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THE ROLE OF GROUNDWATER IN STORM RUNOFF

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ABSTRACT

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Groundwater plays a much more active, responsive and significant role in the generation, of storm and snow-melt runoff in streams than the recent literature on the subject suggests. Basin-wide tracer experiments using environmental isotopes (^{18}O, deuterium, tritium) and hydrometric studies carried out in hydrogeologically diverse watersheds, indicate that for all except the most intense rain storms and the most prolific melting days, groundwater dominates the runoff hydrographs in the study basins. The increased groundwater discharge during runoff events is apparently related to a rapid rise in hydraulic head along the perimeter of transient and perennial discharge areas. This groundwater ridging phenomenon probably arises from the almost instantaneous conversion of the near-surface tension-saturated capillary fringe into phreatic water. The ridging precedes, and is apparently independent of the response of the rest of the basin. In addition to its compatibility with several of the field observations commonly associated with contemporary concepts of runoff generation, the groundwater discharge theory explains some of the temporal variations in stream water chemistry which are not adequately accounted for by other theories.

INTRODUCTION

Most of the recent literature on storm runoff generation has overlooked true groundwater flow as a significant and active factor in the storm and snow-melt runoff process. Freeze (1974) summarized the hydrologic thought on the subject as:

> "True groundwater flow is seldom the cause of the major runoff during storms. Its primary role is in sustaining streams during low-flow periods between rainfall and snow-melt events . . ."

Indeed, it is difficult to conceptualize how slow-moving groundwater can respond rapidly enough to contribute to a storm or snow-melt runoff peak. In the past decade, however, basin-wide tracer experiments using environmental isotope techniques have demonstrated that groundwater often dominates snow-melt runoff in humid to sub-humid regions (e.g., Dincer et al., 1970; Martinec, 1975). Fritz et al. (1976) and Sklash (1978) have reported the occurrence of large groundwater components in both storm and snow-melt runoff in their environmental isotope studies of eight hydrogeologically diverse watersheds in Canada. The exact mechanism which enables groundwater to appear so quickly and in such large quantities in the stream during high runoff events, however, has yet to be established.

The purpose of this paper is two-fold. It presents further documentation for the active, responsive and significant role of groundwater in storm runoff. Secondly, it introduces a theory for storm (and snow-melt) runoff generation which, in addition to explaining how large quantities of groundwater can appear in the peak storm or snow-melt runoff, is compatible with some field phenomena which one might ascribe to other theories for runoff generation.

CONCEPTUAL MODELS FOR STORM RUNOFF GENERATION

The study of storm (and snow-melt) runoff generation can be approached in a variety of ways. For example, one may consider only what portion of the runoff water existed in the basin prior to the runoff event and what portion was added by the runoff-inducing event. Alternatively, one may choose only to examine the manner in which the runoff water travels over the last several tens of metres to the stream. A third approach could be concerned only with the history of the water from its arrival in the basin to its ultimate delivery to the stream. These three approaches, termed: time aspects, ultimate delivery mechanism aspects, and historical aspects, respectively, are outlined in Fig. 1.

Currently, the most widely accepted theories for storm (and snow-melt) runoff generation stem from the ultimate delivery mechanism approach to the subject. Each concept attempts to account for both the rapid response of the stream to runoff-inducing events and the observed increase in stream discharge. Freeze (1974) has summarized the most popular of these theories as: (1) partial area—overland flow; (2) variable source area—overland flow; and (3) variable source area—subsurface storm flow. Brief explanations of these mechanisms follow, however, the reader is referred to Freeze (1974) which provides an excellent review and reference list for each mechanism.

The partial area—overland flow concept suggests that runoff water is produced mainly from certain fixed portions of the watershed (usually controlled by soil characteristics) where the soil becomes saturated from above by the infiltrating water. After surface detention requirements have been satisfied, the excess water runs off rapidly to the stream as overland flow.

Perhaps the most widely accepted runoff generation mechanism concept is the variable source area—overland flow theory. In essence, runoff is generated from watershed areas (usually controlled by topography, geology and soil type) which have become saturated from below by a rising water table. The source areas, generally located near the stream, may expand and

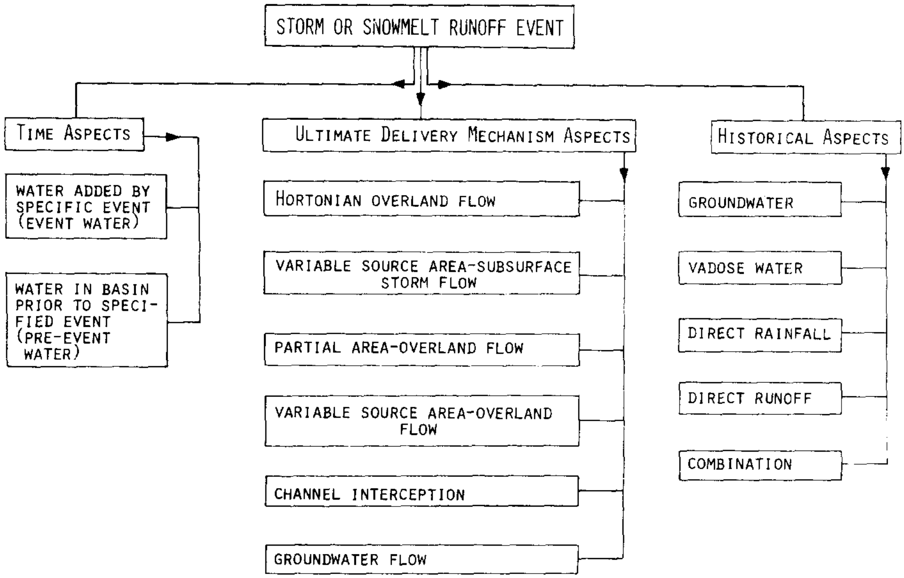


Fig.1. Classification chart for runoff generation terminology.

contract in response to climatic factors. The runoff from the variable source area, consisting of both rain and "return flow", runs off to the stream rapidly as overland flow.

The variable source area—subsurface storm flow concept states that the areas contributing to storm runoff expand and contract in response to climatic factors. Unlike the variable source area—overland flow theory, the transfer of water from the hillside to the stream is accomplished through subsurface routes. An expanding channel network and translatory flow (displacement or bumping of subsurface water toward the stream) allows the runoff water to reach the stream quickly. The subsurface storm flow may be either saturated—unsaturated Darcian flow through the porous soil matrix or turbulent flow through root channels, animal burrows and soilcracks (Cheng et al., 1975; Beasley, 1976).

Most of the research indicating groundwater as a significant factor in the storm (and snow-melt) runoff process can be classified under the heading of time aspect studies. Under this classification, the water which existed in the basin prior to a specified event is considered pre-event water and consists of groundwater, vadose water and surface storage. Water added to the basin by the specified runoff-inducing event, either a rain or snow-melt event, is called event water. Basin-wide tracer experiments involving such parameters as specific conductance, environmental isotopes, and conservative ions, have been used to distinguish pre-event water from event water (e.g., Pinder and Jones, 1969; Martinec, 1975). Groundwater contributions to peak storm and snow-melt runoff have been reported to exceed 50% in some instances.

The time aspect studies have all been stream-oriented; that is, their conclusions are based mainly on the examination of temporal variations of selected tracers in the stream. The ultimate delivery mechanism studies have all been slope-oriented; that is, their conclusions are based mainly on the examination of processes occurring somewhere above the stream. The conclusions from these two approaches have generally been divergent. Historical aspect studies attempt to identify changes in the runoff water chemistry while enroute to the stream in order to reconcile the slope- and stream-oriented results. Kennedy (1977) suggests that rain may infiltrate into micro-ridges (furrows), dissolve soluble materials, discharge from the furrows, and then run off to the stream as overland flow. In this manner, the chemistry of the runoff water may approach that of the groundwater and thereby confound any tracing attempts.

ENVIRONMENTAL ISOTOPE AND SPECIFIC CONDUCTANCE TECHNIQUES

Dincer et al. (1970), Martinec et al. (1974), Fritz et al. (1976), and others have demonstrated that environmental isotopes such as: ^{18}O, deuterium (D) and tritium (T), can be used to distinguish pre-event water from event water in the stream during runoff events. The storm (or snow-melt) runoff hydrograph can then be separated into its simple time components (pre-event and event water) by the simultaneous solution of the steady-state mass balance equations describing the fluxes of water and the tracer isotope in the stream. These equations are of the form:

$$Q_t = Q_p + Q_e \quad \text{and} \quad C_t Q_t = C_p Q_p + C_e Q_e \qquad (1),(2)$$

where Q is the discharge (L^3/T), C represents the tracer concentration, and subscripts t, p and e refer to the total stream discharge, pre-event component, and event component, respectively. Q_p and Q_e are unknowns which can be determined readily subject to the following criteria:

(1) The isotopic content (^{18}O, D, or T) of the event component is significantly different from that of the pre-event component.

(2) The event component maintains a constant isotopic content.

(3) The groundwater and vadose water are isotopically equivalent or vadose water contributions to runoff are negligible due to hydrogeologic constraints.

(4) Surface storage contributes minimally to the runoff event.

The environmental isotope technique for hydrograph separation is the dominant tool in this study. Isotopic, chemical and specific-conductance analyses of the various runoff components enhance the hydrograph interpretations.

HYDROMETRIC TECHNIQUES

The main hydrometric technique in this study involves the establishment of groundwater stage—groundwater discharge rating curves for hydrograph separation. According to this method, curves relating groundwater stage to stream discharge during baseflow periods (when stream discharge is assumed to be only groundwater) are assumed to hold true during high runoff episodes. By monitoring groundwater stage during runoff events, groundwater discharge is estimated by referring to the groundwater stage—groundwater discharge rating curve.

Unlike many of the previous studies (Schicht and Walton, 1961; Stevenson, 1967; Visocky, 1970) which used average groundwater stages for a number of index wells throughout the watershed, small-diameter recording wells installed in the stream bed and a few metres from the stream provide the groundwater stage data for one of the basins in this study. Although the individual wells may not represent the average response of the basin, they are indicative of the nature of the near-stream groundwater response.

Water level responses of wells and piezometers located farther from the stream offer some indication of the groundwater response of the remainder of the basin to runoff-inducing events.

WATERSHED MODELLING

The response of small hypothetical watersheds to runoff-inducing events is examined with the aid of a two-dimensional saturated—unsaturated transient finite-element flow model developed by Segol (1976). Observations are focussed on the groundwater response in the near-stream area when near-stream watershed relief and basin width are varied.

THE STUDY AREAS

Although several small watersheds have been examined during this study, only two, Ruisseau des Eaux Volées and Hillman Creek, are discussed here. The results from the other study basins, dealing mainly with snow-melt runoff, corroborate the findings reported in this paper.

The Ruisseau des Eaux Volées experimental watershed, situated at latitude 47°16′N and longitude 71°09′W, lies some 80 km north of Quebec City, Quebec, Canada. The basin is typical of many of the hanging valley tributaries found in the Laurentian Uplands of the Canadian Shield. Two subbasins, the west branch of Ruisseau des Aulnaies (subbasin *7A*) and the upper portion of Ruisseau des Eaux Volées (subbasin *6*), were monitored during the study (Fig.2). Subbasin *7A* occupies some 1.2 km^2 of heavily forested land between the 880- and 760-m elevation contours. Subbasin *6* covers 3.9 km^2 of heavily forested and experimentally logged land between 780 and 720 m in elevation. The climate of the area is considered moist cold temperate (Plamondon and Naud, 1975).

Surficial deposits, mainly of glacial origin, cover 80% of the basin to depths of 1—20 m. Jointed charnockitic gneiss, underlying the entire basin, outcrops only in the high areas (Rochette, 1971).

The groundwater system is considered unconfined with the bedrock groundwater demonstrating hydraulic connection to the surficial materials (Rochette, 1971). The water table, even in high areas, is close to ground surface.

Groundwater in the surficial materials is characterized by $\delta^{18}O$ and T values of approximately $-12.8^{0}/_{00}$ and 75 TU, respectively (all ^{18}O analyses are given relative to the SMOW standard). Bedrock groundwater has ^{18}O and T values of about $-11.9^{0}/_{00}$ and 175 TU, respectively. Baseflow ^{18}O values at the stream gauging stations for both subbasins range from $-12.6^{0}/_{00}$ in the winter to $-11.9^{0}/_{00}$ in the summer.

Suction lysimeters (soil moisture samplers) installed between depths of 0.26 and 0.47 m below ground surface were used to extract samples of vadose water from several sites (Fig.2). The ^{18}O analyses of the vadose water indicate some influence by the infiltrating rain but the values are consistently heavier than the groundwater by as much as $6^{0}/_{00}$.

The Hillman Creek study area, situated at latitude 42°04′N and longitude 82°39′W, is approximately 50 km SE of Windsor, Ontario, Canada. The drainage area above the stream gauging station is in the order of 1 km^2 which corresponds to a channel length of nearly 1.1 km (Fig.3). Relief over the basin is low with maximum and minimum elevations of approximately 212 and 202 m, respectively. Intensive agriculture in the area leaves only minimal tree cover and exposed soil conditions. An average of 740 mm of precipitation is distributed evenly throughout the year.

The uppermost unit in the basin, from 1 to 5 m of fine to coarse sand with a hydraulic conductivity in the order of 10^{-2} to 10^{-3} cm/s (Gillham et al.,

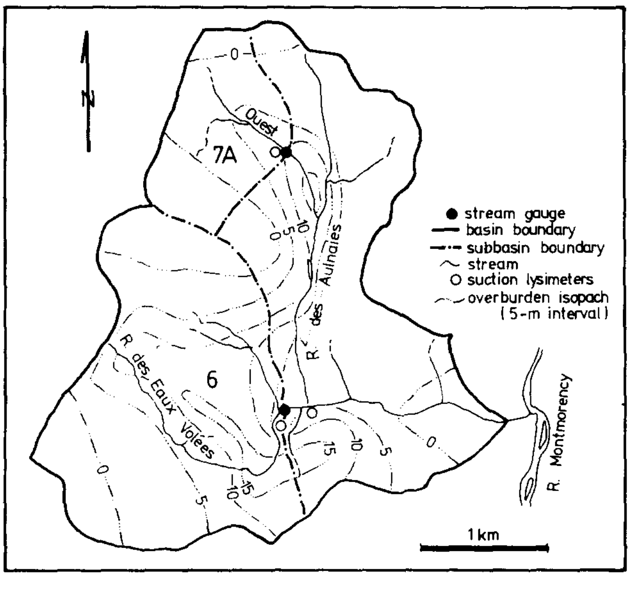


Fig.2. Instrumentation and depth of overburden in Ruisseau des Eaux Volées (after Rochette, 1971).

1978), overlies an impervious silty-clay unit. The water table, with a gradual slope from west to east, lies 1—4 m below ground surface. From water table maps (Gillham et al., 1978) and seepage meter data (Lee et al., 1977), it appears that groundwater discharge is low over the upper 600 m of the stream. From that point downstream beyond the gauging station, groundwater discharge is significant

The groundwater originates both from gravel pits along the western margin of the watershed and from local infiltration. The $\delta^{18}O$ values of the gravel pit groundwater are somewhat heavier than those of the locally infiltrated groundwater. Baseflow $\delta^{18}O$ values at the gauging station, ranging from −6.3 to -8.4°/₀₀, indicate a mixture of the two groundwaters. The specific conductance of the baseflow is approximately 750 μS.

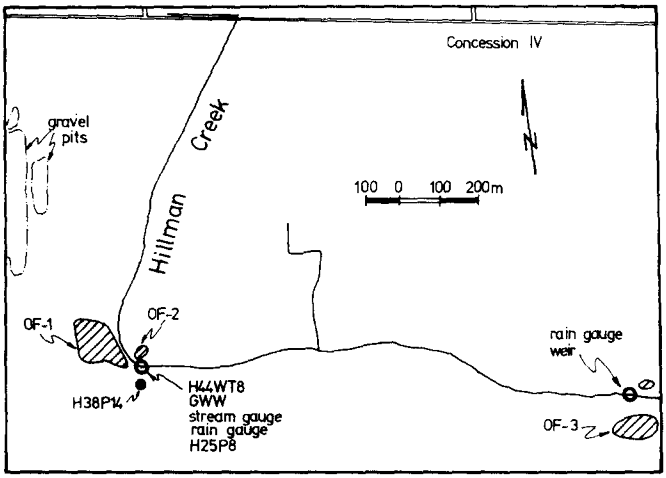


Fig.3. Instrumentation in the Hillman Creek study area.

RESULTS FROM RUISSEAU DES EAUX VOLÉES

Five rain events between August 5 and 25, 1976, resulted in stream discharge increases ranging from 45 to 820% in the two subbasins. Equipment malfunctions and storms unsuitable for the environmental isotope technique reduced the number of usable events which could be analyzed.

On August 5, a 32-mm rain event resulted in a discharge increase from subbasin *7A* of approximately 450% over its pre-storm baseflow discharge (Fig.4). The runoff hydrograph accounts for only 12% of the rainfall. Prior to the storm, baseflow $\delta^{18}O$ values were approximately -12.0°/₀₀. Although the $\delta^{18}O$ value of the rain was -8.3°/₀₀, the peak discharge $\delta^{18}O$ value of the stream only reached -10.8°/₀₀ (Fig.4). Using eq. 1 and 2 and assuming that the vadose water contributions were negligible, it appears that groundwater contributed more than 65% of the peak discharge in the stream.

The validity of the assumption that vadose water contributions are negligible can be evaluated by examining a plot of stream $\delta^{18}O$ vs. stream discharge (Fig.5A). A simple two-component groundwater—rain mixture in the stream should result in essentially collinear $\delta^{18}O$-discharge data points for the rising and falling limbs of the hydrograph. As discussed previously, the vadose water in the basin is isotopically heavier than the groundwater.

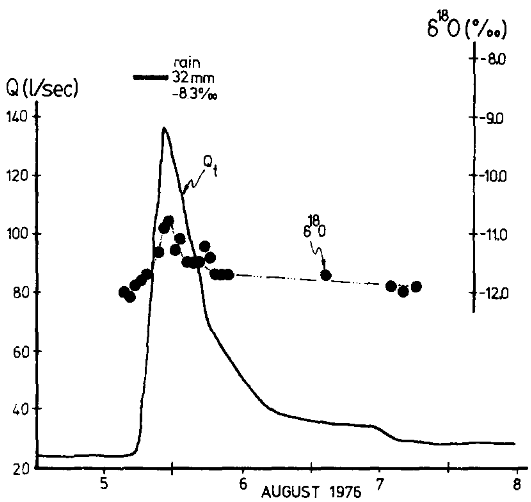


Fig.4. Storm runoff hydrograph and stream $\delta^{18}O$, subbasin *7A*, Ruisseau des Eaux Volées, August 5—8, 1976.

Significant vadose water contributions to storm runoff should cause a shift in the recession limb data to the isotopically heavier side of the groundwater—rain mixing line (which is defined by the data from the earlier part of the rising limb). If the shift exceeds the analytical error for ^{18}O analysis ($\pm 0.2^0/_{00}$), the assumption is questionable. Also, the magnitude of the shift should be directly related to the magnitude of the vadose water contribution.

Fig. 5B is a plot of the stream $\delta^{18}O$ vs. stream discharge for the August 5 storm in subbasin *7A*. The small shift between the rising and falling limb values of $\delta^{18}O$ supports the simple two-component groundwater—rain mixing assumption.

On August 12, a 35-mm rain event in subbasin *6* instigated a discharge increase of approximately 340% over the pre-storm baseflow discharge (Fig.6). The runoff hydrograph accounts for nearly 20% of the rainfall. Prior to the event, the baseflow $\delta^{18}O$ value was $-11.9^0/_{00}$. Although the rain $\delta^{18}O$ value was $-5.7^0/_{00}$, the stream attained a $\delta^{18}O$ value of only $-10.1^0/_{00}$ at peak discharge (Fig.6).

A plot of stream $\delta^{18}O$ vs. stream discharge for this event (Fig.7) suggests a significant vadose water contribution. Although a simple two-component hydrograph separation cannot be made in this case, it is apparent from the isotopic character of the various runoff components that pre-event water (groundwater and/or vadose water) dominated the storm runoff.

On August 22, a very brief but intense storm dropped 6 mm of rain on the basin in less than 15 min. Stream discharges from subbasins *6* and *7A* increased by 55 and 45%, respectively (Fig. 8A and B). Storm yields for both basins were about 6%.

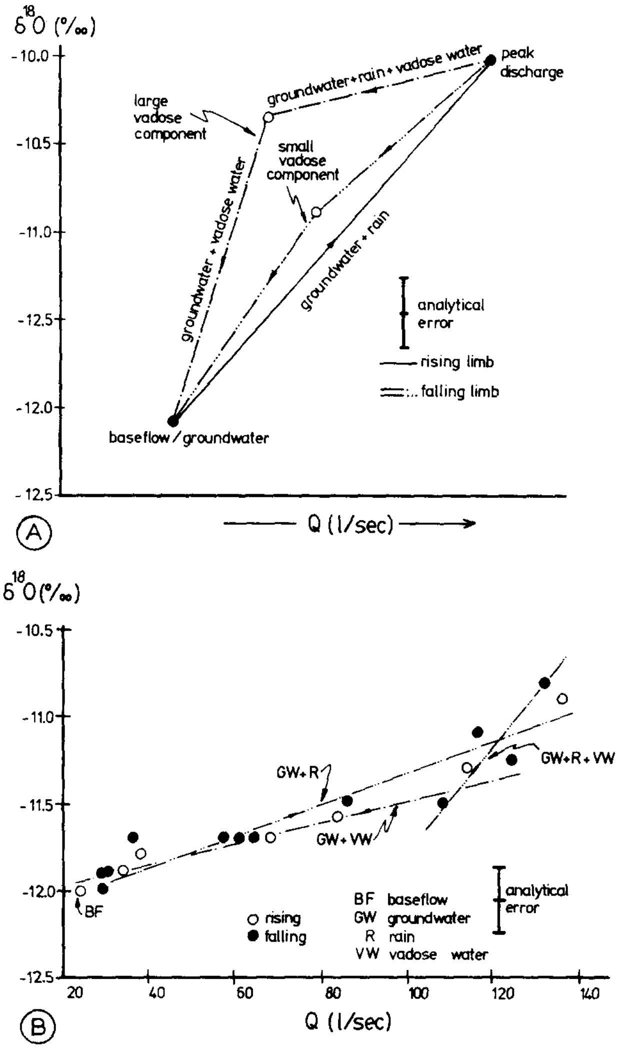


Fig.5. A. Model of $\delta^{18}O$ variations during storm runoff for the Ruisseau des Eaux Volées watershed.
B. $\delta^{18}O$ vs. discharge during storm runoff, subbasin *7A*, Ruisseau des Eaux Volées watershed, August 5—8, 1976.

The rain event was ideal for hydrograph separation by the isotope technique. The short duration and high intensity of the rain meant that the event water was added "instantaneously" to the watershed. Baseflow $\delta^{18}O$ prior to the event was -12.1‰ in subbasin *6* and -11.9‰ in subbasin *7A*. Although the rain $\delta^{18}O$ value was -6.6‰, peak discharge attained $\delta^{18}O$

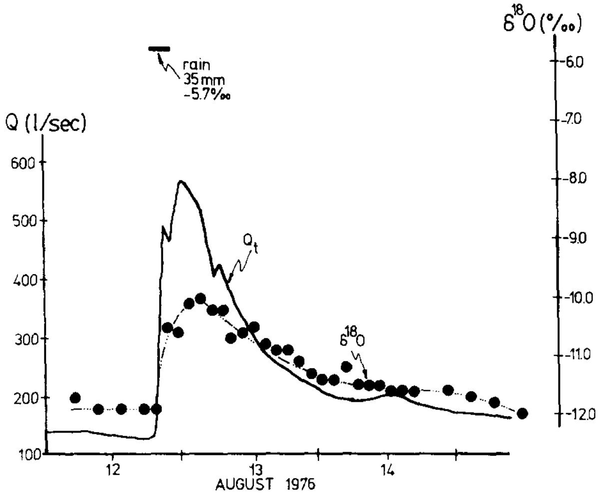


Fig.6. Storm runoff hydrograph and stream $\delta^{18}O$, subbasin *6*, Ruisseau des Eaux Volées watershed, August 12—15, 1976.

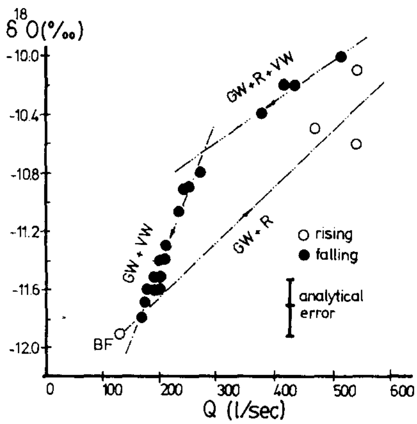


Fig.7. $\delta^{18}O$ vs. discharge during storm runoff event subbasin *6*, Ruisseau des Eaux Volées watershed, August 12—15, 1976.

values of -11.4‰ and -11.5‰ for subbasins *6* and *7A*, respectively (Fig.8). These correspond to groundwater components of more than 80% in peak discharge if vadose water contributions were negligible. A plot of stream $\delta^{18}O$ vs. stream discharge would support that assumption. Deuterium analyses for subbasin *6* gave similar groundwater contributions.

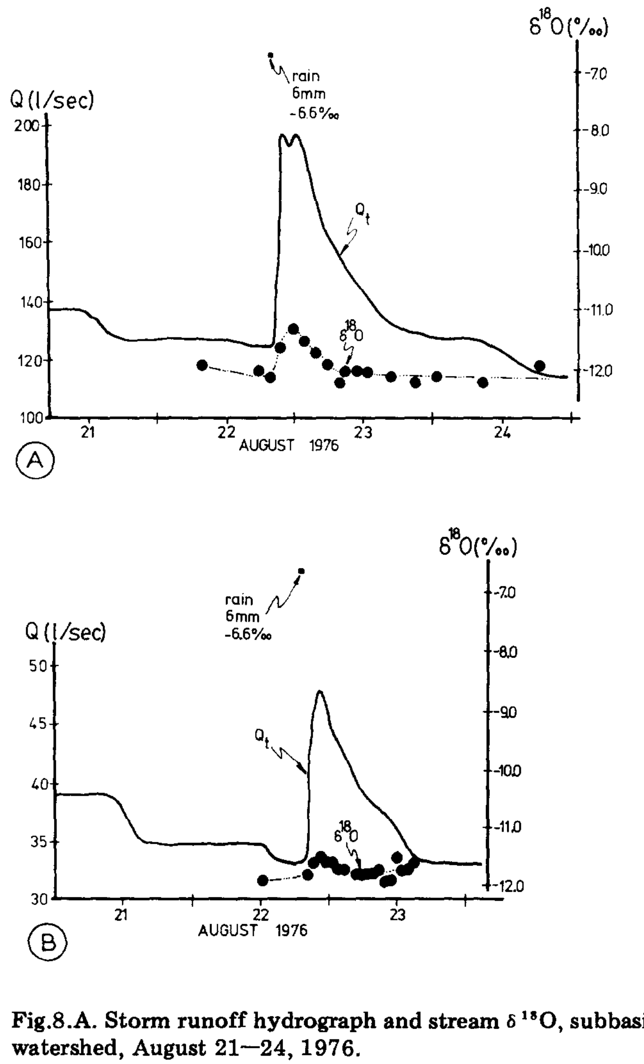


Fig.8.A. Storm runoff hydrograph and stream $\delta^{18}O$, subbasin *6*, Ruisseau des Eaux Volées watershed, August 21—24, 1976.
B. Storm runoff hydrograph and stream $\delta^{18}O$, subbasin *7A*, Ruisseau des Eaux Volées watershed, August 21—24, 1976.

RESULTS FROM HILLMAN CREEK

Groundwater stage—groundwater discharge rating curves for two near-stream observation wells were determined. H44WT8 is a 10-cm diameter, 2.44 m deep, recording water table well located approximately 3 m from the stream bank at the stream gauging site. GWW (Fig.9) is a 9-cm diameter recording piezometer open between 80 and 90 cm below the stream bed and adjacent to H44WT8. Vertical and horizontal hydraulic gradients during base-flow periods were approximately 0.12 and 0.03, respectively, between H44WT8 and GWW. These gradients are an order of magnitude greater than those given for the watershed average by Gillham et al. (1978).

Hydrogeologic constraints in the watershed; namely, low topographic relief and high hydraulic conductivities of the sand, preclude significant

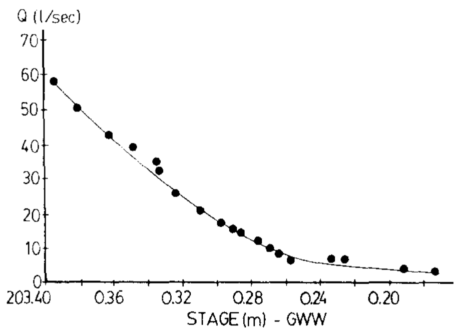


Fig.9. Groundwater stage—groundwater discharge rating curve for GWW, Hillman Creek study area.

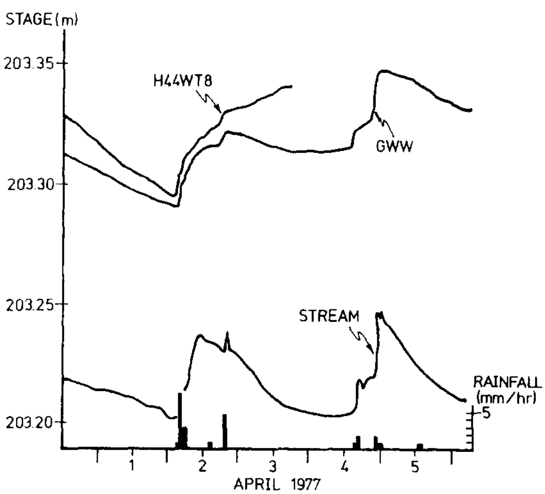


Fig.10. Stream and groundwater hydrographs for Hillman Creek study area, April 1—5, 1977.

vadose water contributions to storm runoff. Groundwater, therefore, is synonymous with pre-event water in this watershed.

Rain events of 19 mm on April 2 and 6 mm on April 4, 1977, caused two distinct runoff events at the Hillman Creek gauging site (Fig.10). Stream discharge increased from 15 l/s prior to the storm to 25 and 30 l/s at the first and second discharge peaks, respectively. The most noteworthy feature of these events is the rapid response of the near-stream groundwater exhibited by H44WT8 and GWW. The stream remained effluent throughout the events and although the hydraulic gradient to the stream decreased slightly during the first event, the gradient in the second event exceeded the pre-storm baseflow gradient. According to the groundwater stage—groundwater discharge rating curve technique, groundwater contributed more than 60 and 80% of the peak discharge on April 2 and 4, respectively. No isotope data are available for these events.

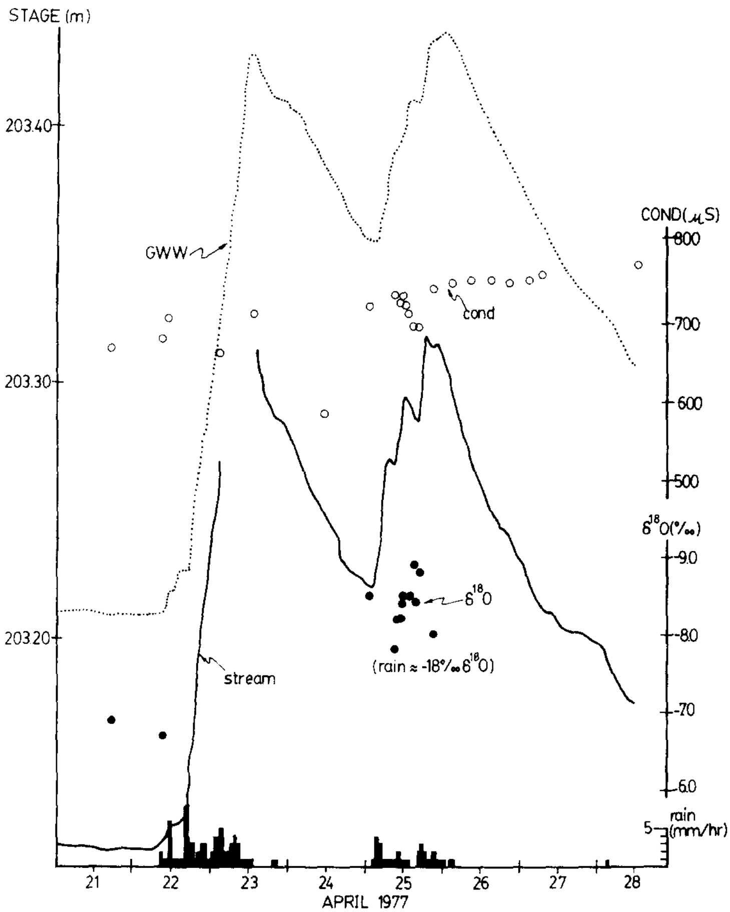


Fig.11. Stream and groundwater hydrographs, and stream $\delta^{18}O$ and specific conductance, Hillman Creek study area, April 21—28, 1977.

Rain events of 38, 35 and 31 mm occurring on April 22, 23 and 25, 1978, respectively, produced dramatic responses in both stream discharge and groundwater stage (Fig.11). Stream discharge increased from about 6 l/s on April 22 to peak discharge of at least 85 and 90 l/s on April 23 and 25, respectively. The length of the storms and instrument malfunctions curtailed some of the isotopic and specific conductance studies, however, many significant observations were made.

The stream remained effluent throughout the events even though stream discharge increased by more than an order of magnitude over the pre-storm discharge. The near-stream groundwater responded quickly to the rain events; however, the groundwater responsiveness apparently decreased away from the stream. Table I shows that over the duration of the study period, the stream discharge was more closely related to the near-stream groundwater stage than to the more remote groundwater. Although the near-stream hydraulic gradient toward the stream decreased slightly at the first discharge peak, the gradient at the second discharge peak was greater than the pre-storm base-flow gradient.

TABLE I

Relationship between stream discharge and depth to groundwater near H44WT8, Hillman Creek Watershed

Well or piezometer	Approximate lateral distance to stream (m)	Linear correlation coefficient between depth to water and stream stage
H38P14	65	-0.175
H25P8	5	-0.869
H44WT8	3	-0.954
GWW	0	-0.925

Visual observations were made and water samples were taken only on April 25. One area west of the stream gauging station (OF-1 on Fig.3) produced sufficient overland flow to erode a channel several centimetres deep to the stream. Two other overland flow producing areas, OF-2 and OF-3, produced much less overland flow.

The $\delta^{18}O$ values of the rain on April 25 ranged from -16.5 to -20.0$^0/_{00}$ with a weighted average of -18.1$^0/_{00}$. Since the baseflow prior to April 22 had $\delta^{18}O$ values of about -6.9$^0/_{00}$ and since the groundwater had $\delta^{18}O$ values of less than -10.0$^0/_{00}$ (Gillham et al., 1978), a very good distinction can be drawn between the groundwater/base flow (pre-event) and rain (event) components. Also, the specific conductance of the rain was less than 100 μS, whereas baseflow specific conductance is about 750 μS.

Fig.12A and B illustrates the temporal variations in $\delta^{18}O$ and specific conductance for the rain, overland flow and stream samples on April 25. The most prolific source of overland flow, OF-1, had $\delta^{18}O$ and specific conductance values indicative of large groundwater contributions. The two other observed sources, OF-2 and OF-3, had rain-like $\delta^{18}O$ and specific conductance. The stream $\delta^{18}O$ and specific conductance strongly suggest a large groundwater component. The groundwater stage—groundwater discharge rating curve technique supports these findings, with both methods giving more than 80% of the discharge as groundwater on April 25. Observed increases in the stream nitrate concentration on April 25 are apparently related to the high nitrate concentrations in the groundwater-dominant overland flow issuing from OF-1.

On May 4, 1977 a 17-mm rain event produced another storm runoff event in which the near-stream groundwater responded rapidly (Fig.13). Stream

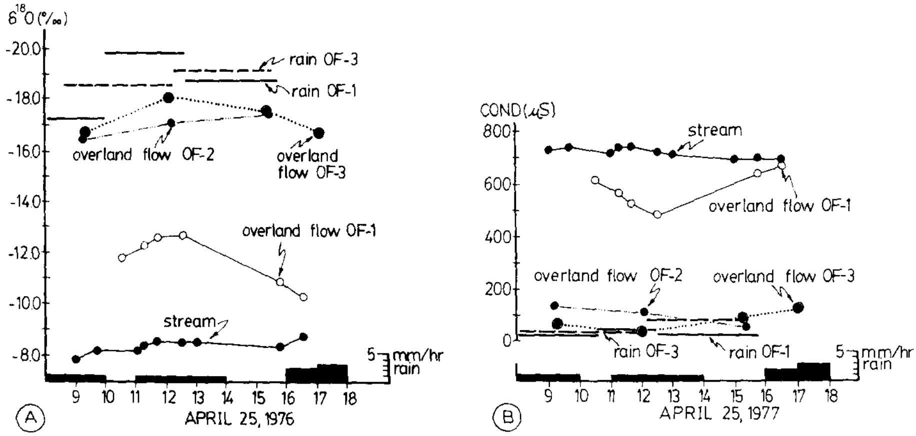


Fig.12. A. Temporal variations in $\delta^{18}O$ of overland flow, rain and the stream, Hillman Creek study area, April 25, 1977.
B. Temporal variations in specific conductance of overland flow, rain, and the stream, Hillman Creek study area, April 25, 1977.

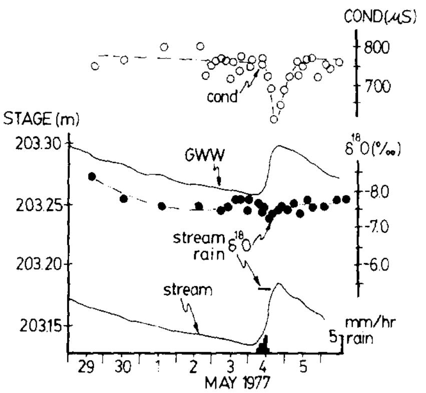


Fig.13. Stream and groundwater hydrograph, and stream $\delta^{18}O$ and specific conductance, Hillman Creek study area, April 29—May 5, 1977.

discharge increased from 9 to 22 l/s at peak discharge, yet the stream remained effluent. No overland flow was observed and baseflow $\delta^{18}O$ and specific conductance were diluted only slightly during the event. Both the groundwater stage—groundwater discharge rating curve and isotope techniques suggest that groundwater contributed over 80% of the peak discharge.

On June 6, 1977, following a month with only 20 mm of rain, a 36-mm rain event produced very prominent hydrographs in the stream and near-stream groundwater (Fig.14). Stream discharge increased from less than 5 l/s before the storm to over 200 l/s at peak discharge. A brief reversal of hy-

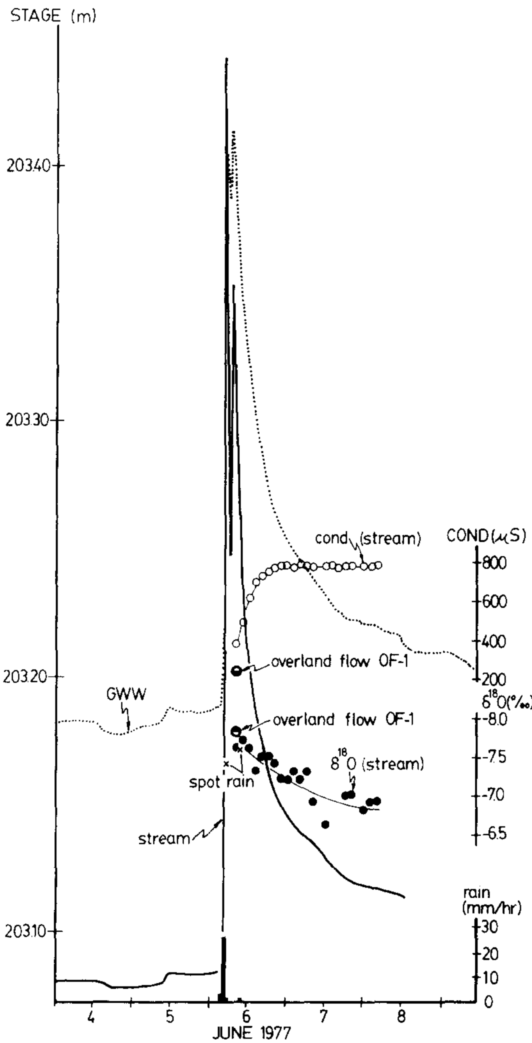


Fig.14. Stream and groundwater hydrographs, and stream $\delta^{18}O$ and specific conductance, Hillman Creek study area, June 4—8, 1977.

draulic gradient caused the stream to become influent for the only time during the study. The near-stream groundwater, however, did respond to the storm very rapidly. Significant amounts of overland flow emanated from OF-1, OF-2 and OF-3.

Fig.14 shows the temporal variations in stream $\delta^{18}O$ and specific conductance. Although the $\delta^{18}O$ value of the rain ($-7.8^0/_{00}$) was too close to the base-flow value ($-6.8^0/_{00}$) for very accurate separations, it is obvious that the stream runoff was dominated by rain runoff. The overland flow from OF-1, which was mostly groundwater during the April 25 storm, had rain-like $\delta^{18}O$ ($-7.8^0/_{00}$), and specific conductance (234 μS). The overland flow from OF-1 also had nitrate concentrations (4.5 mg/l) similar to those of peak discharge in the stream (4.2 mg/l). The stream nitrate concentrations increased to between 8 and 10 mg/l when the groundwater reasserted itself in the stream.

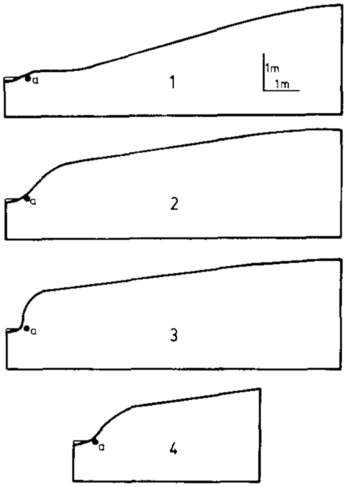
RESULTS FROM COMPUTER SIMULATIONS

Four small hypothetical watershed configurations (Fig.15) are examined to determine how near-stream watershed relief and basin width affect near-stream groundwater response. Watersheds *1*, *2* and *3* have comparatively low, medium and high near-stream topographic relief. Each configuration is 9 m from mid-stream to divide and varies in thickness above an impermeable base from 1 m at mid-stream to 2.9 m at the divide. The finite-element grid for each contains 464 nodes and 420 quadrilateral elements with the grids varying only in their near-stream topographic configuration. Watershed *4* is identical to watershed *2* in element configuration except that it is truncated 5 m from the stream leaving fewer nodes (400) and elements (360). The uppermost elements in the grids represent real thicknesses of no more than 3 cm.

The watersheds are homogeneous and isotropic. The saturated—unsaturated characteristics of the porous media are those of the Botany Sand as described by Watson (1967). The sand has a saturated hydraulic conductivity of 0.0186 cm/s, a porosity of 35%, and a capillary fringe of 39 cm. The initial conditions are static and the stream level is held constant throughout the simulation period. Seepage faces are allowed to form.

A rainfall rate equal to one-tenth of the saturated hydraulic conductivity (0.00186 cm/s) was applied to each watershed for 2.3 h after which drainage was allowed for at least 4.6 h. Computer output, consisting of total and pressure heads, for specified times during the event, are available for all the nodes.

Fig.16 compares the responses in total head for a common near-stream point *a* (Fig.15). Watershed *1*, with the lowest near-stream relief, exhibited the most rapid response to the storm. Watersheds *2* and *3* responded less rapidly but had higher peak stages. A comparison of the early responses of long watershed *2* and short watershed *4* reveals that the upland area has no effect on the early near-stream groundwater response.



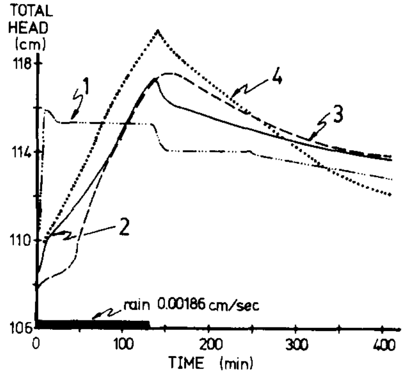


Fig.15. Watershed configurations used in mathematical simulations.

Fig.16. The effects of the near-stream unsaturated zone thickness and upland areas on early near-stream groundwater response to rain.

Fig.17 illustrates the temporal variations in the water table configuration for the rain event on watershed *2*. An apparent groundwater ridge, similar to the one observed by Ragan (1968), forms in the near-stream area prior to the response of the water table in the upland area. A seepage face forms in this case as it does in all the others. The discharges of the various runoff components in a 1-cm slice of watershed *2* are compared in Fig.18. Groundwater dominates the total discharge from the watershed.

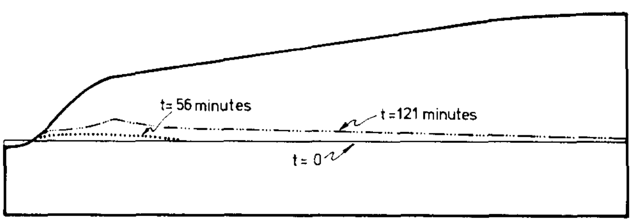


Fig.17. Formation of a near-stream "groundwater ridge" in response to a rain event.

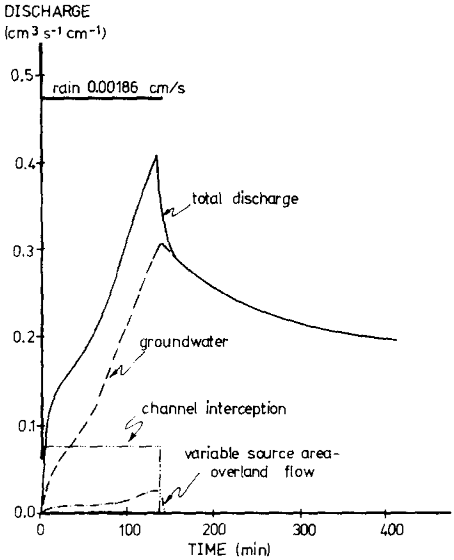


Fig.18. Discharge hydrograph from watershed *2*.

CONCLUSIONS

Groundwater was found to be a major component in virtually all of the runoff events documented in this study. Pinder and Jones (1969), Dincer et al. (1970), Martinec et al. (1974), Fritz et al. (1976), and others have arrived at the same conclusion, that is, groundwater is a significant and active factor in runoff generation. Martinec (1975), however, summarized the dilemma of how the groundwater appears in the stream so quickly as:

"The exact nature of the propagation is not known".

Several clues to the mechanism can be gathered from this study. Both field observations and computer simulations suggest that very large and rapid increases in the hydraulic head in the near-stream groundwater occur soon after the onset of rain. These responses precede, and are apparently independent of, the upland area response. The computer simulations also reveal the formation of a groundwater ridge adjacent to the stream in response to a rain event with the lag time brief and inversely related to the near-stream unsaturated zone thickness. Field observations indicate, however, that the near-stream hydraulic gradient may decrease slightly from its pre-storm value.

Isotopic and specific conductance data for overland flow in the Hillman Creek watershed imply that for one very prolific site (OF-1), overland flow is generated in more than one way. During a moderate intensity storm on a very wet basin, both the overland flow and stream flow were dominated by groundwater. In response to a very intense storm on a much drier basin, both the overland flow and stream were dominated by rain water.

The following theory outlines a physical mechanism which could explain the responsive, active and significant role of groundwater in storm and snow-melt runoff generation. Along the perimeter of transient and perennial discharge areas, the water table and its associated capillary fringe lie very close to the ground surface. Soon after a rain or snow-melt event begins, infiltrating water readily converts the near-surface tension-saturated capillary fringe into a pressure-saturated zone or groundwater ridge (Ragan, 1968). This groundwater ridge not only provides the early increased impetus for the displacement of the groundwater already in a discharge position, but it also results in an increase in the size of the groundwater discharge area which is essential in producing large groundwater contributions to the stream. The response of the upland area groundwater may become important at later times in the runoff event but has little influence in the early part of the runoff event.

The groundwater may discharge directly into the stream through the stream bed or it may issue from the growing near-stream and/or remote seep areas and flow as overland flow to the stream (as in the variable source area—overland flow theory). Following periods of drought during which the water table has fallen far below ground surface, intense storms may result in surface saturation from above and rain-like overland flow (partial area—overland flow) before the water table can emerge.

The recognition of groundwater as an important factor in storm and snowmelt runoff in humid to subhumid areas raises many questions regarding runoff events. What control does groundwater have on surface water quality during high runoff events? How do the increased heads in the near-stream groundwater affect the erodibility of soils? How can we improve predictive hydrologic models?

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John Cherry, Emil Frind, Peter Fritz and Bob Gillham of the University of Waterloo provided many helpful comments during this study. Funds for this study were provided through National Research Council of Canada grants A7712, A6112 and A8368, and from Agriculture Canada and the Ontario Ministry of Agriculture and Food. The senior author wishes to acknowledge the NRCC for the support of his postgraduate education.

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