ZLEGROVE, B. M.
ıfort Sea pipelines.
hore, ASCE, San

Effects of agricultural drainage on streamflow in the Middle Thames River, Ontario, 1949–1980

SERGIO E. SERRANO
Department of Civil Engineering, University of Waterloo, Waterloo, Ont., Canada N2L 3G1

AND

HUGH R. WHITELEY AND ROSS W. IRWIN
School of Engineering, University of Guelph, Guelph, Ont., Canada N1G 2W1

Received May 7, 1984
Revised manuscript accepted August 6, 1985

The effects of surface and subsurface agricultural drainage on streamflow in the Middle Thames River have been studied through the analysis of changes in the volumetric response, changes in the seasonal distribution of streamflow volumes, and changes in the time distribution of runoff response of the Middle Thames in the period 1949–1980.

The results indicated that only small changes in streamflow behaviour occurred in the Middle Thames for the period studied. There is evidence of a reduction of less than 25% in the time-to-peak of storm hydrographs on the watershed, but with little change in peak flow rate or centroid-to-centroid lag time. This is consistent with increased channel velocities in hydraulically improved municipal drains, coupled with an increased proportion of storm flow being diverted from overland runoff to rapid subsurface runoff through subsurface pipe drainage. There is no evidence of appreciable changes in volumes of runoff for individual storms or as annual total streamflow or changes in seasonal distribution of streamflow.

Key words: agricultural drainage, streamflow, unit hydrograph, storm runoff.

Les effets du drainage agricole de surface et souterrain sur l'écoulement dans la rivière Middle Thames ont été étudiés par l'analyse des changements de la réponse volumérique, des changements dans la distribution saisonnière des volumes d'écoulement et des changements dans la distribution temporelle de la réponse de ruissellement de la rivière Middle Thames durant la période 1949–1980.

Les résultats indiquèrent que seulement de faibles changements de comportement d'écoulement ont eu lieu dans la rivière Middle Thames pour la période étudiée. Il y a évidence d'une réduction de moins de 25% du temps de pointe des hydrographes de tempête sur le bassin d'alimentation, mais avec de faibles changements du taux d'écoulement de pointe ou du délai du bassin. Ceci est conséquent avec les vélocités accrues des canaux dans les drains municipaux améliorés hydrauliquement, accouplé à une proportion augmentée de l'écoulement détourné du ruissellement de surface vers un ruissellement souterrain rapide à travers des égouts pluviaux. Il n'y a aucune évidence de changements appréciables dans les volumes de ruissellement pour des tempêtes individuelles, de l'écoulement annuel total, ou des changements dans la distribution saisonnière de l'écoulement.

Mots clés: drainage agricole, écoulement, hydrographe unitaire, ruissellement de tempête.

[Traduit par la revue]

Can. J. Civ. Eng. **12**, 875–885 (1985)

1. Introduction

Agricultural drainage activity became significant in Ontario in the middle of the last century (Kelly 1975). It has increased in extent and intensity especially in the last two decades and particularly across the southern portion of the province. In Ontario, agricultural drainage includes three types of action. These are the installation of subsurface drainage pipes and ditches within fields; the deepening, widening, and straightening of watercourses to provide adequate outlet for the water from the field drains; and the construction and operation of pumping stations for the removal of water from ditches. The extent of agricultural drainage works has created concern about undesirable effects of drainage works on elements of the hydrologic cycle within watersheds. Possible changes include enhanced frequency and magnitude of flood peaks downstream and reduced dry weather flows in downstream channels.

The first study on the effect of drainage in Ontario, by McCubbin (1938), concluded that there was little indication of increasing flooding due to agricultural drainage activities in southern Ontario. More recently, a study was made of annual mean, annual maximum, and annual minimum streamflow in southwestern Ontario to examine effects of agricultural drainage (Eddie 1982). This study also failed to find any discernible trends that might be associated with drainage.

Worldwide experience has demonstrated that surface and subsurface drainage sometimes does and sometimes does not produce important effects on streamflow (O'Kelly 1955; Hollander 1968; Trafford 1973; Whiteley 1975; Dybvig 1977; Shebeko 1978; Moore

---

NOTE: Written discussion of this paper is welcomed and will be received by the Editor until April 30, 1986 (address inside front cover).

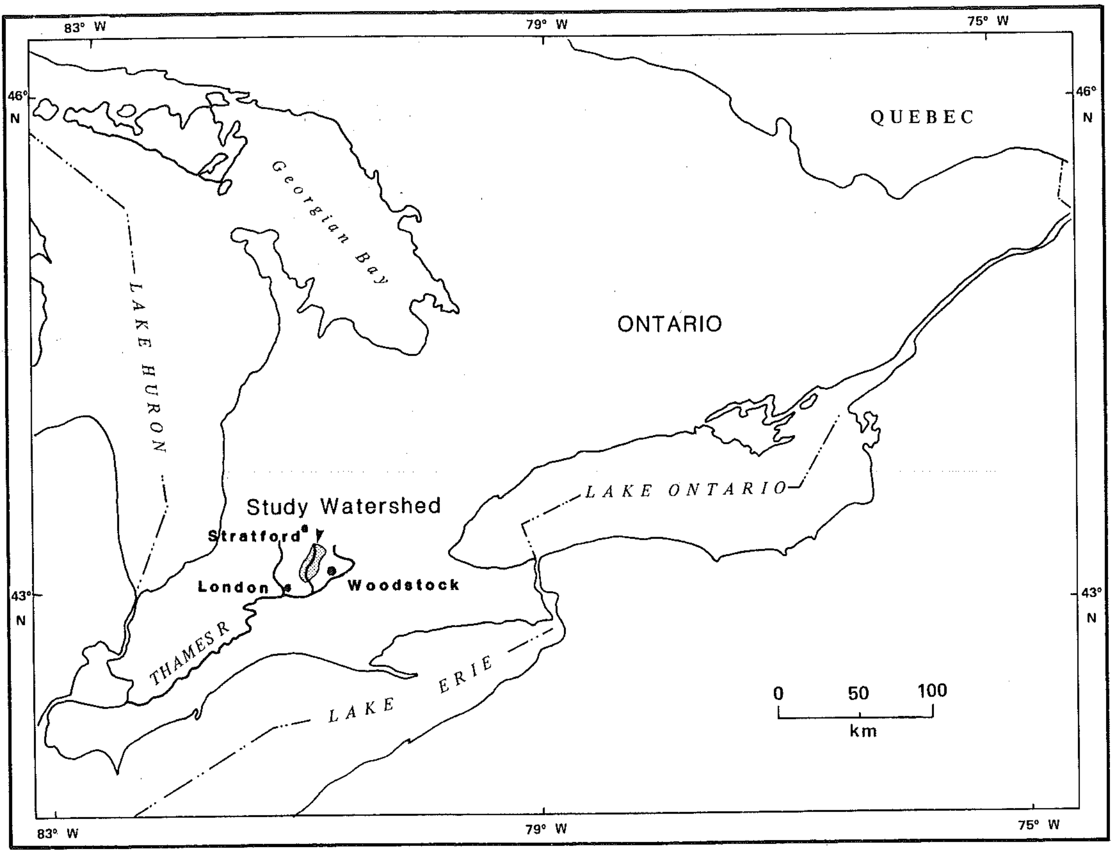

FIG. 1. Map of southern Ontario showing the location of the Middle Thames River watershed.

and Larson 1979). A review of the literature concerning the effects of agricultural drainage on streamflow has been prepared by Irwin and Whiteley (1983).

In order to examine the effects of agricultural land drainage on streamflow in southern Ontario, the School of Engineering at the University of Guelph is conducting a series of studies, one of which is the subject of this paper. A specific watershed was selected based on the following criteria, which express necessary conditions for a successful study of drainage effects on streamflow.

The watershed studied should be uniform in soil, topography, and other physiographic features. This limits choice to small (<1000 km^2) watersheds. Other land-use changes, such as reservoir construction, groundwater exploitation, urbanization, deforestation, or changes from pasture to cultivated crops, should not be present in the watershed, since hydrological methods are not able to easily distinguish between effects due to drainage and effects due to other land-use changes. There should be substantial amounts of drainage construction during the period of hydrological observations. Most important, there should be adequate hydrological and meterological data available.

2. Methods of analysis

Most studies of the effects of changes of land use on streamflow employ data from two periods, one period before and the other after the change. Construction of agricultural drainage typically is gradual and continuous; the extension of construction over many years does not fit a simple before and after pattern.

In this study we dealt with the problem of gradual construction by subdividing the period of record into intervals. Previous analyses (Serrano 1980; Jousma and Serrano 1980; Jousma *et al.* 1981) demonstrated that 6 years was a sufficiently long interval to produce representative mean values of streamflow. We therefore used intervals longer than 6 years so that differences between mean values for the intervals could be interpreted as reasonably showing changes in streamflow.

Intervals greater than 6 years were also long enough to cover a period of substantial drainage construction. The mean condition for each interval thus represented different stages of drain development. We were unable to find an adequate numerical measure of this difference

---

between stages
numerical inde
combined exten
drains.

The package
the detection o
streamflow is lis
package deal (a)
distribution of s
storm-event run
are described in

(a) Water bal
interval based o
streamflow for t
Double-mass an
was conducted
et al. 1975). M
and precipitation
coefficient studi
amounts were d
(Gray 1973).

(b) The analy
volumes was do
monthly volume
sonal variation
storms was exan
of rain events n
examined (Whit

(c) An analys
sponse within i
ducted using ch
1955). This anal
ilar time distribu
storm runoff rec
interval to allow

3. Characteristi

Based on the s
erties and the ne
records, the Mid
km^2) was selecte
of the above crit
of streamflow fo
Ontario.

The Middle T
Huron and Lake
Ontario, as show
shed is approxim
west longitude.
forest began wit
and cereal crops
over 80% of the

The Middle T
tle of drift consis
clay, which vari

between stages of drainage. There is need for a simple numerical index of drainage that can represent the combined extent of surface channel and buried-pipe drains.

The package of hydrological methods we used for the detection of the effects of drainage works on streamflow is listed below. The three components of the package deal (a) with streamflow volume, (b) seasonal distribution of streamflow, and (c) time distribution of storm-event runoff within events. Individual methods are described in more detail by Serrano (1982).

(a) Water balance calculations were done for each interval based on annual volumes of precipitation and streamflow for the watershed (Viessman *et al.* 1977). Double-mass analysis of annual streamflow volumes was conducted for the entire period of study (Linsley *et al.* 1975). Moving-average analysis of streamflow and precipitation was also done (Hannan 1962). Runoff coefficient studies using rainfall and storm runoff total amounts were done for several storms in each interval (Gray 1973).

(b) The analysis of seasonal distribution of water volumes was done separately for each interval based on monthly volumes of streamflow. The pattern of seasonal variation of runoff coefficients for individual storms was examined for each interval. The proportion of rain events not producing runoff response was also examined (Whiteley *et al.* 1980).

(c) An analysis of time distribution of runoff response within individual storm events was also conducted using changes in unit hydrographs (O'Kelly 1955). This analysis used sets of four events with similar time distribution of rainfall and the corresponding storm runoff records. Each set contained one event per interval to allow comparison among intervals.

3. Characteristics of the Middle Thames watershed

Based on the stated requirements for watershed properties and the needed hydrological and meteorological records, the Middle Thames River at Thamesford (298 km^2) was selected for study. This watershed met many of the above criteria and had one of the longest records of streamflow for an agricultural watershed in southern Ontario.

The Middle Thames watershed lies between Lake Huron and Lake Ontario in the most southerly part of Ontario, as shown in Fig. 1. The center of the watershed is approximately 43°15′ north latitude and 81°00′ west longitude. Before 1850, clearing of its original forest began with conversion to the growth of pasture and cereal crops. Census data shows that since 1900 over 80% of the land has been in cultivation.

The Middle Thames watershed is covered by a mantle of drift consisting of boulder clay, sand, gravel, and clay, which varies from a few metres to more than one hundred metres in thickness above flat-lying limestone and sandstone (Wicklund and Richards 1961). The surface geological deposits constitute the parent materials from which the soils of the area have been developed. Generally, the topography is smooth and gently sloping with land slopes commonly less than 4%.

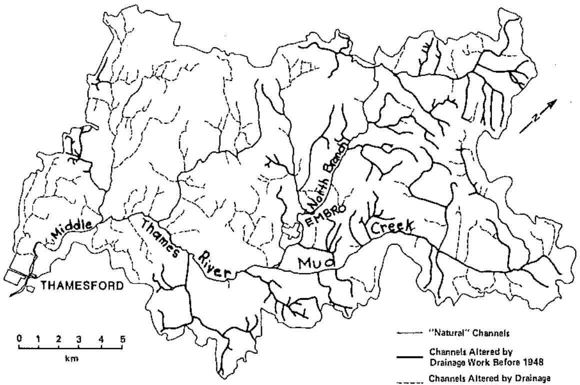

FIG. 2. Map of the Middle Thames River watershed showing categories of channels.

The major soil series found in the Middle Thames watershed are (Wicklund and Richards 1961): (a) Embro Series: These imperfectly drained silty alluvial soils occupy the highest flat parts of the watershed, between the valleys containing the permanent streams. (b) Guelph Series: These soils are composed of well-drained calcareous loam till. They occupy the moderately steeply sloping hill areas surrounding the rivers and creeks. (c) Soils very close to river channels are classified as bottom land and are composed of recent stone-free aluvium materials. The Embro and Guelph Series occupy respectively about 50% and 40% of the watershed area. The remaining 10% is distributed among series (c) and small patches of other series (Honeywood, Bennington, Parkhill, Muck, Crombie).

The largest elements of the natural drainage system of the Middle Thames watershed are two creeks, the North Branch Creek, flowing from northwest to southwest, and Mud Creek, flowing from northeast to southwest (Fig. 2). Close to the town of Embro these two creeks join to form the Middle Thames River, which flows in a general direction from northeast to southwest to the flow rate gauge location in Thamesford. About 10 km downstream from the streamflow gauging station, the Middle Thames joins the main Thames River.

Natural stream channels that have not been altered by digging are shown in Fig. 2 as light lines. Artificial or hydraulically improved channels in this watershed are almost all municipal drains constructed under the Ontario Municipal Drainage Act. The dark lines show the municipal drains built prior to 1948, mainly in areas where Embro soils appear. Many of these drains were initially installed before 1900. A number are covered-pipe drains. The broken lines in Fig. 2 show municipal drains constructed after 1948. This later work is partly an extension of existing municipal drainage work as well as the construction of new elements in soils classified as the Guelph, Honeywood, and Embro Series.

Measurements of lengths of municipal drains were made from a map prepared for the Upper Thames Conservation Authority in 1948 and from maps of the artificial drainage system of Oxford County prepared for the Ministry of Agriculture and Food in 1979 and 1980. Roughly 60% of the municipal drains existing in 1980 were shown on the 1948 map, which suggests that 40% were constructed in the study period, which begins with 1949. However, inspection of aerial photographs in other areas of Ontario has shown us that earlier mapping such as that in 1948 misses many existing drains. We believe that considerably more than half of the length of municipal drains predates the start of the study period.

A quantitative statement on the growth of buried-pipe (tile) drainage with time is not possible, since the first map of buried-pipe drainage location and density was prepared in 1979 whereas construction began before 1880 (Irwin 1961). The subsurface drainage work executed in the Middle Thames has been evaluated qualitatively by studying the amount of money spent as grants-in-aid of tile drainage work in accordance with the provision of the Tile Drainage Act for the townships of Zorra East and Zorra West.

From 1956, when these records start, to 1967 the amount spent was relatively small. After 1967 the expenditure increased significantly. The construction of in-field drains is thus seen to be relatively more concentrated in the second half of the study period. A report on land use for a subwatershed of the Middle Thames by Frank and Ripley (1977) says that by 1977 "almost the whole" subwatershed is drained by buried pipe, generally spaced at 24 m intervals.

4. Hydrological and meteorological data used

As stated earlier, the period of record was subdivided into intervals to allow comparison among different conditions of drainage. The final selection of intervals was based on features of the flow rate data supplied by the Water Survey of Canada (station 02GD004). Flow rates based on daily-read water levels are available for 1949–1955. These 7 years were chosen as the first interval. Continuous records of streamflow are available for the interval 1956–1980. The period 1956–1979 was divided into three intervals, each 8 year long, termed intervals 2, 3, and 4. The last two intervals coincide roughly with the years of more-intensive buried-pipe drainage installation. Analysis of within-storm response was done for these last three intervals, for which hourly flow rates were available.

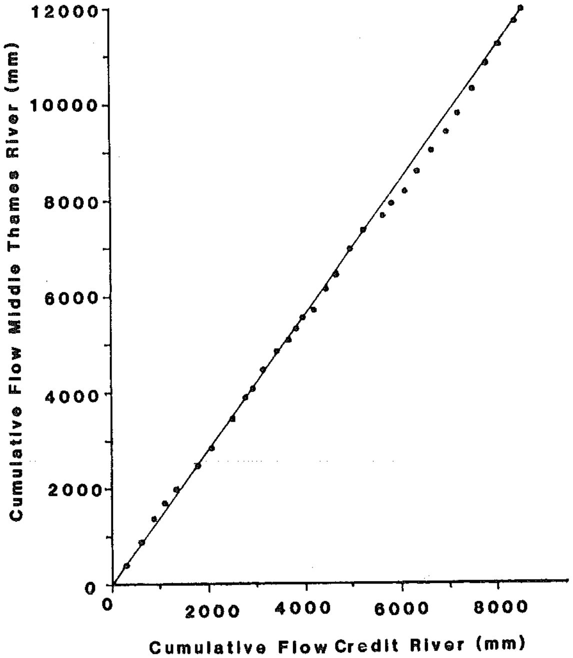

FIG. 3. Double-mass plot of cumulative streamflow in the Credit River versus cumulative streamflow in the Middle Thames River, 1949–1979.

Precipitation records, supplied by the Atmospheric Environment Service for London Airport, Stratford, and Woodstock, were used for both long-term average precipitation and for hourly rainfall data. In the analysis of individual rainstorms, isoheytal maps were drawn for each event using amounts from about 35 surrounding daily-read rain gauges.

Individual storm events analysed do not include any events with a snowmelt component because of difficulty in specifying input rates for such events. Storm flow rate responses were specified by storm flow hydrographs obtained by subtracting estimated base flow from total observed stream flow rates.

5. Results and discussion

5.1 Analysis of volumetric response

Double-mass-curve, water balance, and moving-average analyses were conducted on the Middle Thames watershed. None of the analyses showed any change in annual streamflow volumes that could be attributed to drainage work or land-use change. The double-mass analysis was conducted by plotting the Middle Thames cumulative annual streamflow against that of another Ontario River, the Credit River, on whose watershed little drainage work had been done. A straight-line relationship for the entire period of record was obtained (Fig. 3).

TABLE 1. Water balance for the Middle Thames River for four intervals from 1949–1979

Interval	Mean annual precipitation (mm)				Mean annual runoff (mm)	Mean annual evapotranspiration (mm)
	London	Stratford	Woodstock	Watershed*		
1949–1955	956	1029	944	955	406	549
1956–1963	831	914	870	867	334	533
1964–1971	927	1009	869	895	332	563
1972–1979	968	1119	961	978	435	543
Total period	919	1017	910	924	376	548
Normal (1941–1970)	925	981	904	916		

*Watershed mean precipitation obtained from Thiessen-polygon-weighting of data from London (0.20), Stratford (0.10), and Woodstock (0.70).

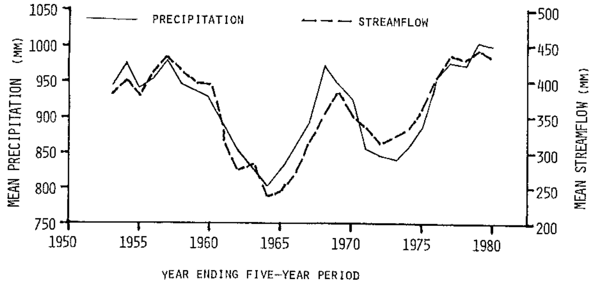

FIG. 4. Five-year moving-average amounts of annual precipitation and annual streamflow on the Middle Thames River watershed.

The mass balance analysis was conducted under the reasonable assumption that over periods longer than 6 years the difference between mean annual precipitation and mean annual streamflow can be interpreted as mean watershed evapotranspiration. In humid regions like southern Ontario, and with low-permeability, glacial-till subsoils, it is reasonable to assume that groundwater flow will enter the stream channels within the watershed boundary.

Mean watershed evapotranspiration was calculated for the four intervals from 1949 to 1979, Table 1. The mean annual values for the intervals ranged from 533 to 563 mm, a maximum departure from the 31-year mean of only 3%. This constancy of evapotranspiration is evidence of a lack of effect of drainage on streamflow volumes during the period of analysis. If drainage causes an increase in streamflow it has to cause a corresponding decrease in evapotranspiration to preserve long-term water balance.

Evapotranspiration is a much better indicator than is mean streamflow that changes in the watershed have effected streamflow. Because of interval-to-interval changes in mean precipitation the mean streamflow in the four example intervals varied extensively, from 12% below the mean to 16% above the mean in the lowest and highest streamflow intervals.

The results of 5-year moving-average calculations of mean watershed annual precipitation and annual streamflow are shown in Fig. 4. This procedure does not require a separation of the data into intervals. The results further confirm the lack of trend of streamflow with time due to any cause other than variation in mean precipitation. The tracking of mean streamflow with mean precipitation is striking.

The 5-year mean streamflow can be predicted from 5-year mean precipitation by either the subtraction of the fixed-period-mean evapotranspiration or by multiplying mean precipitation by a coefficient (C) that varies with mean precipitation (P) in the form

$$C = e^{-P_c/(P-P_0)}$$

where P_c and P_0 are calibrated constants (mm). Using either approach, the root-mean-square error in predicted 5-year mean streamflow is 24 mm, less than 7% of the period-mean streamflow.

5.2 *Analysis of the seasonal distribution of water volumes*

To apply the seasonal-flowrate-distribution analysis, the mean monthly flows for the Middle Thames were computed for the four intervals. To remove the effect of changes in mean annual streamflow through the four intervals, the percentage of mean annual streamflow volume contributed during each month was calculated for each interval (Table 2). Over the four intervals only a small random variation in the monthly percentages was noted. In particular, the individual percentages for the months from June through October randomly varied between 4% and 1%, showing no indication that added drainage work was reducing dry season flow rates from period to period.

The runoff coefficient, defined as the ratio of storm runoff to total rain, was computed for selected individual storm events in each of the last three intervals. The

TABLE 2. Distribution in percentage of mean monthly streamflow volumes for four different periods in the Middle Thames watershed

Interval	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1949–1955	13	14	28	16	4	3	1	1	1	4	4	11	100
1956–1963	5	6	27	21	11	4	4	4	3	3	6	9	100
1964–1971	8	12	22	21	6	3	2	2	1	3	6	13	100
1972–1979	8	8	29	20	7	3	2	2	3	3	6	9	100
1949–1979	9	10	27	19	7	3	2	2	2	4	6	10	100

TABLE 3. The volumetric runoff coefficient for selected storms in the Middle Thames watershed

Storm	Storm number	Rain (mm)	Storm runoff (mm)	Runoff coefficient
59-04-28	1	28.1	3.3	0.12
68-04-03	2	19.9	5.8	0.29
77-11-16	3	11.6	4.1	0.35
60-04-30	4	15.6	2.8	0.18
67-04-17	5	27.4	5.9	0.22
76-03-25	6	9.2	2.6	0.28
61-05-06	7	15.6	2.7	0.17
68-11-28	8	33.8	8.5	0.25
76-03-31	9	23.0	5.3	0.23
63-05-10	10	19.9	4.9	0.25
69-05-18	11	45.6	13.5	0.30
79-04-13	12	50.4	50.4	1.00
80-07-08	13	25.0	3.7	0.15
80-07-28	14	49.0	3.0	0.06
Av. 1956–1963				0.18
Av. 1963–1971				0.27
Av. 1972–1980				0.35
Av. 1956–1980				0.28

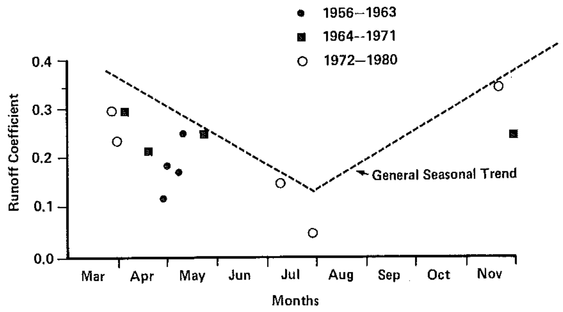

FIG. 5. Seasonal variation in the coefficient of runoff (runoff/rainfall) for sequential intervals 1956–1980, Middle Thames River watershed.

storm events were selected to meet certain uniformity conditions. The storms selected for comparison had similar spatial distribution in the watershed, similar time distribution patterns, similar peak-rainfall intensities and corresponding similar peak-runoff intensities, and similar antecedent soil-water conditions.

The individual values appear in Table 3. Runoff coefficients were then plotted against the day of the year (Fig. 5). The runoff coefficient varies from storm to storm. In terms of seasonal variation it generally has higher values during the spring, decreases to a minimum in the summer, and then increases during the fall. When proper account is taken of the expected seasonal variation in the runoff coefficient, there is no evidence of change in this volumetric measure for the three intervals analysed. Drainage work done in this period does not appear to have affected the characteristics of the watershed in respect to volume of storm runoff produced.

Another method to examine volume change involves numbers of insignificant storm events. The first step is the definition of a large rainfall event. For this study a large rain was 10 mm or more per day. In the frequency–duration–intensity chart for the station of Woodstock, which is near the Middle Thames watershed, a 10 mm in 12 h rainfall has an average return period of about 1 year.

The next step was the definition of a small runoff response. This was chosen to be less than 10% of the total storm amount, that is, storm runoff of 1 mm or less from a rain of at least 10 mm, falling in an average storm duration of 12 h.

To use the most accessible form of streamflow record, which is the daily mean flow rates, it was necessary to obtain the daily mean rate of total streamflow equivalent to 1 mm of storm runoff on the Middle Thames watershed. The procedure for establishing the equivalence is illustrated in Fig. 6. An average 12 h unit hydrograph (1 mm runoff) was derived (Wilson 1974). Then, from this storm flow the peak-daily-mean storm flow flow rate was computed. The maximum rate was 1.90 $m^3 \cdot s^{-1}$. To this value, an average base flow rate of 1.5 $m^3 \cdot s^{-1}$ was added to obtain the maximum, daily-mean, total flow rate of 3.40 $m^3 \cdot s^{-1}$.

The analysis was completed through a study of the daily records of rainfall and daily-mean river flow rates to count the number of days with total precipitation greater than 10 mm that did not produce a subsequent daily-mean-peak runoff rate greater than 3.40 $m^3 \cdot s^{-1}$. The average monthly number of nonevents for the latter

TABLE 4. Ratio of average monthly number of insignificant storm events to average monthly number of daily rain amounts greater than 10 mm

Interval	ND*	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Total
1956–1963	122	0.22	0.31	0.62	0.86	0.74	0.80	0.88	0.47	4.90
1964–1971	149	0.00	0.24	0.67	1.00	0.78	1.00	0.84	0.40	4.93
1972–1979	161	0.00	0.37	0.78	0.84	0.95	0.74	0.65	0.36	4.69

*Number of days with total precipitation greater than 10 mm.

three intervals of study were computed. Finally, the ratio of the average number of insignificant storm events to the average number of rain amounts greater than 10 mm was used as a "nonevent index." Index values were examined between periods to determine if there were changes in index values (Table 4).

There are inconclusive indications of some change in volumetric response in terms of changes in the proportion of rainstorms not producing appreciable runoff. For June there is an increase, over the three intervals analysed, from 0.62 to 0.78, while for October there is a reduction from 0.88 to 0.65, and similarly in November from 0.47 to 0.36. Other months from April to November show only random changes.

These listed changes would be consistent with new subsurface drainage reducing soil water amounts in June, making space available for retention of infiltrated water and reducing streamflow response. In October and November rain intensities are generally low and overland runoff is uncommon whatever the drainage state. Subsurface drains might be expected to respond to seepage in these months and create a small amount of water as storm flow, which would otherwise occur as base flow. The amounts of water involved in these changes must be small since monthly percentages of streamflow were unaffected as noted above.

Although calculations for the determination of flow-duration curves were not done in the Middle Thames, inspection of the daily-mean streamflow record showed no evidence of changes in the magnitude of dry season base flow over the period of record.

5.3 Changes in the time distribution of streamflow during storm events

In order to study the variations in lag-time magnitude, in the runoff coefficient and in the impulse response, it was necessary to select various sets of storm events. Each set consisted of one storm event from each interval of the streamflow record, the rain events in the set being judged "similar" by selected criteria of magnitude and uniformity as mentioned earlier.

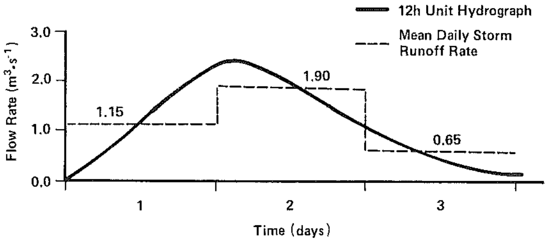

FIG. 6. Relationship of maximum mean daily storm flow to 12 h unit hydrograph, Middle Thames River watershed.

An hourly runoff-generation distribution representative for the watershed was created for every storm. These distributions were computed from the hourly rainfall data such that the total volume agreed with the total volume of storm runoff obtained from the flow rate hydrograph after separation of base flow. Use was made of the Holtan infiltration model applied from the infiltration subroutine of the GAWSER model (Ghate and Whiteley 1977). A check of the results was made by comparison with the runoff-generation intensities derived with a loss rate model (Clark 1980). The procedure and practical details are described in Serrano (1982).

A simple base for comparison of the time distribution of storm-event response is the time-to-peak measured as the time from highest rate of runoff generation to storm runoff peak. This time was computed for each of the storms in a set.

Despite the relatively long record available for the Middle Thames, there was a disappointingly small number of similar rain storms that could be arranged in sets, one storm from each interval of analyses. Four sets were found. The mean result from these four sets in terms of time-to-peak was a reduction from 19 h in the interval 1956–1963 to 18 h in the period 1972–1979 (Table 5). This reduction was present in three of the sets while the other set showed an opposite trend. There were an additional 20 storms that could not be matched to form sets (Table 6). These storms showed a slightly more appreciable reduction in lag time in the mean, from 19 h in 1957–1963 to 17 h in 1972–1979. These storms are so heterogeneous little reliance should be placed on their trend, but it is similar to that of the matched-storm sets.

A more elaborate basis of comparison of the time distribution of storm-event response was developed using parameters of an impulse function for the watershed. For this study a conceptual model with n equal

TABLE 5. Time from runoff–production peak to storm runoff peak for matched storms in the Middle Thames River

Set No.	Storm No.	Storm date	Peak ($m^3 \cdot s^{-1}$)	Time-to-peak (h)
1	1	59-04-28	8.7	20
	2	68-04-03	12.6	20
	3	77-11-16	9.9	17
2	4	60-04-30	7.1	17
	5	67-04-17	15.4	15
	6	76-03-25	8.0	16
3	7	61-05-06	9.4	17
	8	68-11-28	21.1	18
	9	76-03-31	8.7	26
4	10	63-05-10	13.2	23
	11	69-05-18	25.5	18
	12	79-04-13	150.0	13
Av. 1956–1963				19
Av. 1963–1971				18
Av. 1971–1980				18
Av. 1956–1980				18.5

reservoirs, each with recession time constant K, in cascades (Dooge 1973) was chosen to represent the impulse response function of the Middle Thames River. The method of deconvolution used was the matching-moments technique (O'Kane and Dooge 1977).

The analysis was done on the same four storm sets as were used in the lag-time analysis. Beside the two parameters of the impulse response function n and K, the time from start of runoff to peak and the peak flow rate of the impulse response were also noted (Table 7).

The n values declined for sets 3 and 4 over the period of analysis and were erratic for sets 1 and 2. The K values were erratic in sets 1 and 4, declined in set 2, and increased in set 3. The mean value of n decreased consistently over the three intervals of analysis from 2.71 to 2.05. The mean value of K showed an erratic variation between intervals. The product of n times K, which is the total lag of the impulse response function, was almost constant; the values for the three intervals were sequentially 31, 34, and 32 h.

The mean time-to-peak of the impulse response function declined from 18 to 14 h over the three periods, but the mean peak runoff was nearly constant, varying from 2.12 to 2.37 $m^3 \cdot s^{-1}$ and with no consistent trend. Since in every case the result is the mean of only four values, the results do not suggest any conclusive trends. It does appear that the response time of the watershed declined a little during the 24 years of available record, but with little change in peak flow rate or centroid-of-rain to centroid-of-runoff time lag.

These observed features of streamflow change in the Middle Thames cannot be unequivocally attributed to agricultural drainage work. They are consistent with the following two expected effects. The enlargement of open channels should produce higher velocities and hence both reduced time-to-peak and reduced centroid-to-centroid lag. By itself this would produce a concomitant increase in peak flow rate at the downstream end of the watershed.

The increase in subsurface drainage, which has been concurrent with the channel work, would change the proportional distribution of storm runoff, leading more water to the slow-recession, lower-peak subsurface route. This component however peaks not long after overland runoff. This change, by itself, would cause a lower peak runoff and a longer centroid-of-input to centroid-of-output lag but little change in time of peak.

The two changes attributed to drainage together would tend to produce the changes noted, i.e., a shorter time-to-peak, but, because of offsetting effects, little change in peak rate or centroid lag.

The interpretation of the impulse response function analysis is made difficult by a conceptual problem not much addressed in the hydrological literature. As noted above, the output used in the analysis, storm runoff, is composed of several flow-path components. In the case of the Middle Thames watershed the principal two are overland runoff and rapid subsurface runoff through the subsurface drainage. We have just argued that these two components have different response characteristics, and changes in the proportion of the two making up a storm runoff hydrograph changes the fitted impulse response function parameters.

The two components also have different input functions. For overland runoff the input is the superficial (above ground surface) water in excess of retention storage in small depressions. For rapid subsurface runoff the input is the percolating water just below the ground surface that will reach the pipe system and not be absorbed by soil-water storage nor seep down to the regional groundwater. Further theoretical examination of appropriate response-function analysis for this situation is warranted.

6. Conclusions

The conclusions drawn from the results of the analysis of drainage effects on the streamflow in the Middle Thames River can be summarized as follows:

(a) Water balance, double-mass-curve, and moving-average analyses were conducted on the Middle Thames watershed 1949–1979. None of these analyses showed any change in annual streamflow volumes that could be attributed to drainage work or land-use change.

(b) Studying the seasonal distribution of water volumes in the Middle Thames watershed, it was observed that there is not a consistent shift or a reduction in dry

TABLE 6. Time from total rainfall peak to total runoff peak for selected storms in the Middle Thames River

1957–1963			1964–1971			1972–1979		
Storm date	Peak ($m^3 \cdot s^{-1}$)	Time-to-peak (h)	Storm date	Peak ($m^3 \cdot s^{-1}$)	Time-to-peak (h)	Storm date	Peak ($m^3 \cdot s^{-1}$)	Time-to-peak (h)
57-11-19	11	20	64-04-27	5	19	72-04-15	37	15
59-11-23	9	19	64-04-29	8	22	72-05-16	14	12
60-04-21	9	18	64-08-22	17	16	73-04-01	24	18
61-04-16	12	17	67-11-03	12	14	73-04-03	11	16
61-04-17	15	24	68-06-25	21	16	76-03-12	39	20
63-04-19	9	18	69-05-18	29	17	77-04-04	14	20
63-05-10	15	20	71-04-01	67	16			
Average		19	Average		17	Average		17

TABLE 7. Characteristics of the impulse response function derived for selected storms of the Middle Thames River, using the effective precipitation intensities obtained according to the Holtan infiltration

Set No.	Storm No.	Storm date	n	K (h)	Lag, $n \times K$ (h)	Time-to-peak (h)	Peak ($m^3 \cdot s^{-1}$)
1	1	59-04-28	2.78	10.40	28.9	18	2.27
	2	68-04-03	2.21	15.55	34.4	23	1.81
	3	77-11-16	2.54	11.79	29.9	18	2.14
2	4	60-04-30	2.57	11.37	29.2	18	2.21
	5	67-04-17	2.80	9.71	27.2	17	2.42
	6	76-03-25	2.41	8.81	21.2	12	2.97
3	7	61-05-06	3.23	6.23	20.1	14	3.42
	8	68-11-28	2.47	9.59	23.7	14	2.69
	9	76-03-31	1.98	20.33	40.3	20	1.51
4	10	63-05-10	2.30	17.43	40.1	23	1.56
	11	69-05-18	1.58	24.33	38.4	14	1.56
	12	79-04-13	1.25	21.97	27.5	5	2.30
1956–1963			2.71	11.36	31	18	2.37
1964–1971			2.27	14.80	34	17	2.12
1972–1979			2.05	15.72	32	14	2.23
1956–1979			2.34	13.96	33	16	2.24

NOTE: n = number of reservoirs in cascade; K = average storage delay time per reservoir.

season flow rates in the period studied from 1949 to 1979.

(c) A check was made in order to observe the change in the number of events in which a small runoff response was produced from a large rain amount in the Middle Thames watershed. An index developed to measure this feature did not show any important variation in the number of insignificant storm events since 1956. A small decrease in storm runoff activity in June and a small increase in October and November were observed.

(d) The lag time, defined as the time interval between total rainfall peak and total runoff peak, was obtained for 20 selected storm events in the Middle Thames watershed since 1957. There has been a slight decrease in the average magnitude of the lag time from 19 to 17 h.

(e) Characteristics of the impulse response function were derived for 12 storms in four match sets in the Middle Thames River from 1956 to 1979. The characteristics observed were the peak magnitude, the time-to-peak, the parameter K in the conceptual model (average storage delay time in each reservoir), and the parameter n in the conceptual model (the number of reservoirs). A decrease in the time-to-peak from 18 to 14 h suggests that the response time of the watershed declined a little during the 24 years of observed drainage activity, but with no detectable change in peak flow rate or centroid-of-rain to centroid-of-runoff time lag as measured by the product $n \times K$.

(f) In applying the hydrologic methodology to the study of drainage effects on streamflow in the Middle Thames River, the problems of runoff-generation-rate estimation, impulse response function generation, and base flow separation had to be faced. At the present state-of-the-art, there are several theoretical inconsistencies and practical difficulties that make this task difficult to accomplish objectively. Further research should be devoted to the development of new methods or the improvement of the existing ones to fill the gap between the conceptual models developed in the literature and the complex physical processes involved in the generation of streamflow.

(g) All of the results found by the different methods suggest small or zero effects of drainage on streamflow in the Middle Thames watershed for the period observed. This may be due in part to offsetting effects from channel improvement and concurrent installation of buried-pipe drainage. The assessment from historical data of the impact of the initial construction of outlet drainage channels in Ontario is severely limited by the period of observed streamflow, which begins many decades after most of the major drainage channels were first constructed. Some conclusions about the effects of this channel construction might be possible using "hindcasting" with hydrological models calibrated initially for the after-drainage conditions.

Acknowledgements

The work described in this paper was supported by the Natural Sciences and Engineering Research Council of Canada and the Ontario Ministry of Agriculture and Food. The Atmospheric Environment Service and the Water Survey of Canada provided all the precipitation and streamflow records necessary for the study.

CLARK, R. D. S. 1980. Rainfall stormflow analysis to investigate spatial and temporal variability of excess rainfall generation. Journal of Hydrology, **47**, pp. 91–101.

DOOGE, J. 1973. Linear theory of hydrologic systems. Agricultural Research Service, United States Department of Agriculture, Washington, DC, Technical Bulletin No. 1468.

DYBVIG, W. L. 1977. The effect of agricultural drainage on flood flows at Moose Jaw. Environment Saskatchewan, Hydrology Branch, Regina, Sask., Report HYD-5-44.

EDDIE, J. D. 1982. Temporal variation of southwestern Ontario streamflow and the possible influence of agricultural land drainage. Ontario Ministry of the Environment Water Resources. Toronto, Ont., paper 15.

FRANK, R., and RIPLEY, D. B. 1977. Land use activities in eleven agricultural watersheds in southern Ontario, Canada. 1975–1976 International Joint Commission Technical Report Series, Windsor, Ont.

GHATE, S. T., and WHITELEY, H. R. 1977. GAWSER (Guelph agricultural watershed storm-event runoff) model users manual. School of Engineering, University of Guelph, Guelph, Ont., Technical Report 126-37.

GRAY, D. 1973. Handbook on the principles of hydrology. Water Information Center, Port Washington, NY.

HANNAN, E. J. 1962. Time series analysis. John Wiley & Sons, New York, NY.

HOLLANDER, G. W. 1968. Improving old water management systems in the cornbelt. Unpublished paper presented at the 1968 ASAE Winter Meetings. Chicago, IL.

IRWIN, R. W. 1961. A review of land drainage in Ontario. School of Engineering, University of Guelph, Guelph, Ont., Technical Publication No. 7.

IRWIN, R. W., and WHITELEY, H. R. 1983. Effects of land drainage on streamflow. Canadian Water Resources Journal, **8**(2), pp. 88–103.

JOUSMA, G., and SERRANO, S. 1980. Investigacion hidrologica de la media y Bojo Guajira. National Geological Survey INGEOMINAS Official Bulletin, **23**(3), pp. 39–80. ISSN-0120-1425. Apartado Aereo 4865, Bogota, Colombia.

JOUSMA, G., SERRANO, S., and MOLANO, C. 1981. Hidrologie del area de Cucuta. National Geological Survey INGEOMINAS, Report 1826, Apartado Aereo 4865, Bogota, Colombia.

KELLY, K. 1975. The artificial drainage of land in nineteenth-century southern Ontario. Canadian Geographer, **19**(4), pp. 279–298.

LINSLEY, R., KOLHLER, M., and PAULHUS, J. 1975. Hydrology for engineers. McGraw-Hill, New York, NY.

MCCUBBIN, A. 1938. Agricultural drainage in southwestern Ontario—its effects on downstream discharge. Engineering Journal, **21**(2), pp. 66–70.

MOORE, I., and LARSON, C. 1979. Effects of drainage projects on runoff from depressional watersheds. Water Resources Research Center, University of Minnesota, Minneapolis, MN, Bulletin No. 99.

O'KANE, J. P. J., and DOOGE, J. C. I. 1977. PICOMO: a program for the identification of conceptual models. Workshop on Mathematical Models in Hydrology, Pisa, Italy, December, 1974. Published by Ciriani, Marioni and Wallis (Editors). *In* Mathematical models for surface water hydrology, Wiley Interscience, London.

O'KELLY, J. J. 1955. The employment of unit hydrographs to determine the flows of Irish arterial drainage channels. Proceedings of the Institution of Civil Engineers, **4**, pp. 365–445.

SERRANO, S. 1980. Investigacion hidrologica preliminar del Cerrejon. National Geological Survey INGEOMINAS, Report 1798, Apartado Aereo 4865, Bogoto, Colombia.

——— 1982. An assessment of methodologies to detect the impact of drainage on streamflow. M.Sc. thesis, University of Guelph, Guelph, Ont.

SHEBEKO, V. F. 1978. Effects of drainage projects on streamflow. Meteorologiya i Gidrologiya, **4**, pp. 73–81.

TRAFFORD, B. D. 1973. The relationship between field drainage and arterial drainage, theoretical aspects. The U.K. Ministry of Agriculture, Fisheries and Food, ADAS–FDEU Technical Bulletin. 73/10.

VIESSMAN, W., K
T. E. 1977. In
Publishers, Ne
WHITELEY, H. R.
Proceedings o
School of Eng
Ont., Technica
WHITELEY, H. R
QUAST, M. H.

VIESSMAN, W., KNAPP, J. W., LEWIS, G. L., and HARBAUGH, T. E. 1977. Introduction to hydrology. Harper and Row Publishers, New York, NY.

WHITELEY, H. R. 1975. Does drainage add to flood peaks? Proceedings of The Drainage Engineers' Conference. School of Engineering University of Guelph, Guelph, Ont., Technical Publication 126-32, pp. 40–46.

WHITELEY, H. R., DICKINSON, W. T., IRWIN, R. W., and QUAST, M. H. 1980. Urbanization effects on streamflow on the Speedvale watershed, Guelph. Proceedings, Canadian Hydrology Symposium, CHS 80, National Research Council of Canada, Ottawa, Ont., pp. 197–206.

WICKLUND, R. E., and RICHARDS, N. R. 1961. Soil survey of Oxford County. Ontario Department of Agriculture, Guelph, Ont., Report No. 28.

WILSON, E. M. 1974. Engineering hydrology. Halsted Press, John Wiley and Sons, New York, NY.