map. Soil moisture patterns and interception processes under a variety of vegetation covers within the watershed have been previously described by Szudy (1976), Sewell (1979) and Mathers (1979).

The Kawartha Heights Watershed

The Kawartha Heights watershed (0.97 km^2) is located on the western periphery of Peterborough (population 59,000), and is also characterized by gentle gradients on permeable glacial till. In 1973 the watershed was 89% in pasture and 11% wooded, but since 1974 it has been slowly modified by suburban development (Fig. 2).

Previous to the start of development, the watershed was drained by a perennial spring-fed stream with ephemeral tributaries, and quickflow was generated as saturation overland flow from a small saturated zone alongside the channel. This zone fluctuated in size on a seasonal basis and between and within storms, but seldom amounted to more than 7% of the total watershed area. High infiltration capacities, in the range of 150-250 mm/hr, and gentle slopes minimized runoff contributions from surfaces outside this zone. The construction activity for the new subdivision gradually increased the potential quickflow contributing zone (Figs. 2b, c and d). By 1977, 9% of the surface area had been paved and a further 22% had had its permeability considerably reduced. Paved surfaces and rooftops are impervious and field tests with infiltration rings and a hand portable sprinkling infiltrometer have shown that surfaces stripped bare of top soil and compacted by heavy machinery had infiltration capacities between 0 and 34 mm/hr and could be considered impervious to moderate and heavy precipitation. It can be seen there-

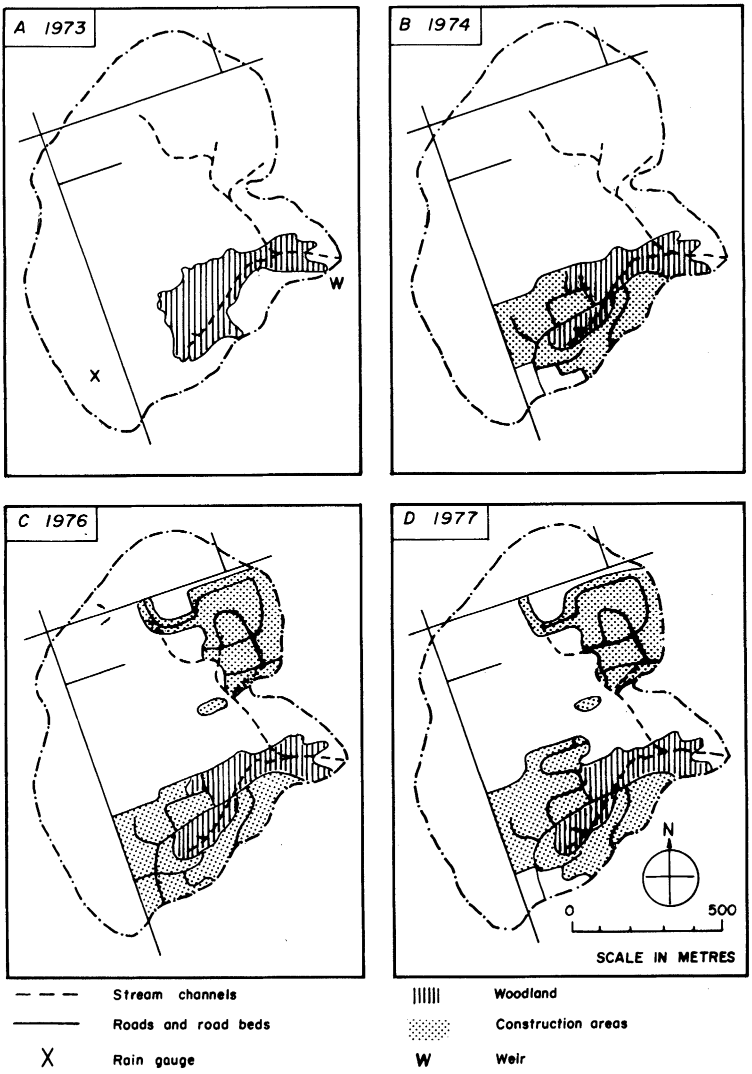


Fig. 2. The Kawartha Heights watershed: land use changes, 1973-1977.

fore, that the potential quickflow contributing area in the Kawartha Heights watershed grew from 7% to approximately 30% between 1973 and 1977.

Discharge from this watershed is measured at a three ft rectangular weir, while rainfall inputs are measured with a tipping-bucket raingauge. Snowmelt inputs have been estimated from random surveys with snow tubes previous to the onset of the melt season (Roth 1979).

The Seasonal Runoff Regime

In both watersheds the quickflow response pattern can be broken down neatly on a seasonal basis. Seasons are differentiated on the basis of runoff behaviour rather than set calendar dates. The winter season runs from the time of freeze-up when a persistent snow cover is established and surface runoff to the streams ceases. This generally occurs between mid-November and early December. The winter season ends and the spring season begins with the first substantial rise in streamflow from snowmelt, generally in late February or early March. The spring includes a number of snowmelt and rain-on-snow events. In the Telford watershed the summer is defined as starting when outflow from the swamp ceases. In each of the three study years this happened within the first three weeks of May. In the Kawartha Heights watershed the summer season is defined as starting immediately after the last discharge peak which could be clearly identified with a snowmelt input, which tends to occur somewhat earlier than in the Telford watershed where the more extensive forest cover preserves the snowpack longer. Because of the difference in definitions, the spring season includes some events from rainfall alone in the Telford watershed, but not in the other. The summer season of course experiences the highest evapotranspiration rates, and although June, July and August commonly receive as much precipitation as other months, the runoff response is minimal. The summer season ends and the fall season begins with the first substantial rise in streamflow after the end of September which occurs because lowered evapotranspiration rates have allowed a rise in water table elevations and an increase in the extent of saturated contributing zones. Because of the large available storage capacity normally available in the Telford watershed at the end of the summer, its stream only flows on average once every three years in the fall months.

To investigate quickflow response behaviour, hydrographs have been separated using the Hewlett and Hibbert (1967) method with a separation line of .0055 l/sec/ha/hr. Quickflow response ratios are used as indices of runoff behaviour. They are calculated by expressing quickflow depth as a percentage of precipitation input (rainfall and/or snowmelt) for individual events. To compare seasonal patterns, the quickflow response ratios are calculated from total quickflow and total precipitation inputs for the time periods as previously defined.

Runoff Response in the Rural Watershed

Measurements were made in the Telford watershed from December 1975 to December 1978. Table 1 summarizes the hydrological budgets for the three years 1975-76 to 1977-78, running from December 1 to November 30 in each case. As will be shown below, the overwhelming majority of runoff emerged during the

Table 1 – Annual water budgets for the rural watershed, 1975-76 to 1977-78

Year	Snowfall water equivalent (mm)	Rainfall (mm)	Total Precipitation (mm)	Total Runoff (mm)	Runoff Response (%)
1975-76	298	603	901	316	35.1
1976-77	167	663	830	151	18.2
1977-78	188	629	817	232	28.4

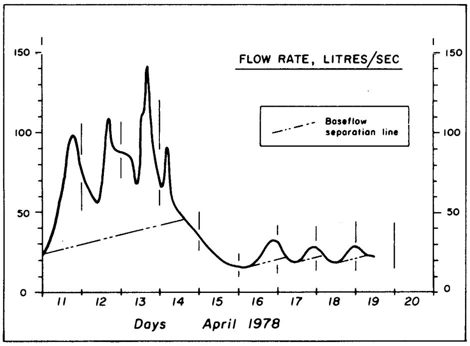
spring seasons as defined earlier, and only in one fall season, 1977, did any runoff occur. As a result of the ephemeral nature of the runoff, total annual volumes were low, amounting to only 35%, 18% and 28% of total precipitation in the three years. This is considerably less than the estimate of 45% for mean annual runoff response derived by Taylor (1975) for a 105 km^2 watershed in the same region.

Table 2 summarizes the runoff characteristics of the seasons when runoff did occur. For the spring periods, the snowpack water equivalents were calculated from a snow survey made immediately prior to the melt period, and are combined with any snowfall and rainfall between that date and when the stream stopped flowing, to derive the estimate of total precipitation available for runoff. Runoff response is expressed for both quickflow and total runoff. Total runoff response ranged between 57% and 88%, with quickflow responses of 22% to 34%, amounting to between 25% and 44% of total runoff. For individual events, quickflow responses as high as 80% were recorded.

The total runoff response of the fall season for 1977, 34%, is somewhat less than those of the spring seasons, however the greatest contrast is in terms of quickflow response. The quickflow response for the fall period was 3%, accounting for only

Table 2 – Runoff for seasons which experienced flow in the rural watershed

Season	Peak snow-pack water equi-valent (mm)	Rain & snow during period (mm)	Total avail-able precipi-tation (mm)	Quick-flow (mm)	Quick-flow respon-se ratio (%)	Total runoff (mm)	Total runoff respon-se (%)
Spring 1976	184.4	222.3	406.7	137.4	33.8	316	77.7
Spring 1977	110.3	89.1	199.4	46.5	23.3	113.4	56.9
Spring 1978	131.0	132.5	263.5	57.4	21.8	231.9	88.0
Fall 1977	–	112.6	112.6	3.33	2.96	37.8	33.6



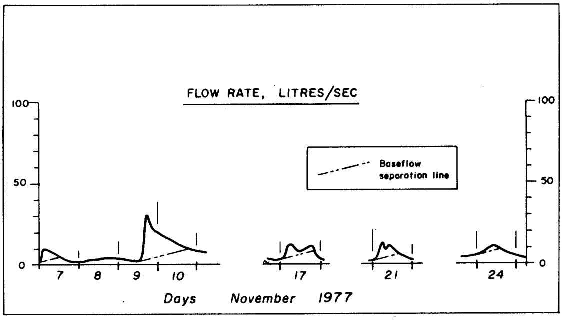


Fig. 3. Examples of outflow hydrographs for the Telford watershed.

Upper: part of the spring period, 1978.

Lower: part of the fall period, 1977.

9% of the total runoff. Although there is only one season of data, there is a strong suggestion that quickflow relative to delayed flow is much less important in the fall compared with the spring. Fig. 3 shows the outflow hydrographs for portions of the spring runoff period in 1978 (a) and the fall season in 1977 (b). The large peaks between April 11th and 14th, 1978, were caused by rain-on-snow, while the smaller peaks on April 16th, 17th and 18th were caused by snowmelt alone. The peaks in the fall of 1977 are more isolated and comprise a much smaller proportion of the total runoff during this season.

In an attempt to develop a better understanding of factors which control variations in quickflow response on an event-to-event basis, a simple predictive model was developed. Assuming that saturation overland flow is the dominant runoff mechanism in this watershed, it should be possible to estimate quickflow volume roughly as the product of precipitation depth and the area of surface saturation, allowing for losses (especially by evapotranspiration) and expansion of the saturated contributing area during an event. This is basically the approach used by Dickinson and Whiteley (1970) in their study of Blue Springs Creek, Ontario.

As pointed out by Dunne et al. (1975), although direct mapping of the saturated zone is the most accurate and desirable way of obtaining data on the extent of saturation, this is rarely possible on a routine basis. They suggest instead the use

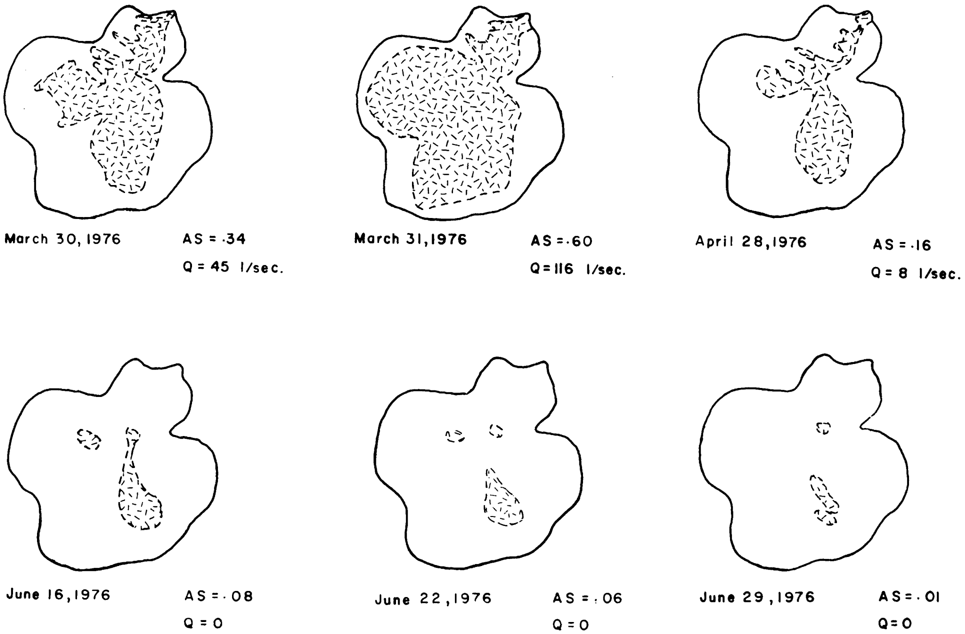


Fig. 4. Selected maps of the surveyed saturated area, Telford watershed.

of surrogate measures of antecedent wetness for which a statistical relationship can be established with surveyed saturated area. A total of 19 maps were prepared by field survey. Fig. 4 shows some examples from 1976 which illustrate how the saturated zone shrank over a three month period. A proportion of the total watershed area which was saturated, measured from such maps, was correlated with discharge, water table elevation (measured at Well B shown in Fig. 1) and an antecedent precipitation index (calculated from the equation suggested by Dunne et al. (1975), using $k = .92$). The relationships are shown in Fig. 5. Although all are statistically significant, the best is that with discharge

$$AS = .155 + .00339\,Q \qquad (r = .967, \quad p = .001)$$

where $AS \equiv$ fraction of the watershed saturated and Q = discharge, 1/sec.

It is possible to use this equation to provide an estimate of the size of the contributing area at any time by substituting the discharge value for that time into the equation. The derived value for the contributing area (as a proportion of total catchment area) can then be multiplied by the depth of precipitation for an event (rainfall and/or snowmelt) to provide an estimate of the quickflow produced as saturation overland flow for that event.

This was done for 27 events (21 caused by rainfall alone and six by snowmelt or

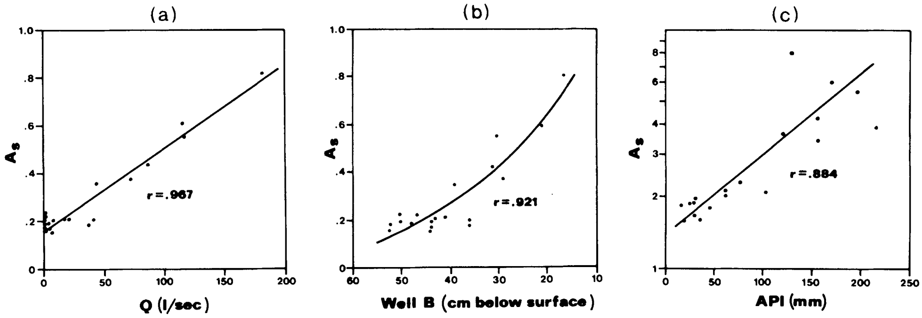


Fig. 5. Relationships of surveyed saturated area (AS, as a fraction of total watershed area), with streamflow (a), water table elevation (b), and antecedent precipitation index (c).

rain-on-snow). Only in 1977 were sufficient snow surveys done during snowmelt to enable the isolation of separate events. The basic data for these events are given in Table 3. When all 27 points are considered together and the discharge at the start of each event is used to estimate saturated areas, the model provides a statistically significant correlation with measured quickflow (line a in Fig. 6, $r = .681$, $p = .001$). However this line is strongly affected by the large rain-on-snow event of March 12-16, 1977. If this point is eliminated the correlation drops below the .05 level of significance. If the events are separated by type and season a much improved relationship emerges for post-snowmelt spring rainstorms, line b in Fig. 6 ($r = .810$, $n = 15$, $p = .001$). When the six fall rainstorms are considered separately they plot well below the line for the spring storms, but do not produce a significant correlation. Although the sample size is very small, this illustrates again the apparent distinction between the quickflow responses of fall and spring events. Smaller volumes of quickflow are generated by similar rainstorms on similar sized saturated areas in the fall compared with the spring. It is possible that higher evaporation rates in the fall, and denser vegetation cover and greater amounts of litter accumulation acting to increase interception loss and retard flow over the wetland surface, would result in smaller volumes of quickflow being generated by similar rainstorms on similar sized saturated areas when compared with the spring. When snowmelt and rain-on-snow events are considered separately in Fig. 6 they also show no clear trend, especially if the largest event is ignored. In the case of these events the flow through the swamp is often impeded by snow and ice which distorts the pattern of quickflow production and measured quickflow over a given time period cannot be so clearly linked to precipitation inputs over the same period.

Another fact shown by Fig. 6 is that using antecedent discharge to estimate contributing areas severely underpredicts actual quickflow volumes, because the saturated areas expand during runoff events. An attempt was made to predict the

Table 3 – Precipitation, quickflow and antecedent moisture data for individual rainstorm, snowmelt and rain-on-snow events in the rural watershed.

Year day/ month	Snowmelt (mm)	Rain (mm)	Total precipitation (mm)	Antecedent well level (below surface) (cm)	Antecedent precipitation index (mm)	Antecedent base flow (l/sec)	Peak discharge (l/sec)	Quickflow (mm)	Quickflow response ratio (%)
1976									
15/4		27.2	27.2	47	66.2	8	44	6.30	23.2
25/4		10.1	10.1	45	43.1	0	14	1.92	19.0
2/5		9.1	9.1	47	31.3	0	1.9	0.19	2.1
6/5		26.7	26.7	45	42.8	0	37	10.20	38.2
11/5		3.4	3.4	42	34.6	10	27	0.99	29.1
14/5		8.8	8.8	47	32.2	0	12	0.95	10.8
16/5		19.4	19.4	43	48.5	0.8	42	7.68	39.6
19/5		11.1	11.1	40	48.0	15	45	3.91	35.2
1977									
10/3	4.5		4.5	28	NA	1.9	12	0.43	9.6
11/3	35.1		35.1	28	NA	3.6	24	0.86	2.5
12-16/3	29.0	20.8	49.8	34	NA	4.2	19.4	38.92	78.2
19-22/3	23.7		23.7	47	85.5	5.0	7.8	.25	1.1
24-26/3	18.0		18.0	50	72.0	7.7	9.9	.47	2.6
27-31/3		9.9	9.9	43	70.1	7.9	30	3.09	31.2
2/4		1.3	1.3	41	49.7	23.7	27	.04	3.1
3/4		9.1	9.1	42	54.1	8.4	21	.73	8.0
5/4		6.9	6.9	42	52.1	7.5	26	1.59	23.0
24/4		11.2	11.2	48	32.3	1.5	5.3	.11	1.0
2/5		6.6	6.6	52	22.6	0.2	2.6	.04	0.6
8/10		23.1	23.1	38	47.0	0	5.6	0.25	1.1
7/11		28.6	28.6	48	29.6	0	9.7	0.46	1.6
10/11		19.6	19.6	38	39.4	3.0	31	2.00	10.2
16/11		20.3	20.3	32	43.4	4.5	12	0.38	1.8
20/11		11.8	11.8	36	40.9	8.2	12	0.07	0.6
23/11		9.2	9.2	38	38.4	6.0	12	0.17	1.8
1978									
20/4		9.9	9.9	4	148	23.3	67	5.67	59.3
13/5		22.1	22.1	8.5	45.2	2.5	81	12.41	56.2

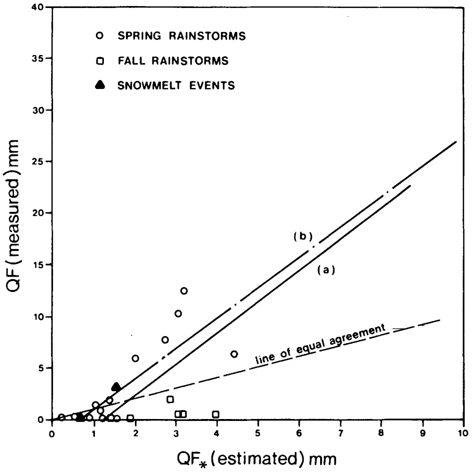


Fig. 6. Relationships between measured quickflow (QF) and estimated quickflow (QF*) based on antecedent baseflow and net precipitation: (a) all events, (b) spring rainstorms only.

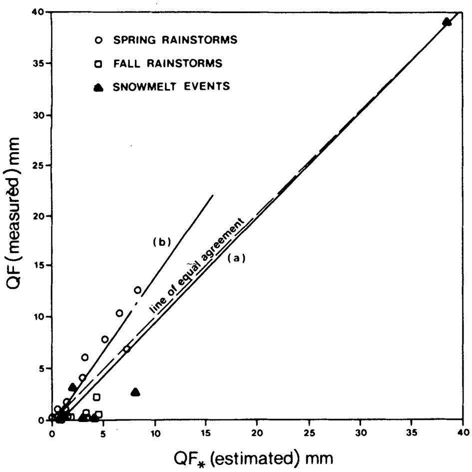


Fig. 7. Relationships between measured quickflow (QF) and estimated quickflow (QF*) based on peak discharge and net precipitation: (a) all events, (b) spring rainstorms only.

amount of expansion from rainfall data, without success. However, if peak discharge is used in the equation to estimate contributing areas there is much better agreement between measured and estimated quickflow volumes (Fig. 7). When all 27 points are included, $r = .953$ ($p = .001$), and this time when the highest value is omitted the relationship is still significant ($r = .705$, $p = .001$). When post-snowmelt spring rainstorms are considered alone, $r = .941$ ($p = .001$), but the regression coefficient is greater than 1.0, showing that the equation using peak saturated areas over-estimates quickflow yields, as would be expected. Again, the points for all rainstorms and snowmelt events fall away from the spring rainstorm regression line (b), indicating a different pattern of response.

The use of peak discharge to estimate saturated area thus provides a closer estimate of quickflow volumes, although this is not surprising since peak discharge and quickflow volume are themselves significantly correlated with each other ($r = .848$, $n = 21$, $p = .001$). Nevertheless these results do show that the inclusion of a factor to allow for expansion of saturated zones during a runoff event in a watershed of this type is necessary if the quickflow response from saturation overland flow is to be accurately predicted.

Runoff Response in the Urbanizing Watershed

The hydrological response of the Kawartha Heights watershed has been measured since September 1973 and described by Taylor and Roth (1979). Table 4 summarizes the spring, summer and fall quickflow responses for rainstorm, snowmelt and rain-on-snow events where data are available. Unfortunately, data for some seasons are missing because of logistical problems in the field. No discharge

Table 4 – Precipitation and quickflow summary for spring, summer and fall seasons in the urbanizing watershed, 1973-1978.

Season	Peak snowpack water equivalent (mm)	Rain & snow during period (mm)	Total available precipitation (mm)	Total quickflow (mm)	Quickflow response ratio (%)	Mean peak discharge (l/sec.)
Spring 1974	69.0	41.2	110.2	6.5	5.9	54
Spring 1977	81.4	48.4	129.8	28.6	22.0	181
Spring 1978	159.2	31.8	191.0	32.0	16.8	89
Summer 1974		132.8	132.8	6.6	5.0	145
Summer 1975		174.5	174.5	10.9	6.2	110
Summer 1976		188.0	188.0	8.7	4.6	36
Summer 1977		265.2	265.2	15.7	5.9	74
Fall 1973		147.5	147.5	10.5	7.1	71
Fall 1975		70.1	70.1	3.4	4.9	23
Fall 1976		107.5	107.5	3.0	2.8	19
Fall 1977		158.7	158.7	10.4	6.6	49

measurements were made in the winters because the pond where the measurements are made is drained for safety reasons. The data in Table 4 relate to quickflow only. It is believed that baseflow in this stream is supplied from an area larger than the topographical watershed, so total runoff volumes cannot be interpreted meaningfully in terms of a water balance.

Unfortunately only one year's data were obtained while the land use in the watershed was still rural. A comparison of the quickflow response ratios for the season of fall 1973, spring 1974 and summer 1974, however, suggests that there was relatively little difference in the seasonal quickflow patterns. This is because the natural runoff contributing zone was always quite small (less than 7% of the total watershed area). Only under extreme conditions (which were not experienced in 1973-74) would the quickflow response be larger than that.

As the watershed became progressively more urbanized (Fig. 2), it was expected that the quickflow response in all seasons would increase. However a comparison of the responses for both summer and fall seasons shown in Table 4 reveals no progressive increase over time; in fact, the largest quickflow response ratio was 7.1%, for the fall of 1973, before development even began. The response for the largest individual event (with an estimated return period of 25 years) was only 8%. It would appear that quickflow from fall and summer rainstorms was being produced from a similarly sized area in 1977 as it had been in 1973-74.

Evidence of a change in response does appear for the spring season however.

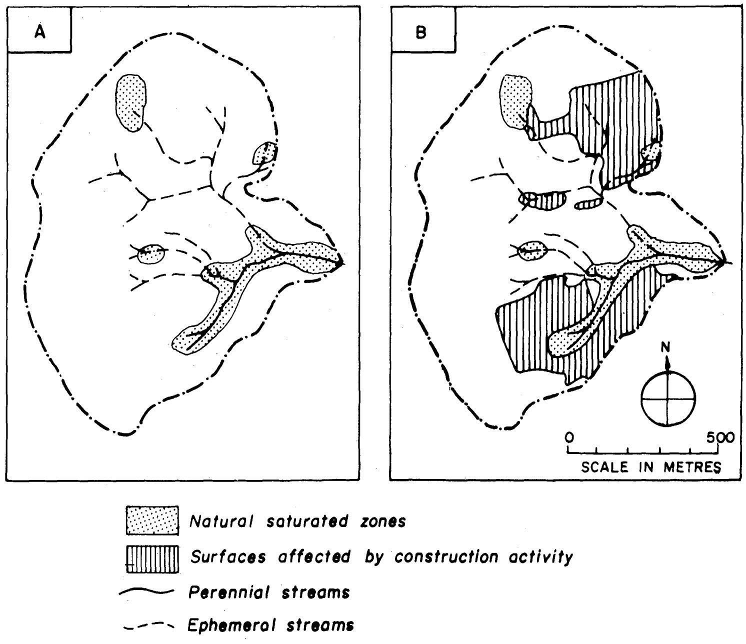


Fig. 8. Potential runoff contributing areas in the Kawartha Heights watershed: (a) Fall 1973 (pre-construction), (b) Spring 1977 (partially developed).

The quickflow response ratios for 1977 and 1978 of 22% and 17% contrast sharply with that for 1974 of only 6%. The comparison of 1974 and 1977 is particularly interesting, since those spring seasons were very similar in terms of precipitation and temperature characteristics (Taylor and Roth 1979). The melt season in 1978 was much cooler and more protracted than the other two, so is difficult to compare. The fact that the quickflow response in 1977 was 3.7 times larger than that in 1974, and the mean peak discharge was 3.4 times larger, suggests that land use changes over the period 1974-77 had a definite effect on runoff generation patterns during snowmelt. Fig. 8a shows the active quickflow contributing zone in 1973-74, located alongside the stream channels and covering approximately 7% of the watershed. Figure 8b shows the potential quickflow producing area in 1977, which includes fully and partially developed areas with severely reduced infiltration capacities and covers approximately 30% of the total area. These disturbed areas are connected to the main channel system by ephemeral streams, which flow only under the wettest conditions. In the summer and fall, most precipitation on the construction surfaces during low and moderate intensity storms infiltrates and any which does run off is absorbed in the ephemeral stream channels. Some threshold of soil moisture content or ground water elevation must be exceeded for the channels to become active. This happens only rarely in the summer and fall (observed during only 15 of 39 rainstorm events in 1977) but more consistently in the spring, with the large volumes of water available from snowmelt along with lower temperatures and evapotranspiration rates. An expansion of the active contributing zone to approach the maximum size produced by suburban construction activity during wet springtime conditions is thus the main reason why seasonal contracts in quickflow response have become accentuated in the Kawartha Heights watershed.

Conclusions

Quickflow generation from saturation overland flow can be expected to depend primarily on the extent of the contributing zone and the depth of precipitation input, corrected for storage and evapotranspiration loss during the event. The quickflow response patterns of different seasons in the rural swampy watershed can therefore be explained as follows. In the winter the quickflow response is minimal or non-existent, because the water table is low and contributing zones are very small, and because precipitation inputs are mainly in frozen form. In the spring the release of the stored water in the snowpack, combined with spring rainstorms, means that large inputs are available and the contributing zones expand to their maximum as the water table rises. At the same time rates of loss from interception and evapotranspiration processes are very low. During the summer, contributing zones are very small because of low water table conditions, and although precipitation inputs may be substantial, the losses from interception and evapotranspiration are at their maximum, and there is considerable storage available in the soil. Quickflow response is therefore minimal in the summer from even extreme events. In the fall the lowered evapotranspiration rates allow a recharge of soil moisture and ground water, so contributing zones expand again. In this season, therefore, some quickflow response is again possible.

A simple regression model linking the size of saturated contributing zones to streamflow enables an interpretation of seasonal and storm-to-storm variations in quickflow response. The product of the predicted extent of saturation and the depth of precipitation input can explain quite well the space measured quickflow output from an event. The nature of the relationships produced does appear to vary on a seasonal basis, with smaller quickflow volumes being produced in the fall than in the spring for a given extent of saturation and a given precipitation input. This is presumably because of different rates of interception, evapotranspiration and flow through the swamp.

In the other study watershed, little seasonal contrast in the pattern of quickflow generation was apparent previous to construction activity taking place. Quickflow was generated from natural saturated contributing zones alongside the channel, which seldom amounted to more than 7% of the total watershed area. Progressive expansion of a new subdivision has expanded the potential quickflow contributing area to approximately 30% of the watershed. However, it is only under the wettest conditions, expecially during spring snowmelt, that a high water table and wet soils allow the disturbed surfaces to contribute quickflow to the main stream via normally dry drainage lines. Under other conditions, as generally apply during the other seasons, runoff from the construction areas infiltrates en route. What the partial urban development has done, therefore, is to exaggerate the seasonal contrasts in runoff response for the watershed. It can be concluded that the spatial relationship between natural contributing zones and new contributing zones provided by man's activities, and the effects of temporal variations in antecedent wetness conditions on this, on both seasonal and event-to-event scales, is very important in determining the effects of land use change on a runoff regime.

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