Hydrologic characteristics of an agricultural watershed in rural Quebec

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Perrone, J., Madramootoo, C.A. and Lapp, P. 1998. **Hydrologic characteristics of an agricultural watershed in rural Quebec**. Can. Agric. Eng. **40**:079-088. The hydrology of a 26.1 km^2 rural Quebec watershed was investigated. Thirty-one rainfall-runoff events were used in the analysis. The average time of concentration (t_c), lag time (t_l), and time to peak (t_p) for these events were measured as 7.4, 8.5, and 13.1 h, respectively. The U.S. Soil Conservation Service and Airport equations provided the best estimates of t_c (6.1 and 5.9 h, respectively), though all equations underestimated t_c. Lag time and t_p were variable and related to storm duration. Equations describing relationships between peak discharge, antecedent flow, total rainfall, and surface runoff were developed. Surface runoff was also correlated to event rainfall and the 14-day antecedent precipitation index. All rainfall-runoff relationships demonstrated strong correlation. Peak and antecedent flow appeared to be correlated to the 30-minute maximum rainfall intensity. These attributes characterize rural watersheds and provide the basis for modelling their hydrological responses. **Keywords**: antecedent flow, lag time, peak flow, precipitation, rainfall intensity, storm duration, surface runoff, time of concentration, time to peak.

Nous avons étudié l'hydrologie d'un petit bassin versant du Québec. Trente-et-un événements hydrologiques ont été analysés. Les temps de concentration, le temps de décalage et le temps de montée moyens mesurés ont été de 7.4, 8.5 et 13.1 heures, respectivement. Les équations SCS et Airport ont donné les meilleurs estimations de t_c (6.1 et 5.9 heures, respectivement). Toutes les équations testées ont sous-estimé t_c. Le temps de décalage et le temps de montée étaient variables et reliés à la durée de la pluie. Des équations décrivant les relations entre le débit de pointe, le débit initial, la pluie totale et le ruissellement de surface ont été développées. Le ruissellement de surface a été corrélé à la pluie totale et l'indice de précipitation antécédente. Toutes les relations précipitation-ruissellement ont démontré une forte corrélation. Le débit de pointe et le débit initial semblaient être fonction de l'intensité maximale de la pluie pour une période de 30 minutes. **Mots clés**: débit initial, débit de pointe, intensité de pluie, précipitation. temps de concentration, temps de décalage, temps de montée, temps de pluie, ruissellement de surface.

INTRODUCTION

An evolving concern in water quality policy and research is the management of non-point source (NPS) pollution. Intensive agricultural production has been associated with NPS pollution in many jurisdictions in North America. In the province of Quebec, the study and management of NPS pollution is limited by the lack of hydrologic data from intensive agricultural watersheds. These data are necessary for the development and testing of water quality models capable of representing the agricultural regions of Quebec.

Adequate watershed characterization requires the collection of data describing several variables such as precipitation depth, intensity, duration, and streamflow volume as well as how these parameters change with time. Data relating soil texture, land use, and topographic variation also contribute to the description of a watershed.

The hydrologic response of a watershed to rainfall events is assessed through analysis of hydrograph parameters such as the time to peak (t_p), the time of concentration (t_c), and the lag time (t_l) as well as surface runoff volume and peak flow. Further watershed characterization can be achieved by investigating relationships that may exist between hydrologic and meteorological parameters.

Presently, most hydrologic modeling studies in Quebec focus on the application of existing models, developed outside the province, to soil and hydrologic conditions in Quebec. Research aimed at characterizing the hydrologic response of Quebec watersheds is limited. Furthermore, available literature is often restricted to relatively uncirculated governmental publications. For example, Desforges (1970) developed linear regression equations to describe rainfall-runoff relationships for rainfall events occurring on four sub-watersheds of the La Chaudière River Basin. The variables studied included runoff, total precipitation, specific initial flow (initial flow divided by watershed area), along with various antecedent precipitation indices and a storm heterogeneity parameter taken as the ratio of maximum to minimum point rainfall observed between meteorological stations. Hoang (1979) used three antecedent precipitation classes to correlate rainfall and runoff on watersheds in the Estrie region. Monfet (1981) used meteorological data from 55 watersheds in southeastern Quebec to construct synthetic unit hydrographs.

A hydrologic and water quality study of the St. Esprit watershed was initiated in 1993. The watershed is located approximately 50 km northeast of Montreal between the towns of St. Esprit and St. Jacques. We investigated the hydrologic relationships within the St. Esprit watershed based on three years of data. General relationships, variables, and parameters often considered for predicting runoff and peak flow were compared. These form the numeric attributes to characterize rural watersheds in Quebec and serve in modelling their hydrologic regimes.

MATERIALS and METHODS

Watershed description

The study watershed consists of an upper portion of the St. Esprit River Basin located approximately 50 km northeast of Montreal (Fig. 1). The area of the watershed is 26.1 km^2. Of the total area, approximately 1680 ha (64%) are annually cropped, 575 ha (22%) are forested, and 350 ha (14%) represent residential or uncropped areas. Approximately 50% of the cropped land is subsurface drained. No village or industrial area lies within the watershed boundary. Agricultural land use on the watershed is described in Table I; soil textural classes are given in Table II.

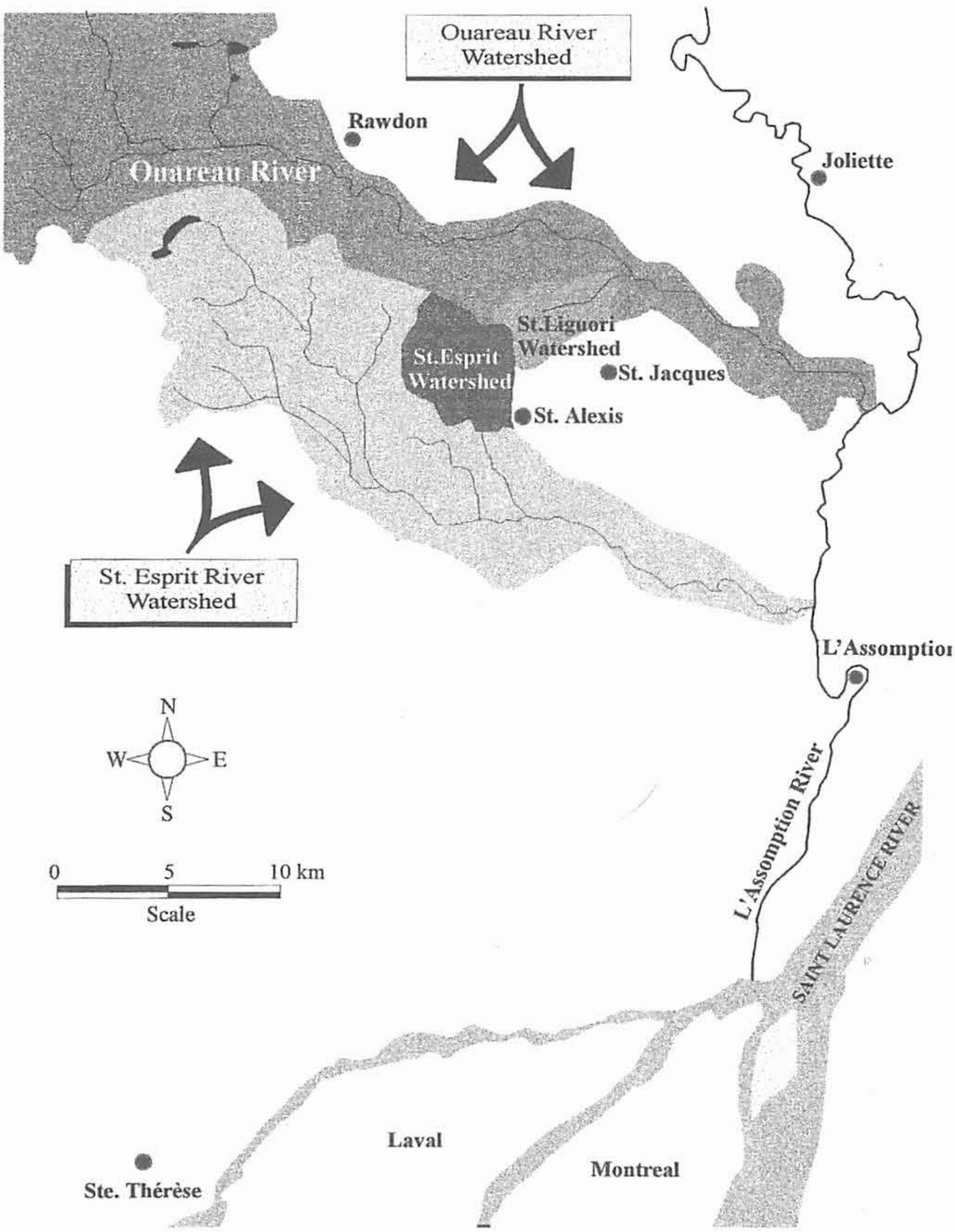

Fig. 1. Location of the St. Espirit Watershed.

The watershed topography is flat to rolling. The slope of cultivated land is generally between 0 and 3%. Tops of ridges, land with slopes over 5%, and stony areas tend to be forested. The average basin slope is approximately 1.65%. The main channel is 9 km in length and experiences a 40 m drop in elevation from the highest point to the outlet.

The climate is temperate. Average annual precipitation is 1087 mm, while average annual evapotranspiration is 572 mm. The average annual temperature is 5.2 °C.

Instrumentation

A stream gauging station at the basin outlet and the meteorological station were established in the winter of 1993-94 (Fig. 2). Instrumentation for the gauging station is housed in a building (1.8 x 2.4 m) constructed adjacent to the control section. The building is supplied with AC elctrical power and is heated. A Campbell CR10 datalogger is installed in the building to monitor all automated sensors. The water level sensor is a Druck 950 (0 to 34.5 kPa range) submersible pressure transducer (SRP Control Systems Ltd., Mississauga, ON) buried in the streambed at the control section. A second water level sensor consists of a UDG01 ultrasonic level sensor (Campbell Scientific Canada Corp., Edmonton, AB). A backup system consisting of a Flowlog datalogger (AGC System and Technologies Inc., Mirabel, QC) is used to measure water level and flow velocity independently.

A rating curve was developed for the river at the control section. An OSS-PC1 propeller meter was used to take velocity measurements in 0.5 m intervals across the control section. A three-point method was used when water levels permitted. One and two point methods were used during low flow periods. The rating curve was programmed into the Campbell datalogger. The datalogger was programmed to calculate and store discharge data at 15-minute intervals.

The meteorological station was also equipped with a Campbell CR10 datalogger and automated sensors for measuring air and soil temperature, solar radiation, wind speed and direction, snow accumulation, and precipitation.

Table I. Agricultural land-use on the St. Esprit Watershed

Land-use	Area (ha)	Area (%)
Corn	604	35.9
Cereals	347	20.6
Soybeans	82	4.9
Vegetables	236	14.0
Hay	307	18.3
Pasture	106	6.3
Total	1682	100.0

Data analysis

The hydrologic response of a watershed to rainfall events is assessed through analysis of hydrograph time parameters. The most commonly used parameters to describe the rising limb of a hydrograph are time to peak (t_p), time of concentration (t_c), and lag time (t_l) (Fig. 3). Time to peak is defined as the time from the onset of excess rainfall to the attainment of peak flow at the outlet of the watershed. Time of concentration is defined as the time for all areas of the watershed to contribute runoff at the outlet. It can be measured as the time from the onset of rainfall to the positive inflection point on the rising limb of the hydrograph or as the time interval between the cessation of rainfall and the inflection point on the receding limb of the hydrograph (Viessman et al. 1989). Lag time is defined as the difference in time between the centre of mass of effective rainfall and the centre of mass of runoff at the outlet, or alternatively as the mean flood wave travel time (Viessman et al. 1989). Both the time of concentration and lag time are theoretically regarded as constants for a given watershed.

Table II. Soil textural classes on the St. Esprit Watershed

Soil class	Area (ha)	Area (%)
Sand	214	8.2
Loamy sand	147	5.7
Sandy loam	960	36.8
Loam	117	4.5
Silty clay loam	80	3.1
Sandy clay	27	1.0
Clay loam	487	18.6
Clay	576	22.1
Total	2608	100.0

The receding limb of a hydrograph can be represented by recession constants (K, C). The recession constant (K) is measured as the slope and C is the intercept of the best-fit line of q_1 as a function of q_0 over a constant time interval, where q_0 is the discharge at the beginning of the interval and q_1 is the discharge at the end of the interval. Recession constants were determined for hydrologic events in order to investigate possible applications for hydrologic simulation.

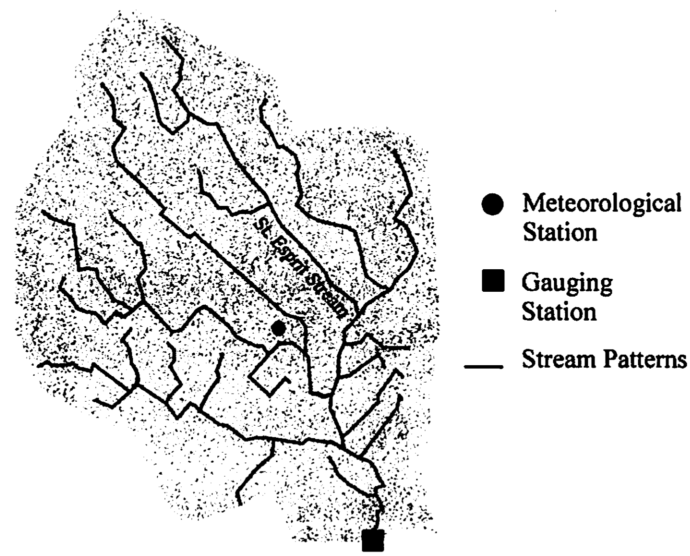

Fig. 2. Instrumentation and stream paterns on the St. Espirit Watershed.

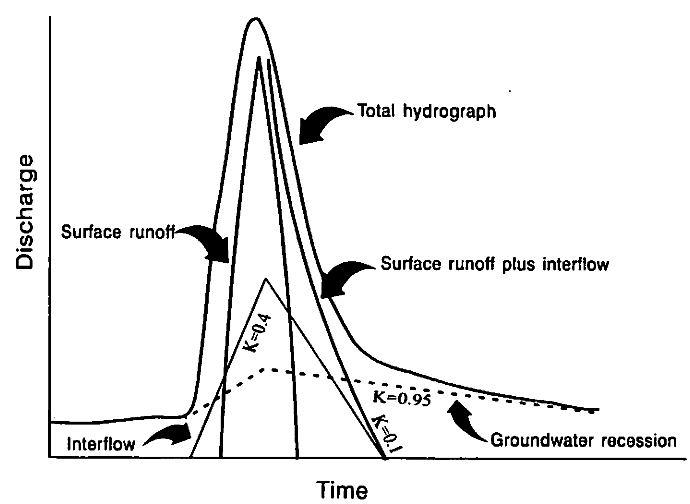

Fig. 3. Hydrograph properties.

Thirty-one rainfall-runoff events were observed from the period April 1994 to November 1996 and were subjected to further analysis. Measured parameters for each event are total precipitation, storm duration, maximum 30-minute and one-hour precipitation intensity, peak flow at the outlet, antecedent flow or flow prior to onset of rainfall at the outlet, runoff volume, t_p, t_c, t_l, and the recession constants. Unless otherwise indicated, time of concentration for each event was measured as the interval between the onset of rainfall and the inflection point on the rising limb of the hydrograph, because inflection points on the rising limb were generally more easy to define than those on the receding limb. Recession constants were determined for two recession phases for each hydrograph. The first phase applies from peak flow to the inflection point on the receding limb; it is represented by the constants K_1 and C_1, where K_1 and C_1 represent the slope and y-intercept of the best-fit line defining the relationship between q_1 versus q_0 during the first recession phase. The second phase is from the inflection point to the base of the receding limb and is represented by similar parameters, K_2 and C_2.

The measured values of t_c and t_l were compared to values calculated by some widely used methods. Such calculations were performed to determine whether these methods are applicable to t_c and t_l estimation on the St. Esprit Basin. The calculation methods chosen are of a similar form with channel length and slope being the variables common to each equation.

SCS method (SCS 1972)

$$t_l = 0.0063 L^{0.8} \left[\frac{111}{N} - 1 \right]^{0.7} S^{-0.5} \quad (1)$$

where:
- t_l = lag time (h),
- L = length of main channel (m),
- S = average basin slope (%), and
- N = curve number which was taken as 80, based on the average N for each event required to produce the runoff measured.

Based on this equation, the time of concentration (t_c) is given as t_l /0.6.

Kirpich equation (OMTC 1982)

$$t_c = \frac{0.0195 L^{0.77}}{S^{0.385}} \quad (2)$$

where:
- t_c = time of concentration (min),
- L = length of main channel (m), and
- S = basin gradient (m/m).

Bransby-Williams (Maidment 1993)

$$t_c = \frac{14.6 L}{S^{0.2} A^{0.1}} \quad (3)$$

where:
- L = length of main channel (km),
- S = slope of travel path (m/m), and
- A = drainage area (km^2).

Airport (OMTC 1982)

$$t_c = \frac{3.26(1.1 - C) L^{0.5}}{S^{0.33}} \quad (4)$$

where:
- C = runoff coefficient taken as 0.23,
- L = length of main channel (m), and
- S = slope of travel path (%).

Empirically derived relations were assessed for their applicability to model hydrologic behaviour of the watershed. Hydrograph time parameters, peak discharge, and surface runoff were the main variables investigated. The following possible, sometimes previously tested (Desforges1970; Hoang 1979; Monfet 1981), relationships in Quebec, were considered:

$$t_p, t_l, t_c = f(D, P, P_{60}, P_{30}, P_{av}, Q_p) \quad (5)$$

$$Q_p = f(D, I, P, P_{60}, P_{30}, P_{av}, R) \quad (6)$$

$$R = f(D, I, P, P_{60}, P_{30}, P_{av}) \quad (7)$$

where:
- Q_p = peak flow (m^3/s),
- R = surface runoff (mm),
- D = rainfall duration (h),
- I = antecedent flow (m_3/s),
- P = precipitation depth (mm),
- P_{60} = maximum 1-hour rainfall intensity (mm/h),
- P_{30} = maximum 30-minute rainfall intensity (mm/h), and
- P_{av} = average rainfall intensity calculated as P/D (mm/h).

Stream discharge prior to the beginning of a storm was considered for peak flow and surface runoff prediction, as it is a good index of moisture conditions in humid and subhumid areas (Linsley et al. 1949). Furthermore, antecedent flow is sometimes used in watershed studies (Hewlett et al. 1977; Hewlett and Bosch 1984).

Rainfall intensity was investigated as a possible correlation parameter because short bursts of rainfall are considered to be important to total storm rainfall and the peak discharge attained (Bonta et al. 1992). When determining rainfall-runoff relationships, rainfall intensity is often included as a variable (Hewlett et al. 1977; Bonta et al. 1992; Felton 1994). Several possible relationships between rainfall intensity (average, 60-minute, and 30-minute) and other hydrologic parameters were investigated. Rainfall events producing peak flows less than 1 m^3/s were not considered.

Other variables used in this analysis include the percentage of rainfall appearing as surface runoff (R_r) and the antecedent precipitation index (API) defined by the equations:

$$R_r = \frac{R(100)}{P} \quad (8)$$

$$API = kP_1 + k^2 P_2 + \ldots\ldots + k^n P_n \quad (9)$$

where:
- $P_1, P_2, \ldots P_n$ = precipitation depth 1, 2, ... n days prior to the event, and
- k = a constant < 1 and = 0.85 for Quebec (Monfet 1979).

Empirical relations were developed in order to assess the adequacy of simple mathematical models to explain the runoff hydrology of the watershed. In general, it can be said that the antecedent flow and antecedent precipitation index aided greatly in the establishment of relationships between peak flow, event rainfall, and surface runoff.

Table III. Observed hydrologic events

Date	P (mm)	D (h)	P_{60} (mm/h)	P_{30} (mm/h)	Q_p (m^3/s)	I (m^3/s)	t_p (h)	t_l (h)	t_c (h)	R (mm)
94-04-16	14.5	7.25	5.1	6.2	11.02	4.56	7.25	4.5	4.0	5.16
94-04-27	8.1	6.75	1.0	1.2	2.66	1.62	11.8	7.75	5.0	0.98
94-05-01	20.8	17	3.6	4.4	3.06	0.88	18.5	11.5	4.0*	2.98
94-05-16	46.4	24.25	6.6	7.2	3.47	0.39	17.5	12.75	11.5	5.78
94-05-26	18.2	10.5	3.7	4.8	1.13	0.41	12.8	8	9.5	0.86
94-06-13	23.8	5	8.4	10.2	3.28	0.49	9.75	6.25	7.25	1.94
94-06-25	47.0	7.5	14.6	16.0	4.01	0.19	10.75	7	3.5	4.14
94-06-27	41.0	5.25	17.9	20.8	12.13	1.11	8.5	5.75	3.75	9.68
94-06-29	19.8	4.0	5.7	6	5.25	1.40	8.5	6.75	4.25	3.24
94-07-02	9.2	2.75	5.3	7.8	1.58	0.85	7.5	6.5	5.5	0.47
94-07-05	20.2	3.5	10.1	15.2	2.31	0.55	8.5	6.5	5.75	1.22
94-07-09	16.2	0.75	25.1	42.2	2.9	0.65	5.75	5	3.25	1.56
94-07-16	12.0	2.25	15.8	28.2	0.49	0.3	8	6.5	4	0.16
94-07-23	21.2	5.25	12.5	17.6	2.06	0.19	11.3	9	8.0*	1.51
94-07-26	4.2	1.25	10.5	11.4	0.63	0.38	7.5	6.75	8.0*	0.16
94-08-02	42.6	6.5	11.1	14.4	3.46	0.24	10.0	7.0	5.5	3.55
94-08-04	19.2	5.0	15.4	29.4	2.75	0.52	9.0	7.25	5	2.39
94-11-01	52.2	26.5	5.7	6.4	1.06	0.1	30	16.75	6.0*	1.85
94-11-06	13.8	16.0	1.7	2.4	0.74	0.33	20.25	13.0	8.0*	0.63
95-04-12	20.4	13.5	5.0	7.4	1.69	0.38	18.75	10.25	15.0	1.33
95-04-19	11.4	9.75	6.0	9.6	0.78	0.43	13.5	9.25	8.25	0.5
95-04-21	14.0	4.5	6.8	7.2	1.23	0.49	9.5	7.5	7.5*	0.8
95-05-17	15.8	6.5	4.9	5.2	1.68	0.52	12	8.0	9.25	0.88
95-07-20	12.2	2.75	13.7	17.6	0.30	0.14	7.5	6.0	6.75	0.17
95-07-23	35.8	7.25	11.9	21.2	0.77	0.12	9.5	7.0	6.0	0.81
95-07-26	12.2	0.5	-	24.4	0.39	0.20	8	7.75	6.5	0.19
95-10-06	54.0	30.0	8.3	9.0	0.98	0.13	31.75	23.25	13.5	2.25
95-10-22	39.3	8.0	7.8	8.8	2.39	0.23	11.75	2.0	9.75	2.05
95-11-02	32.8	13..0	4.4	4.8	2.73	0.58	14.5	13.25	9.5	2.80
96-10-21	82.1	26.0	7.6	8.0	7.07	0.15	21.0	16.5	11.0	9.13
96-11-09	99.0	28.0	14.2	19.6	17.13	0.32	26.75	7.75	12.5	28.9

*t_c measured from peak flow to inflection point on receding limb

RESULTS and DISCUSSION

Measured parameters for the selected rainfall-runoff events are given in Table III. They include total event precipitation depth (P), rainfall duration (D), maximum 60 and 30-minute rainfall intensity (P_{60}, P_{30}), peak discharge (Q_p), antecedent flow (I), time to peak (t_p), time of lag (t_l), time of concentration (t_c), and surface runoff (R).

Hydrograph parameters

The mean value of t_c was determined to be 7.4 h with a standard deviation of 3.1 h. No apparent correlation was found between the value of t_c and any of the other parameters. Based on these preliminary results, although the measured value of t_c varied considerably, this variation is attributed to errors in deriving time of concentration directly from hydrographs, because no clear statistical or correlation trend was elucidated by the data. Storm pattern characteristics that were not evident in the data analysis may have also contributed to the variation in t_c. However, considering the range of t_c values (3.5 to 15 h), it would appear that t_c cannot be considered a constant on this basin. This implies that methods developed to estimate t_c must allow for some variability in t_c duration.

Time of concentration as determined by the SCS, Kirpich, Bransby-Williams, and Airport equations are given in Table IV along with the average measured value. The value determined by the Kirpich equation (3.1 h) underpredicted the time of concentration by more than half. The Bransby-Williams equation also underestimated t_c as 4.7 h. The underprediction of the time of concentration by the Kirpich and Bransby-Williams equations for watersheds in the Ottawa-St. Lawrence lowlands was noted as well by Madramootoo and Enright (1988) who attributed the result to the fact that the Kirpich equation was developed on steeper watersheds. The SCS and Airport equations yielded estimates of 6.1 h and 5.9 h, respectively, and were the closest to the average measured value, 7.4 h. These more accurate predictions may be attributed to the fact that both equations, Eqs. 1 and 4, provide factors that account for soil texture and land use characteristics (curve number and runoff coefficient). All four equations underestimated the average time of concentration, because none of the four was able to account for some of the watershed factors such as relatively flat slope. Under flat slope conditions, surface storage may become an important hydrologic factor and contribute to a higher t_c.

Table IV. Measured and calculated values of t_c.

Method	t_c (h)
Measured	7.4
SCS	6.1
Kirpich	3.1
Bransby-Williams	4.7
Airport	5.9

The apparent relative success of the SCS equation is overshadowed by the fact that an estimated value of 6.1 h for t_c yields an estimated lag time of 3.7 h (Eq. 1). This is less than half the mean of the measured values of t_l, 8.5 h with a standard deviation of 4.2 h. If only storms with a duration less than the time of concentration are considered, then the mean of the measured lag times is 7.1 hr with a standard deviation of 1.3 hr. This measure of lag time decreases the value of t_l as well as its variability; it represents a reasonable assumption, because lag time is a measure of mean flood wave travel time. The flood wave generated by storms of a duration less than t_c should not be dependent on storm characteristics and, therefore, should provide a better estimate of lag time. This suggests that although lag time is theoretically considered a constant, it appears to be variable, depending on storm characteristics. Figure 4 shows the best-fit plot of lag time versus rainfall duration. The curve is defined by the relationship:

$$t_l = \frac{1}{0.157 - 0.00347D} \quad (10)$$

The r^2 value for this line is only 0.70 but increases to 0.91 if the outlier at a rainfall duration of 28 h is omitted. It seems that in this instance, lag time is not a constant and depends on rainfall duration. Errors involved in the measure of lag time include the problem posed by using point rainfall data to estimate the centroid of rainfall excess for the whole basin. This method of lag time estimation may especially influence events of long duration and irregular storm pattern such as the outlier storm of November 9, 1996.

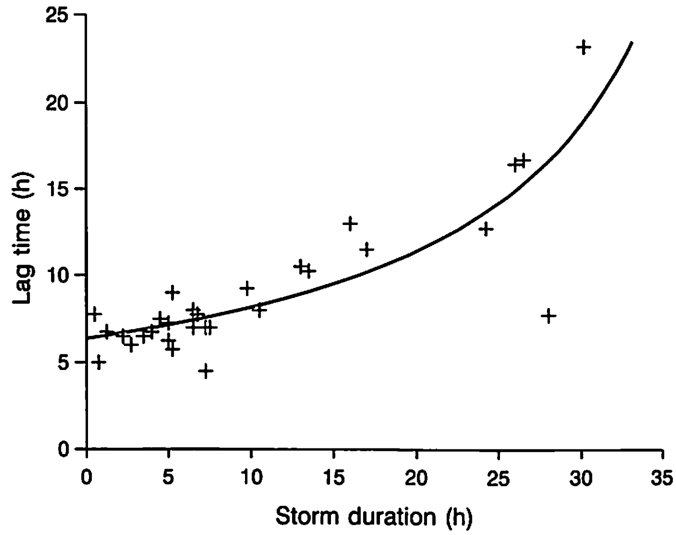

Fig. 4. Lag time versus rainfall (storm) duration.

The average time to peak was 13.1 h with a standard deviation of 6.8 h. Time-to-peak was related to the rainfall duration as shown in Fig. 5. The mathematical relationship of the best-fit line is:

$$t_p = 0.743D + 5.77 \quad (11)$$

The r^2 value for this fit equals 0.90. The constant in Eq. 11 (5.77) is of some significance as it represents the time-to-peak of an instantaneous storm, that is, a theoretical rainfall of duration zero and is therefore an alternate measure of the lag time (t_l). This constant is similar in value to the y-intercept of 6.37 in Eq. 10. This suggests a range of approximately 5.75 to 6.5 h as a minimum lag time. The good correlation of Eq. 11 suggests that t_p is highly dependent on rainfall duration. The inclusion of other storm characteristics in the relation may improve the correlation, although the significance of such an improvement would be marginal.

Recession constants

For the determination of the recession constants, the value of r^2 as a measure of goodness-of-fit exceeded 0.93 for all events for the determination of K_1 and C_1, and it exceeded 0.99 for all events for the determination of K_2 and C_2. The mean value of K_1 is 1.13. The value of C_1 was related to the magnitude of flow as shown in Fig. 6. Based on these results, the first recession phase of the hydrograph can be described by:

$$q_1 = 1.13q_0 - 0.107Q_p - 0.1 \qquad Q_p < 4m^3/s \quad (12a)$$

applied from peak flow to the inflection point on the receding limb. However, this equation may yield erroneous results for peak flows greater than 4 m^3/s. This stems from a lack of available data for events yielding peak flows above this discharge value. A more complete data set will help to validate Eq. 12a.

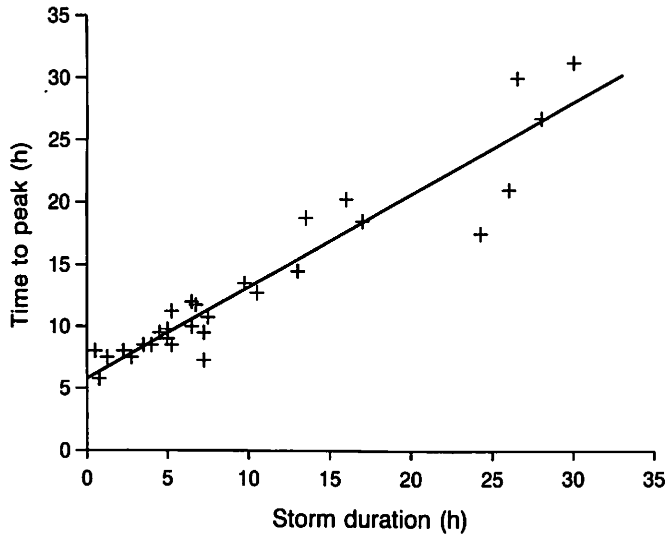

Fig. 5. Time to peak flow versus rainfall (storm) duration.

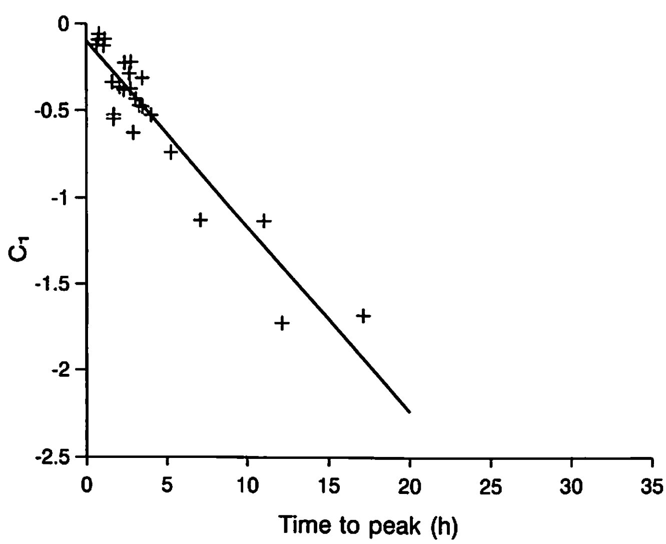

Fig. 6. C_1 versus time to peak flow.

The value of C_2 is approximately equal to zero. Therefore, the recession in the second phase is governed only by the value of K_2, the mean of which was found to be 0.974. Consequently, the recession from the inflection point to the base of the recession limb can be described by:

$$q_1 = 0.974 q_0 \tag{12b}$$

Equation 12b describes the general pattern of the second recession phase and appears to behave independently of any other hydrologic or meteorological characteristics.

Rainfall-runoff relationships

Figure 7 shows a plot of the peak flow-antecedent flow ratio versus event rainfall volume. The best-fit curve describes the relationship as:

$$\frac{Q_p}{I} = 0.00513P^2 + 0.0518P + 1.0545 \tag{13}$$

where all parameters are as previously defined. The r^2 value for this curve is 0.93, indicating a strong relationship. No satisfactory relationship was found when only peak flow was considered. The inclusion of antecedent flow provided a relative measure of antecedent watershed moisture conditions. The accuracy of Eq. 13 would likely improve if rainfall were measured at several points across the watershed.

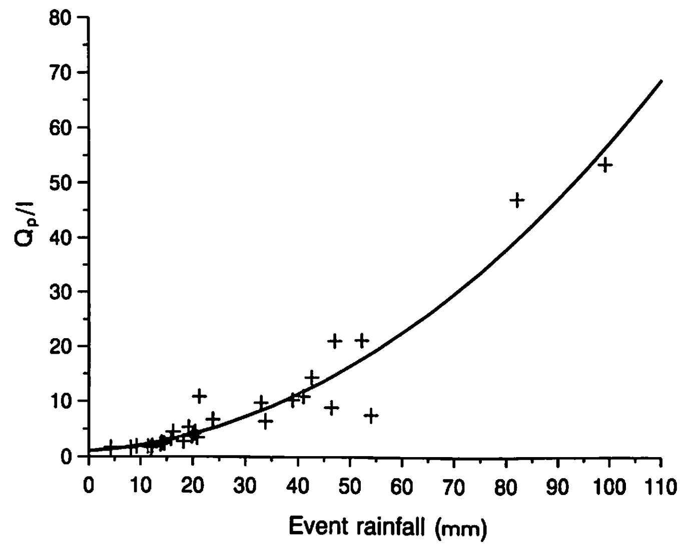

Fig. 7. Peak flow (Q) to antecedent flow (I) ratio versus event rainfall volume.

Figure 8 is a plot of peak flow above antecedent flow (Q_p - I) versus surface runoff. The best-fit curve for this plot also follows the form of a quadratic equation and can be described as:

$$Q_p - I = -0.016R^2 + 1.0465R - 0.0135 \tag{14}$$

where all parameters are as previously defined. The r^2 value for this equation equals 0.94. Only events producing a minimum of 1 mm of surface runoff were used to derive Eq. 14. Events that occurred in April or late November were excluded because these storms occurred under considerably different hydrologic conditions (i.e., snowmelt, partially crusted soil) than runoff events that took place during the growing season. The presence of different hydrologic conditions during these months and the difficulty of simulating surface runoff yields of less than 1 mm were suggested by the application of an existing hydrologic model to this basin (Perrone and Madramootoo 1997).

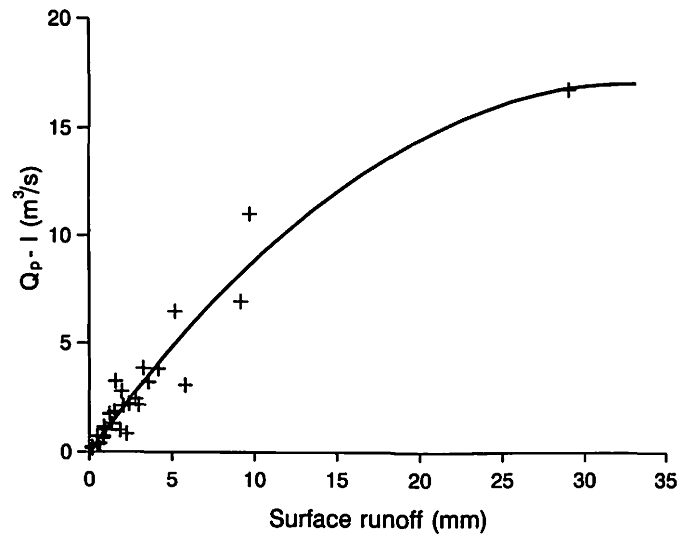

Fig. 8. Peak flow (Q_p) above antecedent flow (I) versus surface runoff.

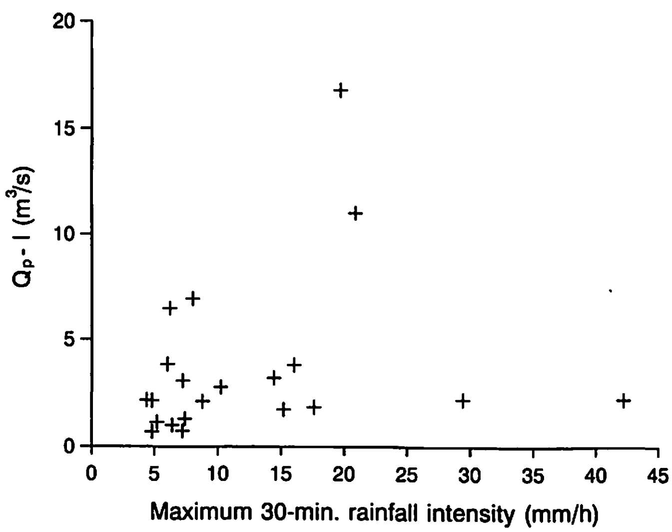

Fig. 10. Peak flow (Q_p) above antecedent flow (I) versus maximum 30-min rainfall intensity.

If Eqs. 13 and 14 are combined and the constants for Eqs. 13 and 14 are simplified as being 1 and 0, respectively, then an expression is obtained:

$$R(1.0465 - 0.016R) = IP(0.00513P + 0.0518) \quad (15)$$

Equation 15 represents a relatively simple expression of surface runoff as a function of total storm rainfall depth and antecedent flow. Therefore, if the value of I is known, surface runoff can be estimated for any rainfall depth. The validity of any of the three equations is subject to verification with future data from rainfalls of relatively large magnitude. However, the existing data do show a definite trend worthy of further investigation.

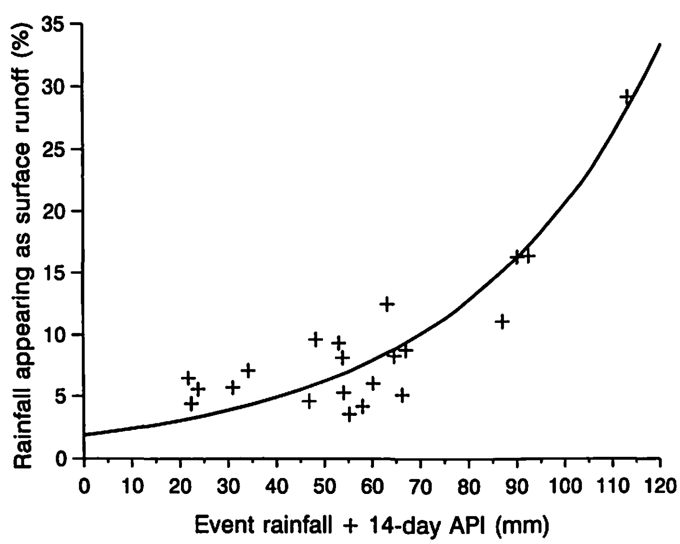

Fig. 9. Rainfall appearing as surface runoff versus cumulative event rainfall and 14-day Antecedent Precipitation Index.

A plot of the percentage of rainfall from a storm appearing as surface runoff versus the sum of event rainfall and the 14-day antecedent precipitation index for each event is shown in Fig. 9. The equation for the best-fit curve is:

$$R_r = 1.88\exp[0.024(P + API)] \quad (16)$$

The r^2 value for this fit is 0.84. As with Eq. 14, selected events had to meet a minimum runoff as well as a seasonal requirement. The use of a weighted antecedent moisture variable such as API helped a great deal in defining this relationship. However, when the U.S. Soil Conservation Service's five-day Antecedent Moisture Condition, which simply represents the cumulative rainfall occurring during the previous

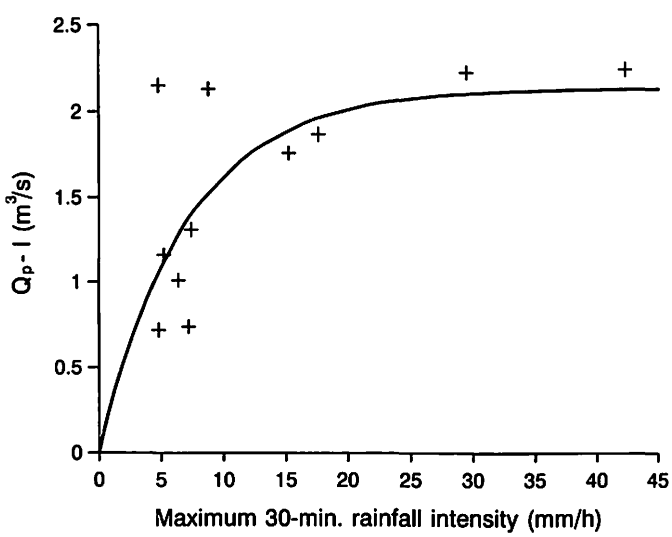

Fig. 11. Peak flow (Q_p) above antecedent flow (I) versus 30-min rainfall intensity ($3 > Q_p > 1$).

five days, replaced the API in Eq. 16, the r^2 value was only 0.52. Improved rainfall measurement over the basin area would increase the correlation of this relationship. Errors were also introduced in the determination of surface runoff from hydrograph separation procedures.

Rainfall intensity

The only apparent relationship discovered between rainfall intensity and all other parameters is shown in Figs. 10 to 13. Figure 10 shows the scatter plot that is obtained when all events are grouped together. Upon closer analysis, if events are classified with respect to the magnitude of peak discharge, the relationships described by Figs. 11 to 13 are produced. These figures represent best-fit curves of peak flow above antecedent flow (Q_p - I) versus the maximum 30-minute rainfall intensity. Figure 11 represents low flow events yielding peak discharges between 1 and 3 m^3/s. Figure 12 represents medium size events for $5 > Q_p > 3$ m^3/s and Fig. 13 represents the relatively large events for $Q_p > 5$ m^3/s.

The three peak flow classes represent broad categories for the data gathered so far. The best-fit curve for each class follows an exponential pattern with associated equation and coefficient of determination:

$$Q_p - I = 2.14[1 - \exp(-0.141 P_{30})] \quad 3 > Q_p > 1 m^3/s \quad (r^2 = 0.63) \qquad (17)$$

$$Q_p - I = 3.59[1 - \exp(-0.212 P_{30})] \quad 5 > Q_p > 3 m^3/s \quad (r^2 = 0.94) \qquad (18)$$

$$Q_p - I = 22.77[1 - \exp(-0.047 P_{30})] \quad Q_p > 5 m^3/s \quad (r^2 = 0.86) \qquad (19)$$

where all variables are as previously defined. Two of the three equations (Eqs. 18 and 19) yield r^2 values greater than 0.85, indicating a good fit. Equation 17 has a considerably lower r^2 value, but improves to 0.88 if one of the outliers ($P_{30} = 4.8$, Q_p-I = 2.15) is omitted. It is possible that inclusion of more data and other variables or parameters in these equations could yield better relationships.

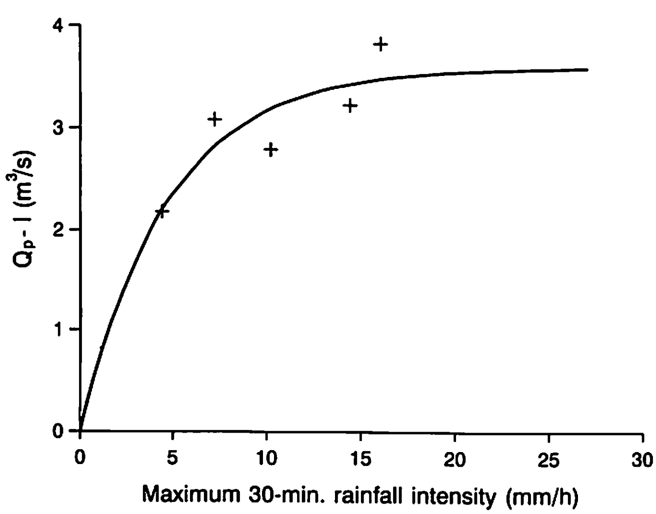

Fig. 12. Peak flow (Q_p) above antecedent flow (I) versus 30-min rainfall intensity ($5 > Q_p > 3$).

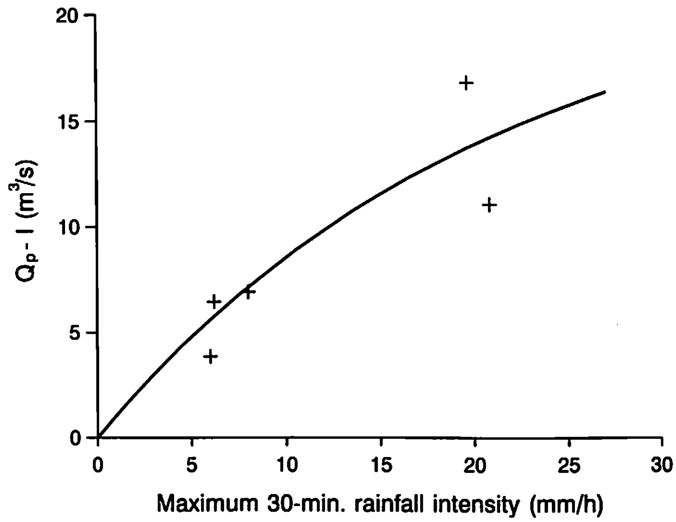

Fig. 13. Peak flow (Q_p) above antecedent flow (I) versus 30-min rainfall intensity ($Q_p > 5$).

The large variability in rainfall intensity within the watershed tends to question the use and validity of point rainfall data for such an investigation. With additional data in the future, determination of any relationship between rainfall intensity and streamflow will be more apparent.

CONCLUSIONS

A hydrologic study of a 26 km^2 agricultural watershed in Quebec was undertaken. The objective of this study was to develop some empirical relationships to better understand the hydrologic characteristics of the basin. These relationships could be used in the future to aid in the development of hydrologic and water quality models applicable to the agricultural regions of Quebec.

Although the measured time of concentration (t_c) was variable, the parameter's variation was probably due to the inherent error of deriving t_c from hydrographs, because no apparent relationship was found to exist between t_c and storm characteristics. Lag time (t_l) was found to vary from storm to storm. However, a linear relationship was identified between t_l and storm duration. A similar relationship was found between time to peak and storm duration. Recession characteristics were identified which were consistent for each storm.

Simple empirical relationships were evaluated with respect to rainfall and runoff. Several relationships were formulated to describe the hydrology of the watershed. Quadratic equations were used to relate peak and antecedent flow to event rainfall volume and surface runoff. An exponential relationship was found to exist between surface runoff and rainfall and antecedent precipitation. The rainfall-runoff relationships exhibited generally strong correlation.

Relationships were found to exist between peak and antecedent flow and the maximum 30-minute rainfall intensity. Though larger coefficients of determination were calculated for two of the three equations, the separation of events into three peak discharge classes diminished the amount of data available for each of the three correlations attempted.

Point rainfall measurements and graphically derived runoff volumes and hydrograph characteristics contributed to most of the error in the relationships presented. As more data become available, more complete databases should be constructed to refine the empirical relations described herein, as well as to investigate other possible hydrologic and meteorological relationships.

The preliminary investigation reported should prove useful in assessing and developing models to describe the hydrology and water quality of this basin as well as other watersheds in Quebec of the same physiographic type.

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REFERENCES

Bonta, J.V. and A.R. Rao. 1992. Estimating peak flows from small agricultural watersheds. *ASCE Journal of Irrigation and Drainage Engineering* 118(1): 122-137.

Bruce, J.P. and R.H. Clark. 1966. *Introduction to Hydrometeorology*. Oxford, England: Pergamon Press.

Desforges, P. 1970. Relations pluie-ruissellement bassin versant de la Chaudière. Publication HP-26. Direction générale des eaux, Service de l'hydrométrie, Ministère des Richesses Naturelles, Québec, QC.

Felton, G.K. 1994. Hydrologic response of a karst watershed. *Transactions of the ASAE* 37(1): 143-150.

Hewlett, J.D. and J.M. Bosch. 1984. The dependence of storm flows on rainfall intensity and vegetal cover in South Africa. *Journal of Hydrology* 75: 365-381.

Hewlett, J.D., J.C. Fortson and G.B. Cunningham. 1977. The effect of rainfall intensity on storm flow and peak discharge from forest land. *Water Resources Research* 13(2): 259-66.

Hoang, V.D. 1979. Études du coefficient de ruissellement sur des petits bassins versants des regions de l'Estrie et des Bois Francs. Publication HP-49. Direction générale des eaux, Service de l'hydrométrie, Ministère des Richesses Naturelles, Québec, QC.

Linsley, R.K., M.A. Kohler and J.L.H. Paulhus. 1949. *Applied Hydrology*. McGraw-Hill Civil Engineering Series. New York, NY: McGraw-Hill.

Madramootoo, C.A. and P. Enright. 1988. Applicability of the Soil Conservation Service equations for runoff prediction in the Ottawa-St. Lawrence lowlands. *Canadian Journal of Civil Engineering* 15(5): 759-765.

Maidment, D.R. (ed.). 1993. *Handbook of Hydrology*. New York, NY: McGraw-Hill.

Monfet, J. 1979. Evaluation du coefficient de ruissellement à l'aide de la méthode SCS modifiée. Publication HP-51. Service de l'hydromètrie, Ministere de l'Environnement du Québec, Québec, QC.

Monfet, J. 1981. La construction d'un hydrogramme unitaire synthétique. Publication HP-53. Direction des inventaires et de la recherche, Service des eaux de surface, Ministere de l'Environnement du Québec, Québec, QC.

OMTC. 1982. *Drainage Manual*, Vol. 1. Ontario Ministry of Transportation and Communications, Downsview, ON.

Perrone, J, and C.A. Madramootoo. 1997. Use of AGNPS for watershed modeling in Quebec. *Transactions of the ASAE* 40(5): 1349-1354.

SCS. 1972. Hydrology. Sect. 4. In *National Engineering Handbook*. Beltsville, MD: United States Department of Agriculture, Soil Conservation Service.

Viessman, W. Jr., G.L. Lewis and J.W. Knapp. 1989. *Introduction to Hydrology*, third edition. New York, NY: Harper Collins.