THE SOURCES OF VARIATION IN STORM RUNOFF QUANTITY AND QUALITY IN THE PARTIALLY URBANIZED LEARY'S BROOK BASIN, ST. JOHN'S, NEWFOUNDLAND

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by

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Abstract

The known variation of water quality during storm runoff makes infrequent sampling unreliable. Though the variation of water quality from non-point source urban areas can be determined with frequent sampling, the extent of change due to the urbanization has been infrequently determined. Mixing of urban storm runoff with water from other source areas may be deleterious because of high yield rates of dissolved and suspended solids. The sampling programme of this research was designed for frequent sampling of three different urban and two non-urban sub-catchments and the outlet of Leary's Brook in St. John's, Newfoundland. Suburban residential, commercial/industrial, parking lot, rural and forested sub-catchments were sampled rotationally by hand on an hourly schedule for sixteen hours during the storm runoff period of November 13-14, 1979, and the outlet was automatically sampled hourly over 24 hours for the same rainfall event. Sampling of all sites for the same storm allowed comparison between the contributions in quantity and quality of storm runoff for the five land use types and the basin as a whole for effectively the same precipitation and antecedent moisture conditions. Temperature and conductivity of hand collected samples were determined in the field. Discharge was measured by stage and later calculated by the Manning equation or by rating with current meter measurements. Laboratory analysis was also carried out on all samples using spectro-photometric techniques for pH, turbidity, phosphate and nitrates. The response of Leary's Brook basin to the November 13-14 storm was dominated by the non-

urbanized portions of the basin, although the urban high fast response in water, solute and suspended sediment yield rates produced a considerable short term effect on the outlet. The overall response of the basin was an aggregate of the urban and non-urban components. Although the outlet solute and sediment yield rates were considerably larger than those of the forested area, the outlet yield rates were not as high as many other urbanized areas. Parking lot runoff demonstrated that not all urban land use causes runoff deterioration. Planning and management may ameliorate urban runoff effects. This study demonstrated a variation in outlet response to non-uniform flood generation controlled by land use rather than precipitation distribution. Hourly rotational sampling proved useful for single storm sampling of five sites, but more frequent sampling of urban runoff would be an improvement. Dry weather sampling of 35 sites in the basin showed the choice of the representative sub-catchments to be reliable.

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1.0 SOLUTES AND SUSPENDED SEDIMENTS CARRIED BY URBAN AND NON-URBAN RUNOFF

1.1 Objective of study

Water quality continues to be an important concern of society and the hydrologist alike; but, for the hydrologist, the study of water quality has the potential for the determination of the processes of runoff. The objective of this study was to compare the water quality and its variation with runoff of a complete heterogeneous drainage basin with that from several sub-catchments within it, particularly the urban areas. The sub-catchments were selected to represent the contribution of different land-use types to the quality of the total discharge from the basin. Particular emphasis was given to comparison of solute and suspended sediment yield rates of urban and non-urban runoff under comparable antecedent moisture conditions and precipitation input.

In analogy with the hydrograph, the plot of the variability through time of the chemical constituents of runoff has been termed the chemograph (Davis, 1971; cited in Glover and Johnson, 1974). Recently, the controls of natural stream chemographs have become better understood and these studies have proved useful in the understanding of natural runoff processes (e.g. Toler, 1965; Nakamura, 1971; Walling and Foster, 1975).

Many studies have been made of the variation of urban runoff quality with discharge (for example, Wiebel, Anderson and Woodward, 1964; American Public Works Association, 1969; McGriff, 1972; Angino, 1972; Sartor and Boyd, 1974; Droste and Hartt, 1975a+b; Cordery, 1977; McCuen, Cook and Powell, 1980). However, the specific comparison of urban and non-urban chemographs has been limited (Crippen, 1967; Cherkauer, 1975; Klein, 1979). In this study, the simultaneous measurement of water quality variability with discharge from several land-use types was undertaken so that direct comparison of chemographs of urban and non-urban areas could be made.

1.2 The chemograph

This study entailed an attempt to bridge a conceptual gap in the research of hydrology relating to urban effects on water quality. Urban runoff and runoff quality studies may ignore non-urban conditions, or imply a comparison with pre-urban conditions. Few studies have actually made a comparison both directly and contemporaneously between urban and non-urban effects on hydrology, and specifically on short-term storm flow quantity and quality from urban and non-urban basins.

In the comparison made by this research, the non-urban and in particular the forested sub-catchment was used as a "control" condition for the assessment of urban runoff. The forested sub-catchment was assumed as a "natural" condition, and therefore differences in runoff from other land-use were considered to be deviations from that norm.

With this viewpoint, a review of the natural stream chemograph is given below, by which natural simply means non-urban and forested, and which appears to be the underlying assumption in most of the hydrological literature. Subsequently, a review of urban hydrological effects is made. That is to say the extent of deviation of urban hydrology from the stated or implied natural condition is outlined both quantitatively and qualitatively.

In a natural basin, concentrations of most, but not all, ions drop as discharge increases. This drop is largely a dilution effect. With the progression of the storm, increasing amounts of rainfall enter the channel with little or no contact with solute sources. In the most simple terms, this is a dilution of baseflow by flood water (Walling and Foster, 1975). In temperate forests, however, Hewlett and Hibbert (1967) have found that subsurface flow is dominant and most runoff occurs as "quick flow" without any overland flow. Thus, the resultant discharge and chemograph is a complex mixing of translatory flow and ground water flow, which may be solute laden, and a variable source area of waters which remain dilute, since they do not come in contact with sources of solutes.

Some solutes may show a variable response. Nitrates may exhibit complex behaviour, and potassium concentrations are often in proportion to runoff, although closely spaced storms may result in potassium dilution (Walling and Foster, 1975). This has been attributed to complex ionic interaction with the colloidal fraction (Hem, 1970).

A further complexity in the chemograph of many solutes is a peak in ionic concentration near the start of storm runoff. The flushing effect is accounted for by the initial flushing of accumulated solutes into storm runoff (Edwards, 1973; Walling and Foster, 1975). In the variable source area model, this flush of ions is a pulse of solute laden translatory flow, which enters the channel before dilution begins to occur. When storm events are closely spaced, the flushing effect does not occur if there is inadequate time for the build up of solutes.

The trough or peak of solute concentrations does not always coincide with the flood peak, but often lags behind. Glover and Johnson (1975) described this chemical lag effect, or delay, of solute trough after flood peak, and explained it simply in terms of the difference in speed between the flood peak travelling as a kinematic wave and the solute trough moving with the mean water velocity. They determined that this process of lag generation was only noticeable for large basins. With hourly sampling, no lag was detectable in catchments smaller than the order of magnitude of 100 km^2. Glover and Johnson also pointed out that the lag phenomenon they described is the cause of hysteresis frequently observed in dissolved solids-discharge ratings.

A lag effect has since been observed by Walling and Foster (1975) to occur even for small catchments (e.g. Back Brook 2.45km^2). Also, observations of the chemograph trough preceding the flood peak have been made (Toler, 1965; Walling and Foster, 1975). Different solutes may even demonstrate different lag times for the same storm. A similar variability of lag time was earlier reported by Nakamura (1971) from a 10 km^2 basin.

Walling and Foster (1975) were able to suggest a process other than kinematic wave generation which produced a chemical lag effect. They found, as had Glover and Johnson, that maximum lag times were associated with dry antecedent conditions and lower runoff. Under those conditions, the dry ground and upper soil levels would accumulate readily soluble material. During the storm, these sources would supply solutes to maintain higher concentrations past peak flow; but depletion of solutes would subsequently produce a chemograph trough after the flood peak, thus producing a lag effect. With higher antecedent soil wetness, fewer solutes would have accumulated and depletion would be more rapid, resulting in a shorter lag.

This mechanism produces a hysteresis in the rating of solute concentrations against discharge. Walling and Webb (1980) point out that hysteresis is produced by the lag effect, even if that is a function of routing. Two earlier papers also illustrate this. Hendrickson and Krieger (1960) described a clockwise hysteretic effect from solute trough lag after runoff peak, and Toler (1965) described the opposite effect by which solute troughs were advanced before runoff peak, producing anti-clockwise hysteresis. In the first case, Hendrickson and Krieger postulated a depletion effect, following on the early storm runoff flush of accumulated solutes. They suggested variations of an idealized hysteretic loop were the result of spatial variation of solute sources and rainfall. In the other case, Toler described the advance of the chemograph trough before peak discharge as the result of dilution of groundwater carrying high solutes concentrations on the rising hydrograph limb, followed by increased ground water contribution on the falling limb. Both of these studies were carried out in large basins, and both found greater hysteretic looping with lower flows.

Anti-clockwise hysteresis and associated lag of chemograph trough were also found by Walling and Webb (1980), and were explained as a routing process controlled by over bank flooding. Also, they described variations in hysteretic looping and the direction of looping for the

River Exe in terms of the spatial variation in solute source areas and the timing of their contribution. The heterogeneity of contributing areas and in the distribution of rainfall was reflected in the aggregate response measured at the outlet.

Variations in the timing of suspended sediment load relative to discharge have also been described. Heidel (1966) described suspended sediment rise lagged behind flood rise in the Bighorn river, which drains an area of 20,000 km^2. He explained the effect as the result of kinematic wave movement of flood peak. From studies of much smaller basins, Walling and Teed (1971) and Walling (1978) described the opposite effect of clockwise hysteresis of suspended sediment rating, which usually was reflected in the advance of suspended sediment peak before discharge peak. Walling (1978) suggested both routing of different suspended loads from various source areas and the depletion of supply of sediments with storm progression as the processes controlling this hysteresis. He further suggested spatial variation in runoff generation as a control of both sediment and solute response.

1.3 Urban hydrological effects

1.31 Quantitative effects

Although urban areas cover but a small part of the land surface, the hydrologic effects of urbanization are extreme. Leopold (1968, p.2) has gone so far as to say that "... of all the land-use changes affecting the hydrology of an area, urbanization is by far the most forceful". Urbanization includes the changes in land-use from rural to suburban, industrial and other urban community uses.

It is projected that by the year 2000, ninety percent of the Canadian population will occupy urban areas covering less than two percent of the land mass. With population growth, availability of transportation and land price pressures, suburban and industrial sprawl is likely to continue (MacNeill, 1971). In the Leary's Brook area of St. John's, added impetus to urban growth is likely to be given by the developments related to offshore oil exploration.

The two central causes of hydrological change with urbanization are the increase of impervious areas and the alteration of the drainage pattern by channelization and sewering (Leopold, 1968). The process of urbanization involves the disruption of vegetation and soils, the paving and roofing over of areas, making them impermeable, and frequently the alteration of topography. This process has been little planned, or planned as Roberts (1972) described it as though development were taking place across a "Von Thunen-like featureless plain" in which topography and the water regime are disregarded.

Precipitation on the urban surface is seen as little more than a nuisance. Storm water is considered an inconvenience which is to be disposed of as quickly as possible in such a way as to reduce disruption by flooding. The resulting stream channelling and storm sewer construction are then an engineering problem in removing an amount of precipitation of a certain return period in the most expedient manner for the least cost.

The most outstanding consequence of the drainage and ground cover changes of urbanization is an increase in peak runoff rates, and this has received a great deal of interest in the literature (for example, Savini and Kammerer, 1961; Viessman, 1966; Waananen, 1969; Espey and Winslow, 1974). Urbanization, however, has effects on all aspects of the hydrological regime. Evaporation and transpiration are reduced and infiltration is reduced or prevented. Overland flow and runoff are increased in quantity and changed in timing. Groundwater levels are affected in various ways as outlined by Leopold (1968). There are direct changes in basin morphology, drainage density and channel morphology. However, because of the engineering design requirements, much attention has been given to quantitative studies of urban peak flow and hydrograph prediction.

Peak flow is very much increased by urbanization. Large impervious areas, graded surfaces, gutters and storm sewers contribute to rapid runoff and high peak flows. Leopold (1968) predicted from the synthesis of available data that peak flow could be increased by 6 times with 100% impervious cover and 100% sewer coverage of a basin, for the mean annual flood. For larger storms, this urban effect is reduced. The difference is response time and yield between urban and non-urban areas is reduced with higher intensity and longer storms, as larger areas contribute to runoff and water yield increases for non-urban areas (Espey and Winslow, 1974).

It has been noted that connectivity of impervious areas to the storm sewer system is a major control of heightened and quickened peak flow.

Hammer's (1972) investigation of stream channel enlargement showed this effect. Areas with sidewalks and streets not sewered had little channel enlargement compared with sewered areas. Also, Terstriep and Stall (1969) found the Road Research Laboratory method of flood hydrograph prediction to be very effective using only impervious areas connected directly to drainage channels.

1.32 Qualitative effects

The quantitative effects of the urban development alone must produce changes in the timing and dilution of runoff, but also surface materials and available solutes are dramatically different in urban areas than non-urban.

The increase of available waste materials tends to increase the dissolved solids and suspended solids content of runoff in urbanized areas and decreases the dissolved oxygen. It was obvious some time ago that urban storm water runoff could not be ignored when urban water quality was considered (Wiebel et al., 1964). However, urban storm water runoff quality has been found difficult to predict and is complex in behaviour, largely due to its non-point source (Barton, 1978).

There is a variety of materials which contribute to urban runoff quality including: particulate fall-out, animal wastes, leaves, grass clippings, engine oils (spilled and dumped), combustion by-products, vehicle wear and tire shredding, soil erosion (Ellis, 1976) as well as street litter, sanitary sewer overflows and pesticide and fertilizers from lawns (Barton, 1978). The supply of these materials will vary with land use, climate, traffic flow, landscaping surface materials, and age of residences (Singh, 1975). Urban runoff may contain significant loads of organic compounds, nutrients, faecal bacteria, heavy metals and suspended solids (Ellis, 1976).

These quality characteristics, when considered with the quantitative characteristics of urban runoff outlined in the previous section, produce distinctively urban chemographs. In concise summary, "... rapid and massive increase in flow is accompanied by very efficient flushing effects as suspended, volatile and dissolved solids are simultaneously purged out of the system" (Ellis, 1976, p. 731).

Timing of urban water quality variation shows some properties like those described for natural runoff, although magnitudes are greater. Ellis (1977) found that water quality of storm water discharge in an area of London, England, was dominated by the load of suspended sediment carried. The solids yield frequently showed a double peak of a pre-discharge peak "first flush" and a secondary lagged peak. The two examples of suspended sediment "chemographs" presented showed a strong lag of sediment concentration, which would plot as distinct anti-clockwise hysteretic loops. Ellis suggested that the flushing of an inter-storm organic mat from the pipe system created the flushing effect. In terms of suspended solids, Ellis found that the London storm water runoff was similar to and "often very much worse" than effluent from secondary sewage treatment.

Droste and Hartt (1975) sampling residential storm runoff in Windsor, Ontario, also found that annual yields of storm runoff produced nearly double the pollutant yield in terms of suspended solids than raw sewage from the equivalent area. They found annual yield rates of 19.3 mg $ha^{-1} s^{-1}$ of suspended sediments in storm runoff compared with 10.0 mg $ha^{-1} s^{-1}$ in raw sanitary sewage from the same area. In comparison with secondary treatment plant effluents, the Windsor storm runoff was of the same order of magnitude in yield rate of orthophosphates and BOD_5. The annual yield rates of nitrates and orthophosphates were estimated as 0.04 and 0.02 mg $ha^{-1} s^{-1}$ respectively. These values are identical to the estimated annual yield rates for nitrates and phosphates (from soluble reactive phosphorous values) in urban storm runoff of Madison, Wisconsin made by Kluesener and Lee (1974).

Like the water yield effect of the connectivity of impervious areas to the urban drainage system, Mattraw (1978) found a relationship between urban storm water quality and impervious area connectivity. Mattraw measured the runoff and quality of runoff from three urban areas in Florida - residential, highway and shopping centre. He reported factors affecting storm runoff quality to include the connectivity of impervious areas and seasonal rainfall distribution as well as land use. He noted the high variability of quality, indicating the need for extensive sampling to determine nutrient and sediment yield rates.

Whipple *et al.* (1978) report that urban runoff dissolved and suspended solid loads which are considered to be from non-point sources may be to a considerable extent from unrecorded point sources. They also found in several areas that phosphates and suspended sediments had non-linear relationships to discharge in urban runoff.

1.4 A comparison of urban and non-urban runoff quality

There have been few studies reported in which direct comparison of urban and non-urban runoff quality over a short sampling period has been made. Research by Cherkauer (1975a, 1975b) was similar to the study reported here. Cherkauer compared storm runoff quantity and quality for four small adjacent basins of differing land use, in the area of Milwaukee, Wisconsin. During storm events, frequent sampling as well as precipitation and discharge measurements were made from a rural, largely agricultural basin, a residential and commercial basin, draining through a small artificial lake, a suburban residential basin and a basin under development. Runoff from these basins was thought not to include any point source components. Single storm average yields for the rural and residential basins are shown in Table 1. The residential basin produced significantly higher yields of both suspended and dissolved solids; however, the concentrations of dissolved solids were generally lower in the urban runoff. Dilution of dissolved load was much greater in the sub-urban residential runoff.

Discharge peak from a 2.2 cm rainfall after seven days without rain was eight times higher from the suburban basin than from the rural. Peak flows from the two basins were concurrent but the recession of the urban runoff was quicker.

TABLE 1

Single-storm mean yield, Milwaukee, Wisconsin

kg ha^{-1} (Cherkauer, 1975 a + b)

	RURAL	SUBURBAN RESIDENTIAL	DEVELOPING	LAKE
Suspended sediment	0.01	2.9	--	--
Total dissolved solids	0.07	1.8	4.8	14.6

A more extensive study of land-use effects on storm runoff quality was reported by Griffin, Grizzard, Randall and Hartigan (1978). They measured discharge and runoff quality of 21 sub-catchments within two large basins in the vicinity of Washington, D.C. The sub-catchments were under a wide range of land uses, enabling comparison of land use effect on water quality. Sequential discrete samples were collected for each storm event. By calculation of yield rates (reported as yields of pounds/acre/day), comparison was possible between different sized basins grouped as land use types, which received varying timing and amounts of precipitation.

A selection of Griffin et al. (1978) results are presented in Table 2. These values show the possibility of larger nutrient and suspended solids loads from non-urban than from urban areas, although rural total phosphorous and total nitrogen yield rate was found to be very much less than from other land uses, including agricultural. However, the rural suspended sediment yield rate was somewhat larger than from medium density residential areas. Their data analysis led Griffin et al. to conclude that the present imperviousness of an area had a highly significant influence on nutrient and suspended sediment yields.

Grizzard, Randall, Hoehn and Sanders (1978) published a portion of the study reported by Griffin et al. (1978). They found annual yield rates for non-urban runoff of 0.46 mg $ha^{-1}s^{-1}$ total nitrogen, and 0.03 mg $ha^{-1}s^{-1}$ total phosphorous, and the larger values for urban runoff of 1.07 mg $ha^{-1}s^{-1}$ and 0.06 mg $ha^{-1}s^{-1}$ for total nitrogen and phosphorous respectively, demonstrating a doubling of the nutrient yield rate of urban land-use compared with non-urban.

TABLE 2

Mean storm yield rates for various land uses
in area of Washington, D.C.
(Griffin, Grizzard, Randall, and Hartigan, 1978)
as mg ha^{-1}s^{-1}

	NON-URBAN		URBAN	
	RURAL	AGRICULTURAL	MED. DENSITY RESIDENTIAL	COMMERCIAL AND SHOPPING
Total N	0.11	0.75	0.92	1.24
Total P	0.02	0.23	0.15	0.15
Suspended sediment	37.3	107.6	27.6	55.7

Another study in the Washington, D.C., area by Ragan, Dietemann and Moore (1977) of runoff quality of various land uses found urban runoff to be of "good" quality in terms of BOD_5 relative to non-urban sources, except where raw sewage was introduced. Those urban areas were of recent construction and reportedly well planned and designed. They concluded that with good design, quality of urban runoff became less important than quantity changes, which also may be ameliorated with design measures.

The atmosphere may provide substantial supply of nutrients to runoff, especially in urban areas. This was suggested by Griffin et al. (1978) and also found by Betson (1978) who measured nutrients in bulk precipitation samples. He also found in the Knoxville, Tennessee area that urban runoff quality was similar to comparable rural areas.

In strong contrast to the urban value of 19.3 mg $ha^{-1}s^{-1}$ suspended sediment yield rate estimated by Droste and Hartt (1975b), the annual (nine year mean) suspended sediment yield rate for a forested basin near St. John's, Newfoundland, was 1.03 mg $h^{-1}s^{-1}$ and for the month of November 1.09 mg $ha^{-1}s^{-1}$ (NAQUADAT, 1980). Other water quality data for Northeast Pond River are presented in Table 3. For the mean water yield rate for the same period of 0.35 l $ha^{-1}s^{-1}$, estimated dissolved solids mean yields are 9.1 mg $ha^{-1}s^{-1}$ TDS, 0.002 mg $ha^{-1}s^{-1}$ total phosphorous and 0.013 mg $ha^{-1}s^{-1}$ dissolved nitrogen. This phosphorous yield rate is an order of magnitude lower than urban storm runoff values found by Droste and Hartt (1975b) and Kluesener and Lee (1974), but the nitrogen yield rates were

TABLE 3

Water quality variation of Northeast Pond River
May 4, 1970 to July 1, 1978 (NAQUADAT, 1980)

	pH	TURBIDITY	CONDUCTIVITY	TDS	TOTAL PHOSPHORUS	NITROGEN DISSOLVED $NO_3 + NO_2$ as N
		JTU+	($\mu S\ cm^{-1}$)	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$
Average	-	0.6	52	26	0.007	0.038
St. dev.	-	0.4	15	6	0.003	0.064
Minimum	3.9	*0.1	31	17	0.001	0.001
Median 50% percentile	5.7	0.5	50	25	0.007	0.01
Maximum	7.8	2.0	158	40	0.015	0.48

* = less than

+ Jackson Turbidity Units

smaller but the of the same order of magnitude as for the above reported urban storm runoff. However, both the nutrient yield rates calculated for Northeast Pond River were an order of magnitude less than rural storm runoff nutrient yield rates, and two orders of magnitude less than both agricultural and urban nutrient yield rates reported by Griffin et al. (1978; Table 2, p. 15).

Also in the vicinity of Leary's Brook, single water samples were collected from fourteen non-urban rivers on the Avalon Peninsula near St. John's (Jamieson, 1974). The mean values of pH, conductivity and turbidity were similar to the median values of Northeast Pond River. Although there were several turbidity values close to the Northeast Pond River median of 0.5 JTU, the mean value of the fourteen sites was more than twice that. Also, the mean pH value was somewhat higher than the median for Northeast Pond River. Table 4 gives median and range of three water quality parameter values for the fourteen sites.

As outlined above, urban storm runoff has been shown to carry significant nutrient concentrations relative to sanitary sewage, and frequently much higher suspended solids. Compared with natural waters, urban storm runoff often produces higher dissolved and suspended solids yield rates, although the timing of changes in suspended sediment concentrations in urban runoff may be similar to that from non-urban areas. From research in other areas, it could be expected that urban areas of Leary's Brook would produce high yield rates and concentrations of dissolved solids, nutrients and suspended solids. In contrast, the natural areas of Leary's

TABLE 4

Water quality of fourteen rivers in the vicinity of St. John's, Newfoundland (Jamieson, 1974)

	pH	CONDUCTIVITY ($\mu S\ cm^{-1}$)	TURBIDITY JTU
mean	6.1	40	1.1
range	5.6 to 6.5	22 to 65	0.4 to 2.0

Brook could be expected to produce very low yield rates of water quality variables, on the basis of the water quality of natural runoff in other basins in the vicinity. The water quality of the Leary's Brook basin, as the aggregate of urban and non-urban runoff might be expected to be dominated by the urban portion of the basin.

2.0 SIGNIFICANCE OF URBAN AND NON-URBAN WATER QUALITY IN LEARY'S BROOK

2.1 Purpose of study and contribution to hydrology

The greatest emphasis in this study was placed on urban runoff and runoff quality. Nevertheless, an essential part of the sampling and analysis was consideration of non-urban runoff, to which the significance of urban runoff variables could be compared. Although no area within the Leary's Brook basin has been unaffected anthropogenically, the forested component of the basin's runoff was seen as the original and natural state, upon which the urban and possibly rural development has imposed changes. With the basin and sub-catchments selected and the sampling method used in this study, the assumptions of good non-urban runoff quality and poor urban runoff quality could be assessed, at both the level of individual land use types and as components of the runoff aggregate reaching the basin outlet.

The expected effect of land use was that rural areas would produce slow runoff response, with low suspended and dissolved solids yield rates, without great variation through a storm period. In contrast, urban areas were expected to produce rapid runoff response, high suspended and dissolved solids yield rates and wide variations in these water quality parameters over a storm runoff period. This comparison of runoff from six sites simultaneously for a single storm event provided effectively the same rainfall input and antecedent moisture conditions for all sub-catchments and the basin as a whole. The sub-catchments were selected so that as much as possible the predominant difference between them was land use. In addition, as the sub-catchments were selected to represent the major land use variations of the whole Leary's Brook basin, simultaneous sampling and discharge measurement of the sub-catchments and the outlet were intended to determine the land-use controls on the hydrograph, chemograph and suspended sediment variation of the basin.

2.2 Local importance of study

Concern for the quality of water leaving the St. John's urban area has prompted construction of a collection system for secondary treatment of sanitary sewage (Newfoundland Design Associates Ltd., 1974). The non-point source of water pollution - urban storm water - will thus become relatively more significant. As stated above in Chapter 1, suspended sediment and solute yields from urban runoff can be substantial. Particularly with the flushing effect, urban storm water runoff pollutant yield rates can exceed that of domestic sanitary sewage (DeFilippi and Shih, 1971). In general, urban storm runoff does not carry such heavy concentrations of solids or solutes as sanitary sewage, but when the very large storm water yield rates from urban areas are considered, suspended solids and soluble yield rates may be higher than for sanitary sewage from the same area. Annually some constituent yields may exceed those in effluent from secondary sewage treatment and for some variables may exceed sanitary sewage yields (Droste and Hartt, 1975a).

If public spending on water pollution control is to be planned for economic efficiency and environmental quality, then non-point sources of pollution merit serious consideration for pollution abatement before further treatment of point discharges are contemplated. Also where rapid urban development is likely to occur, as in St. John's, planning should include measures to prevent significant deterioration of runoff quality. The location in the immediate human environment of the streams and ponds which receive urban storm runoff gives them immediate importance. Possible deterioration of these water bodies presents a loss to the community of recreational and aesthetic value. This study was also carried out to determine some of the effects the urban storm runoff has on Leary's Brook, and to determine to some extent what could be the effect if further urban development were to be continued in the present form.

II.

3.0 LEARY'S BROOK BASIN

3.1 Location of study area

The Leary's Brook drainage basin selected for study is located to the west and north of the city of St. John's, Newfoundland, with the basin outlet draining into Long Pond, at 47°34'25"N, 52°44'28"W. Long Pond drains through Rennies River and via Quidi Vidi Lake to the Atlantic Ocean. Of the total 20 km^2 of the Leary's Brook basin, 5 km^2 is within the city limits of St. John's.

3.2 Climatic summary

The climate of the area is cold maritime, with a mean annual precipitation of 151 cm, of which 36 cm water equivalent falls as snow, and with an annual mean of 210 precipitation days. The mean daily temperature is 4.9°C, with a mean daily maximum of 8.6°C and minimum of 1.2°C. The mean frost-free period is 130 days. The month of November, during which the all-basin sampling was made, has a mean daily maximum of 6.5°C, minimum of 0.4°C and mean of 3.5°C, that month has a mean total precipitation of 16.1 cm, of which 1.8 cm falls as snow. These data, presented from Hare and Thomas (1975), are for the Torbay weather station, which is within 5 km of the study basin at an elevation of 137 m.

3.3 Basin characteristics

3.31 Topography

The Leary's Brook basin (Figure 1) has a somewhat triangular shape, with its apex and drainage towards the east, and with an elevation at the outlet, pictured in Figure 2, of 54 m above sea level. The highest elevation of 238 m is on the southern margin of the basin on Kenmount Hill. The Trans-Canada Highway crosses the divide at an elevation of 202 m. Mount Scio rises steeply just north of the outlet to 181 m, but the western and northwestern margins of the basin are more moderate in slope. Where Thorburn Road crosses the divide the elevation is 185 m and the divide is at 170 m, a kilometre north of there.

3.32 Geology: surficial and bedrock

The basin's surficial geology as described by Vanderveer (1975) is dominated by a ground moraine which is discontinuous over upland areas, where bedrock is exposed, and is covered by thick organic soils in some lowland areas. The moraine is a strong till, 1.5-6 m thick, which is predominantly hummocky and occasionally veneered. Some drumlinoid moraine occurs in the north of the basin.

The basin is underlain by the late Pre-Cambrian Drook and Mistaken Point Formations of the Conception Group. The largest portion of the basin is underlain by the Drook Formation, which is made up of green siliceous volcaniclastics, which weathers buff or white. The Mistaken Point Formation is made up of siliceous sandstone and dark red shales. The geology has been renamed and described by Williams and King (1979)

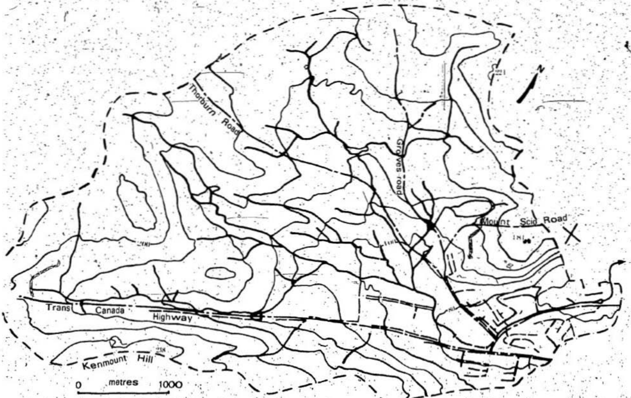

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Figure 1 Topography and drainage of Leary's Broo[k] basin

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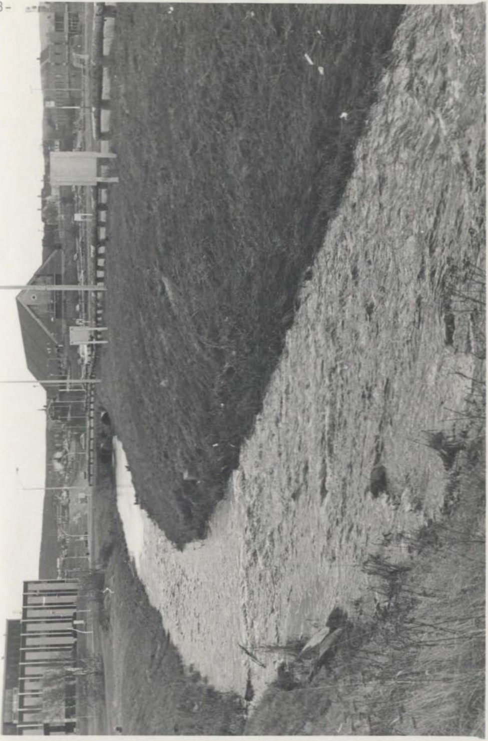
Figure 2 Leary's Brook basin outlet and sample point



and for the Leary's Brook basin area described by King (1979 and personal communication). However, complexity of folding and inadequate exposure make the surface contact between the Drook and Mistaken Point Formations in the basin area poorly defined. For this reason, no attempt has been made to present a map of the bedrock distribution in the study area. Nevertheless, it can be stated that the Pitcher's Path forested sub-catchment and the Groves Road rural sub-catchment, and probably the O'Leary Avenue sub-catchment are underlain by the Drook Formation. The Ayreshire Place residential sub-catchment and the Hospital parking lot sub-catchment as well as much of the residential portion of the basin are underlain by the Mistaken Point Formation.

Since runoff from urban areas is to a great extent controlled by the impervious surface materials connected to the channel system, it seems unlikely that the bedrock geology would have a significant effect on urban runoff quality. Also where the throughflow quality, or in the case of the O'Leary Avenue area, overland flow quality, may be affected by contact with till, it is likely that the predominant rock content of the till would be derived from the Drook Formation. Henderson (1972) indicated a southwest to northeast glacial movement which would not have imported other rock types to the basin. The short travel distances would provide only Drook Formation materials to the basin. Thus, the sub-catchments of the basin may reasonably be compared for water quality without the introduction of effects from widely differing rock types.

3.33 Vegetation

The natural forest vegetation of the basin is boreal coniferous forest, consisting of black spruce, white spruce, balsam fir, infrequently white birch as well as various deciduous shrubs. Where the forest cover has been disturbed by fire or cutting, revegetation by a shrub covering has occurred. Soils developed under these boreal forests are typically podzolic. Where soils are poorly developed on hill tops, vegetation is sparse, and is attributed by Henderson (1972) to the thin tills. However, forest or shrub covers 70% or 14 km^2 of the basin. In the low lying areas of approximate area 80 ha organic soils are developed under bog and fen.

Except for upland areas, distal from stream channels, it could be expected that the forested areas of the basin would be highly permeable to rainfall and provide no major sources of suspended sediments outside the stream channels.

Of the rural areas in agricultural use very little is under tillage. Most is used for pasturage or forage cutting. These areas can be expected to have relatively high permeability and few sources of solids which would reach the stream channel in quantity as suspended load.

In contrast, the vegetation of urban areas is very limited in extent. Generally, the natural vegetation and associated soils have been stripped away and replaced by a sod cover, paving or a building. The residential areas are not highly tree covered. The small lots do not allow for dense tree growth and there has not been time since development for the few trees in those areas to grow to maturity. There was little sign of available soil for removal with runoff during the study period in the residential area. Both the O'Leary Avenue commercial/industrial and the Hospital parking sub-catchments have isolated small patches of relatively undisturbed forest vegetation; however, it is unlikely that these areas contributed significantly to the storm runoff sampled. The O'Leary area also had extensive areas of devegetated and unpaved soils which may have contributed significantly to the suspended sediments of storm runoff.

3.34 Land use

Urban development of the basin is concentrated to the east end around the outlet, and mostly within the city limits (see Figure 3). A square kilometer or five percent of the basin is residential, and is mostly single and two family suburban housing. Another 1.3 km^2 or seven percent of the basin is light industrial, commercial and institutional in use. The largest commercial use is a large shopping centre, the Avalon Mall, with a parking area under which 300 m of Leary's Brook is channelized in culvert.

Rural development covers approximately 165 ha or eight percent of the basin. This land use including rural housing and some agriculture is concentrated on the periphery of the urban area, and along the roads radiating away from that area.

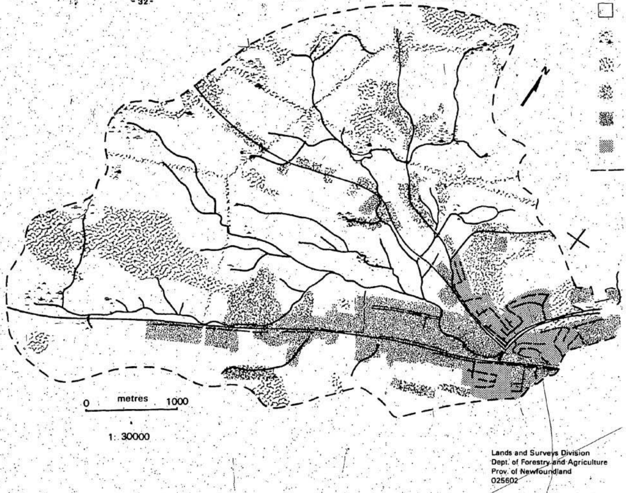


Figure 3 Land use and drainage of Leary's Brook basin

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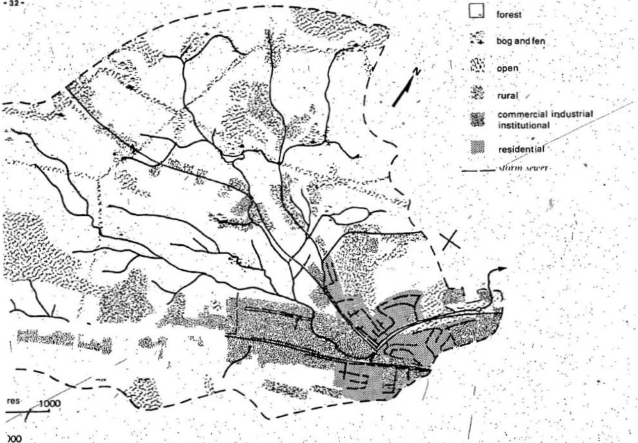

Land use and drainage of Leary's Brook basin

2 of 2

Four roads radiate from the Mall area. Three are towards the outer basin divide - the Trans-Canada Highway, Thorburn Road and Groves Road. The fourth, Prince Phillip Parkway, passes near the outlet.

In the year prior to the November 13-14 sampling period, major new development in the basin was the widening of the Trans-Canada Highway to four lanes and the preparation for industrial park use of an area straddling the brook west of the Avalon Mall. Preparation included removal of a forest cover, channelization of stream sections and construction of roads.

3.4 Description of sampled sub-catchments

3.41 Hospital parking lot

The smallest sub-catchment was a parking area near the basin outlet, to the west of the General Hospital Health Sciences Complex. Locations of this and other sampled sub-catchments are shown in Figure 4, and detail of the parking lot sub-catchment in Figure 5. The parking sub-catchment was chosen to determine the contribution to water quality from a paved area which was not affected in any way by housing or commercial/industrial use, either by surface drainage or possible spill over in the ground from sanitary sewage. The one hectare area of the sub-catchment was made up of curbed and asphalted parking in two segments (area 0.50 ha), as well as an uncurbed road section (area 0.07 ha). The remainder of the area was partly bounded by an uncurbed

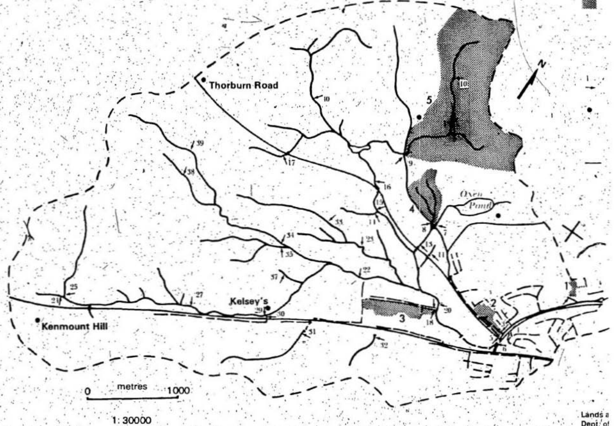

Figure 4 Location of sampled sub-catchments of Leary's Brook basin

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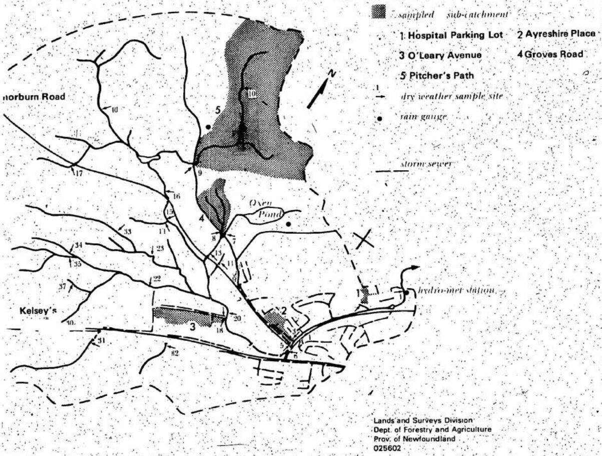
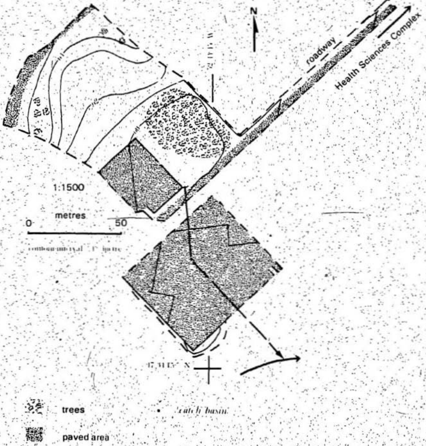


-catchments of Leary's Brook basin



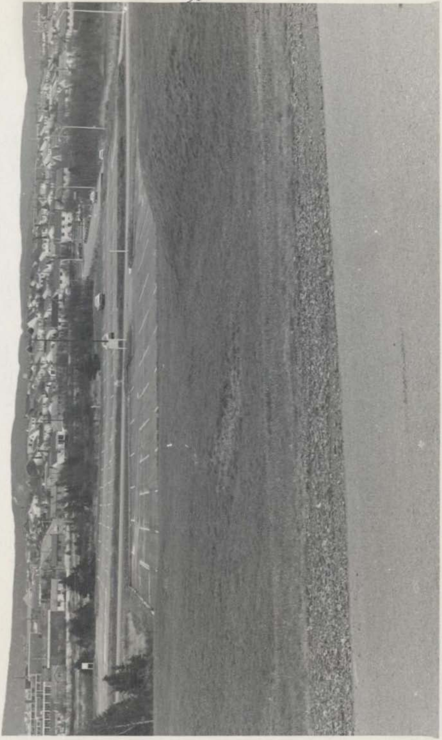
General Hospital Corporation
Health Sciences Complex
Site Plans

Figure 5 Map of hospital parking lot sub-catchment roadway draining from an upper elevation of 65.2 m onto a grass covered area, which included a small copse of trees. The upper parking area of 30 car capacity was 60.4 to 59 m in elevation and drained through the curb at the southeast corner of the lot to the open end of a storm sewer. The central roadway drained through a vegetated ditch and drained to the same culvert opening, as did about half of the treed and grass covered area. The remainder drained across the curb to the northern edge of the parking area. The lower parking area of 80 car capacity was graded from 60.4 to 59 m elevation into two storm grates over concrete catch basins. Drainage from the sub-catchment passed through a 0.35 m diameter concrete pipe at an elevation of 56.7 m into an open ditch. A view from the road on the northern perimeter of the sub-catchment (Figure 6) shows the grass covered area in the foreground, the parking and road areas beyond. The main Leary's Brook channel is beyond the trees in the middle distance and flow direction is from right to left.

3.42 Ayreshire Place residential area

The Ayreshire Place sub-catchment was chosen as representative of a suburban residential land use as a contributor to basin water quality. The sub-catchment of area 5.4 ha consisted of single family dwellings, associated roadways, and the playing field of a school. The plan of the area is shown in Figure 7 and a view of the sub-catchment outfall pipe, as well as typical housing is shown in Figure 8.

Figure 6 View of hospital parking lot sub-catchment from northern perimeter



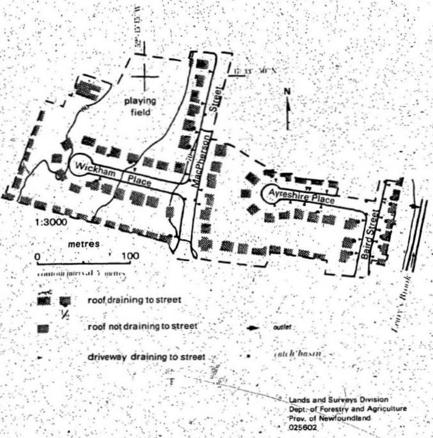


Figure 7 Map of Ayreshire Place residential sub-catchment

Figure 8 View of Ayreshire Place outfall and typical housing

Forty-four full lots were included in the sub-catchment, typically 0.05 ha in area, although corner lots were larger. Twenty-nine partial lots also contributed to the runoff area. Runoff was collected by the separate storm sewer system from two through streets with sidewalks and two dead-end streets with curbing. An estimated 0.82 ha of impervious paving or roofing was connected by gutter to the sewer system, of which 0.13 ha was driveway contribution and 0.09 was roofing.

The separate storm sewer system drained through a 0.46 m diameter concrete pipe, directly into the main river channel, about 1400 m from the basin outlet. The sub-catchment surface sloped from 81 m to 65 m elevation, and discharged into the brook at 62.5 m.

The basin has been defined by the storm sewer system draining to the outfall, and by the sewer layout of surrounding areas. The sub-catchment surface area was separated from surrounding drainage by storm sewers on roads to the south, west, and north and by the main brook channel to the east.

3.43 O'Leary Avenue commercial/industrial area

An area on the south side of O'Leary Avenue, shown in Figure 9, p. 42, was chosen to determine the water quality contribution from light industrial, warehousing and retail commercial land use. The area of ten hectares was drained by a one metre diameter pipe emptying into the main Leary's Brook channel, 2.5 km from the basin outlet. Figure 10 is a map of the area.

Figure 9 View of O'Leary Avenue outfall and street

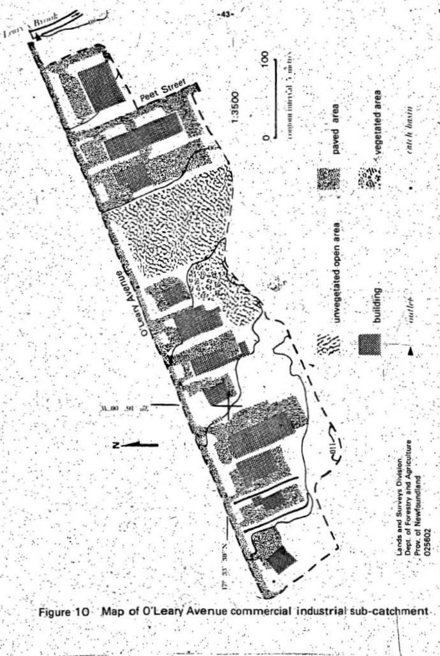


Figure 10 Map of O'Leary Avenue commercial industrial sub-catchment

Contribution to the storm sewer from impervious areas, totalling 4.3 ha, was received from the south half of O'Leary Avenue, part of Peet Street, plus large paved parking areas and large flat industrial-commercial building roofs. Also storm runoff was probably contributed from a 1.3 ha unpaved, poorly graded, but well compacted heavy equipment parking area in the central part of the sub-catchment. This area and a devegetated area to the west of it were possible areas of high suspended sediment yield.

The highest southwest extremity of the sub-catchment had an elevation of 109 m and discharge left the outfall at 80 m.

3.44 Groves Road rural area

A rural area adjacent to Groves Road was chosen for sampling, as shown in Figure 11, and was expected to be unlike either the urban areas or the less developed forested sub-catchment in water quality. The Groves Road sub-catchment was roughly triangular in shape, and bounded on the southwest by Groves Road and on the northeast by Gullies Pond Road. The western divide was forested. There were 19 houses with large grassed lots included in the sub-catchment along the lateral peripheries adjacent to the roads, but the central area of the sub-catchment was forested. All the houses were connected to septic tanks.

The sub-catchment drained through a 0.43 m diameter culvert shown in Figure 12, under Groves Road at an elevation of 118 meters. The highest point in the sub-catchment of 150 m was at the northernmost extremity of the sub-catchment divide.

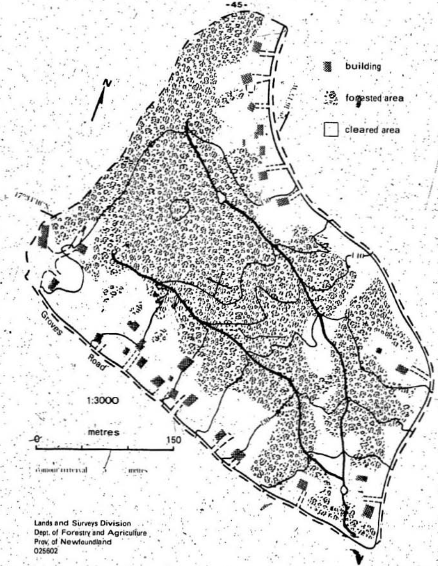


Figure 11 Map of Groves Road rural sub-catchment

Figure 12 View of Groves Road rural sub-catchment gauging site in foreground and sample site across road

3.45 Pitcher's Path forested area

Although the 1.2 km^2 forested sub-catchment chosen included some rural development, this sub-catchment was considered typical of forested areas in the Leary's Brook basin. The sub-catchment, as shown in Figure 13, was bounded on the southwestern margin by upper Groves Road and Pitcher's Path. The rest of the divide was topographically controlled and largely forested. The northwestern divide crosses a sparsely vegetated area around a radio tower installation and a 300 m section to the south coincided with a power line cut.

Five houses with septic tank sewage disposal were situated in the sub-catchment along Pitcher's Path. There were also 750 m of power line cut through the sub-catchment, as well as several trails and some small areas cleared by cutting. Some areas adjacent to the stream channel are bog and fen covered, but the greatest area of the sub-catchment is forested. The elevation ranges from 145 m at the outlet and sampling point (Figure 14) to 224 m at the divide to the northeast.

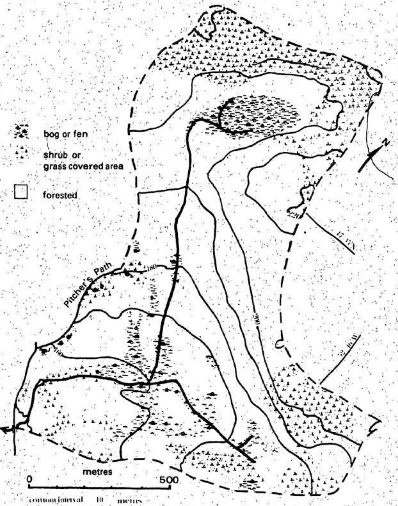


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Figure 13   Map of Pitcher's Path forested sub-catchment

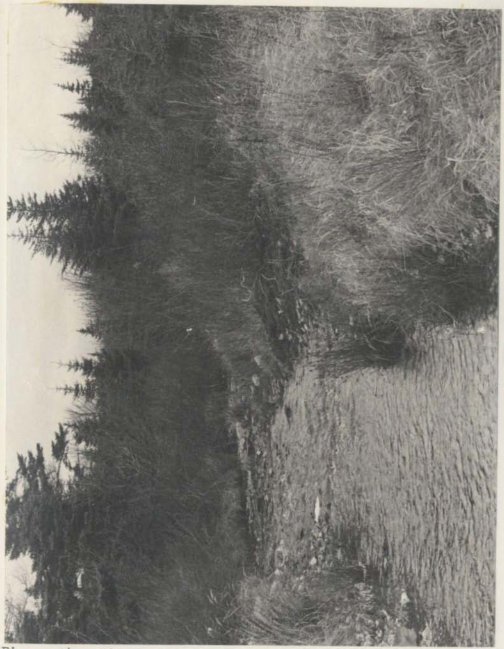


Figure 14 View of Pitcher's Path forested sub-catchment sample and gauging site

4.0 METHOD

4.1 Methodology and sampling strategy

There were three components of the sampling method. The first and most central component was the all basin sampling, for which the basin outlet and five sub-catchments were sampled sequentially in rotation during and after a single storm event. Secondly, individual sub-catchment sampling was done, in which each of the five sub-catchments was sampled during a separate event. The third sampling method was a dry weather sampling of flow from a large number of sites within the basin.

4.11 All-basin sampling

All-basin sampling was carried out in order to characterize the differences between various land uses in runoff quality. Walling (1975) has pointed out that much more than spot determinations of solute concentrations are needed to determine their variation. Neither peak concentrations nor yield can be determined with a small number of samples and solute and suspended sediment dynamic effects of lag and hysteresis can be undetectable without continuous or frequent sampling. On the other hand, long term and frequent sampling of even two different runoff sources would require major costs in time and monetary expenditure. Although an indication of seasonal variation might be provided in sampling a number of storms, Daniel <u>et al</u>. (1978) have found that less than five years of monitoring cannot give a reasonable indication of average yield, or give information usable for reliable prediction. With consideration of these constraints, a short term high frequency programme of sampling from several sites was selected.

All-basin sampling was attempted for the duration of a rain event and a period, at least as long, following. This was carried out over a period of sixteen hours on November 13-14, 1979. The selection of sampling sub-catchments was not only on the basis of suitable representation of specific land-use types, but also in order to facilitate a short and rapid driving circuit to five sampling sites in rotation. Neither the equipment nor the labour was available for coincident or continuous sampling at six sites. Consideration in selection was also given to the ease of measuring discharge from the sub-catchments. The travel time around the five hand sampling sites, the time for sampling and stage measurement and the time required for field testing of samples, allowed each of the sites to be sampled hourly.

The basin outlet was sampled by a 24 hour automatic hourly sampler, described in Appendix A. This was located inside a protective fence together with the stilling well and stage recorder, and meteorological equipment adjacent to the outlet gauging section.

The all-basin sampling strategy provided controls over antecedent moisture and precipitation which otherwise would make comparisons between sub-catchments difficult. Sampling of all sites during one storm could provide virtually the same antecedent moisture input for all sites. Also since the sub-catchments were in close proximity nearly identical precipitation distributions were possible for all five sub-catchments during the single event sampled.

4.12 Individual sub-catchment sampling

Since only hourly samples could be collected during the all-basin sampling, there was a requirement to test the reliability of extrapolation of values between sample times. The secondary component of the sampling strategy, individual sub-catchment sampling, was carried out mainly for this reason. The smaller fast response urban sub-catchments in particular were thought most likely to have highly variable water quality. To test the hourly sampling reliability each of the sub-catchments was sampled individually on a frequent sampling schedule during separate rain events. All sub-catchments were sampled individually at a 15 minute interval, except the hospital parking lot which was sampled on a ten minute schedule. This last rate was found to be the practical upper limit of sampling frequency because of the time required for temperature and conductivity measurements made immediately following sample collections.

4.13 Dry weather sampling

Thirty-five samples of dry weather flow were collected at 35 sites indicated on Figure 4, p. 34, on July 17, 1980. This sampling was required to determine that the five sub-catchments selected for detailed sampling were reasonably representative of their designated land use type, and similarly to detect anomalous sources of water quality. The mapping of solute yield rates was not intended, as was the objective of Walling and Webb (1975) who sampled in a similar way over a large basin, so discharge measurements were not made.

Three individuals carried out the sampling survey. One carried out the sampling itself while the driver of the van and another individual carried out the analysis in the van. Total time of sampling and time between sampling and analysis were minimized as much as possible to optimize comparability and reliability of results. The hospital parking lot was not included in this sampling as it carried no flow at the time.

4.2 Method of field analysis and sample collection

All but the automatically collected samples were collected in clean 500 ml plastic bottles, while the automatic sampler held one litre bottles. For all hand collected samples, where water depth was adequate, depth integration of samples was carried out. Each bottle was raised and lowered through the depth of flow repeatedly until the bottle was full and samples were collected in mid-channel.

Immediate testing of collected samples would be ideal, but as Daniel et al. (1978) point out it is almost never possible and some delay is standard practice. The necessity of rapid completion of sample analysis after collection, as well as the limitations of the stamina of the individual doing the sampling, were the factors which led to the 16 hour length of sampling time for the all-basin sampling.

Water quality parameters measured were the simple tests of pH and temperature, as well as turbidity, conductivity, nitrates and phosphates. Attempts to monitor toxins were not made.

In the field, temperature was measured immediately after a sample was collected. Not only was this an easily measured quality variable, but also the temperature must be known for the correct determination of conductivity. Temperature was measured with a thermistor probe, for the all-basin sampling in the sample bottle, and for the individual sub-catchment sampling in 60 ml of sample in a 100 ml beaker.

Conductivity was also measured immediately after sample collection with a Hach mini-portable conductivity meter. The probe was inserted in 60 ml of sample in a 100 ml beaker. Temperature of the sample was checked and temperature correction of conductivity to 25°C was made on the instrument. Consistent use of the beaker was required for constant volume of water to give a consistent field effect around the probe and thus reliable conductivity readings (Church and Kellerhalls, 1970).

Conductivity was, after temperature, the simplest quality measure taken and was very quick to determine. Also conductivity provides "... at least as good a criterion of the degree of mineralization as the more commonly used 'Total Dissolved Solids' for assessing the effect of diverse ions on chemical equilibria, physiological effects on plants or animals, corrosion rates, etc." (APHA, 1975, p. 72).

The pH of all individual sub-catchment samples was measured in the field using a Hach portable spectrophotometer and a Hach wide range pH indicator solution. As well as a water quality indicator, pH was measured to determine that conductivity changes during the runoff sampling were not only the result of a pH shift, a possibility of which Young (1972) has warned.

The Hach spectrophotometer pH determination used was a colorimetric method which followed APHA (1975) methods. One millilitre of a pH indicator solution was added to 25 ml of sample. The spectrophotometer was standardized with a blank of the sample water and absorbtion of the sample and indicator was read from a scale calibrated for pH. Most of the pH values tested fell in the range requiring a wavelength setting of 615 nm and a few required 520 nm.

For dry weather samples collected, analyses of temperature, conductivity, pH and turbidity were carried out in the field in the van after collection. Temperature was measured with a mercury thermometer to a tenth of a degree Celsius. The other tests were carried out with the Hach portable conductivity meter and spectrophotometer. Turbidity measurement is described in the following section.

4.3 Method of laboratory analysis

The pH of samples collected for the major storm was determined in the lab with a Hach DR 2 spectrophotometer using Hach wide range pH indicator solution. This instrument was also used to determine turbidity and phosphate, following the Hach manual of instructions (Hach, 1977). Chloride determinations were initiated but values from all sites were found almost undetectable with available instruments and this test was discontinued.

Turbidity was measured by comparison of the sample with a cell filled with distilled water at a spectrophotometer wavelength setting of 450 nm. Values are reported in Formazin Turbidity Units (FTU), units which are a measure of light transmission like the standard Jackson Turbidity Units (APHA, 1975), but apparently not directly comparable.

The phosphates measured were as "reactive phosphorus", or orthophosphates plus any condensed phosphate hydrolyzed by the reagent. The Hach (1977) procedure used was a modification of the APHA standard method using the combined reagents of the molybdenum blue procedure. The pre-measured reagents were added to 25 ml of sample, which was compared with a cell filled with a sample blank at 700 nm wavelength. Absorption was measured on a scale calibrated as phosphate in mg/l.

Nitrate determinations were made according to the procedures of the APHA (1975), using a Perkin-Elmer UV-VIS spectrophotometer. Absorption was determined at both 220 and 275 nm. Twice the 275 nm value was subtracted from the 220 nm value to remove the effect of organic interference. This value was multiplied by the calibration factor, determined from standard solutions, to give nitrogen as NO_3 in mg/l. Before testing, samples were allowed to settle to avoid suspended sediment interference.

4.4 Sample treatment

For all samples, temperature and conductivity were measured immediately after collection. During the sampling period, pH was determined for individual sub-catchment samples. After the all-basin sampling, pH was the first variable measured in the laboratory.

Sample bottles were kept in a cooler with ice during the all-basin sampling and subsequently during lab analysis. This provided low temperatures close to the desired $4^{o}C$ and darkness to limit biological and chemical changes to the sample. Turbidity analysis, and following that, phosphate analysis was carried out in the lab as soon as possible after the end of the sampling period. The large number of samples and tests resulted in delay in testing; however, all analyses except nitrates were carried out within 48 hours of sample collection time.

All samples were frozen within 48 hours of collection. Later these samples were thawed in warm water for immediate nitrate determination. Freezing was to prevent bio-chemical changes in nitrates and to allow a delay of sample analysis.

4.5 Discharge measurements

At the Leary's Brook outlet, a Weather Measure weekly stage recorder mounted on a stilling well was used. A rating curve which was determined using a Price current meter near the outlet, 50 m upstream of the recording station, was applied to the stage record.

A one foot standard sized H-flume was constructed for measurement of discharge through culverts and sewer pipes. Further details of the H-flumes construction and installation are contained in Appendix B. The H-flume was used for discharge determination during individual sub-catchment sampling of the Ayreshire Place residential, O'Leary Avenue industrial/commercial and Groves Road rural sub-catchments. Hospital parking lot discharge was measured as stage in the storm sewer outfall and later determined using the Manning equation. The H-flume was not used unless attended because of the high likelihood of vandalism.

During all-basin sampling, sub-catchment discharges, except those from the forested Pitcher's Path sub-catchment, were measured as stage in the outfall pipe and discharge values were later calculated using the Manning equation. Slope of pipe determinations were made with a surveying level on the longest pipe length accessible.

Stage on a steel stake was recorded at the Pitcher's Path outlet. The stage-discharge rating curve was determined at a later date using a Price meter to determine discharge.

4.6 Precipitation data collection

As each individual sub-catchment sample was collected, note was also taken of the cumulative rainfall collected in a transparent cylindrical rain gauge, placed near the sample site.

During the all-basin sampling, rainfall was measured at the outlet with a weighing bucket recording gauge. Also to determine that rainfall distribution was even over the basin, five plastic wedge gauges were in place within the basin, at locations shown in Figure 4. Total rainfall was measured by checking these before and after sampling.

Further rain distribution information was available from recording rain gauges at Torbay airport to the north of the basin and from the Mount Pearl agricultural research station to the southwest.

5.0 RESULTS

5.1 All-basin sampling

The results of all-basin sampling are reported first below, as these are central to the objectives of this study. These results are reported by variable - water temperature, pH, discharge, conductivity, phosphates, nitrates and turbidity. With the exception of pH and temperature, variables are also presented as yield rates (mass $area^{-1}$ $time^{-1}$). The term yield rate is used in preference to load or loading as these latter terms have been used ambiguously in the literature.

Various usages of the terms load and yield appear in the literature, and although load and yield might be used interchangeably, they are conceptually different. Load conceptually points to the effect of the introduction of specified amounts of material to a receiving water body below the measuring point, while yield directs the attention to an amount of mass removed from an area upstream of the measuring point. Since the orientation of this study was to the determination of source areas of solutes and suspended solids and the comparative contribution of various land uses, the term yield rate is used in the presentation, comparison and discussion of data. The yield rate as mg $ha^{-1}s^{-1}$ is used where appropriate as the most useful measure for the areal and time scales of the study.

Each variable is reported below with a plot of storm variation on a time base. This is presented to illustrate time variance of response, particularly the timing of peak or minimum values. However, the effect of the rotational sequential sampling schedule should be noted. The effect can be seen clearly in the plot of water yield for all sample sites (Fig. 21, p. 68). The samples coincident with measured peak discharge at the residential and industrial/commercial sub-catchments were collected 20 minutes apart. The water yield is plotted on the time scale for those sample times. Between the two sub-catchments, there appears to be a 20 minute difference in time of peak flow, which is probably largely a function of the sampling method. The actual times and values of peak flow were undetermined, and would only be determinable with continuous discharge measurement.

Results are also presented in tabulated form by variable of the measured maximum, mean, minimum, standard deviation, range, and lag or lead (as negative values) from peak runoff of extreme values. These are reported for comparison of average values and comparison of deviation from the mean.

Comparisons are also made between sub-catchments by variable with simple linear regression. Statistically significant correlation coefficients are reported.

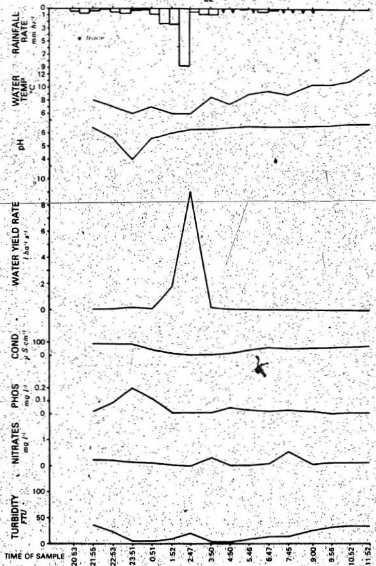
Following all-basin sampling results the precipitation measurements for the November 13-14 storm are presented. These were measured within the basin and data were collected at two nearby automated stations.

Subsequently results of the two other sampling programmes are reported. The details of 10 or 15 minute storm runoff sampling at individual sub-catchments are presented, not for the comparison of sub-catchments, but to determine the reliability of one hour samples to describe adequately sub-catchment and basin runoff quantitative and qualitative response for comparative purposes. The individual sampling was not considered useful for comparison between sub-catchments since each was sampled for different rainfall, antecedent moisture conditions and seasonal effect. However, the individual sampling may be compared to the results of all-basin sampling for the same storm since the runoff occurred from the same source area.

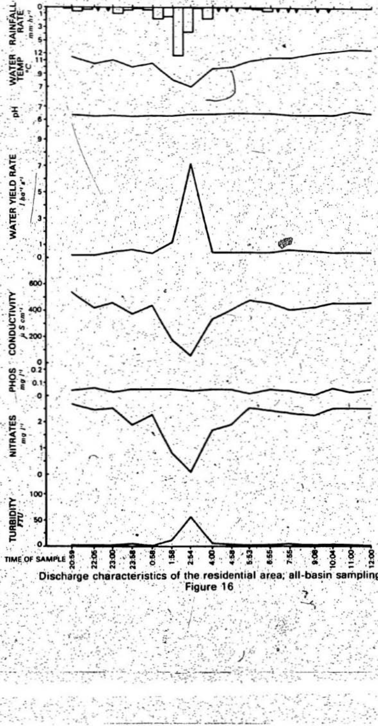
The results of the third sampling procedure, dry weather flow sampling of 35 sites in one day, are reported last. These were made to determine the reliability of presenting the all-basin sampling sub-catchments as representative of the particular land-use type in the basin. This sampling was also for the purpose of detection of anomalous contributions to the basin runoff.

5.11 Discharge

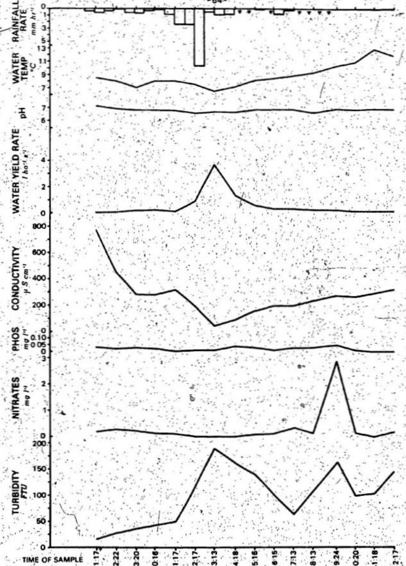
For comparison between sub-catchments, discharge values have been presented as water yield rate. Measured discharge values (as l s^{-1}) are presented in Appendix C and as first order statistics in Table 5. Water yield rates for urban sites are plotted at the same scale in Figures 15, 16, and 17, and differing scales for the rural, forested and outlet sites in Figures 18, 19 and 20 respectively. The water yield rates for all six sites are presented at the same scale in Figure 21.



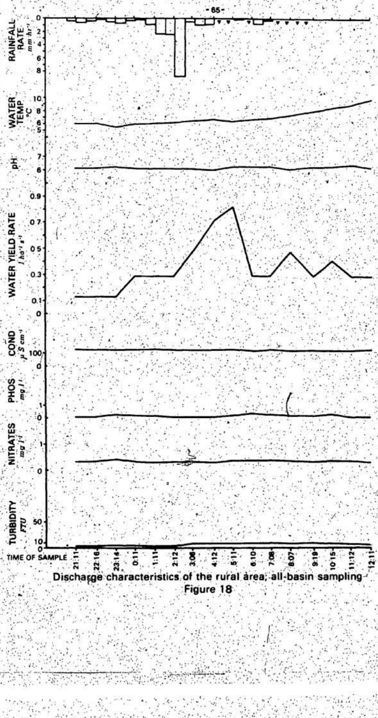
Discharge characteristics of the parking lot, all-basin sampling
Figure 15



Discharge characteristics of the residential area; all-basin sampling
Figure 16

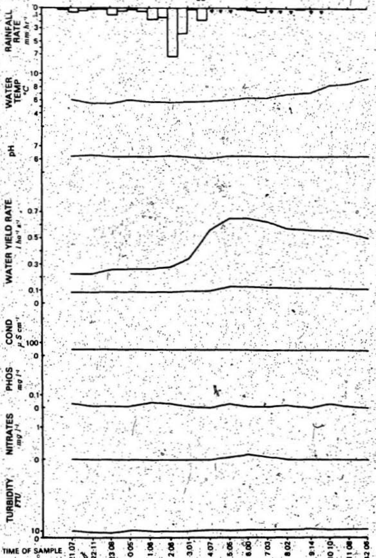


Discharge characteristics of the commercial/industrial area; all-basin sampling
Figure 17

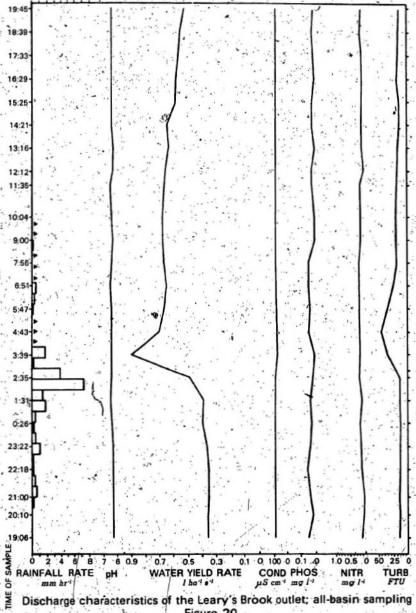


Discharge characteristics of the rural area; all-basin sampling

Figure 18



Discharge characteristics of the forested area; all-basin sampling
Figure 19



Discharge characteristics of the Leary's Brook outlet; all-basin sampling
Figure 20

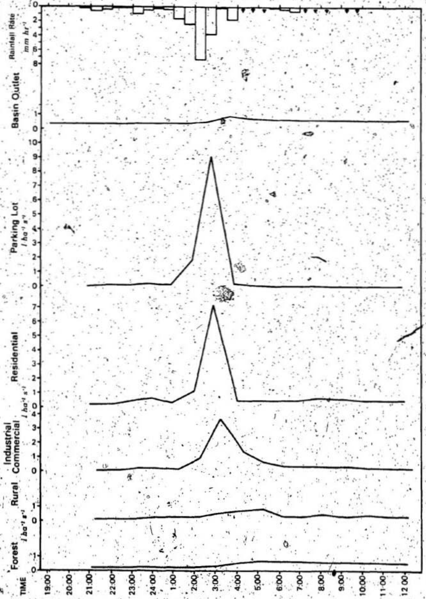


Figure 21 Water yield rate of basin and sub-catchments; all-basin sampling

TABLE 5

Discharge summary, all-basin sampling

	MAX.	MIN.	MEAN	STD.DEV.	RANGE	LAG OF MAX. (FROM RAIN BEAK, HOURS)
OUTLET						
Discharge $l\ s^{-1}$	1802	704	115.8	291.3	109.8	1
Water Yield	0.90	0.35	0.56	0.15	0.55	1
PARKING						
Discharge $l\ s^{-1}$	9.1	0.0	0.74	2.27	9.1	0
Water Yield $l\ ha^{-1}\ s^{-1}$	9.09	0.00	0.74	2.27	9.09	0
RESIDENTIAL						
Discharge $l\ s^{-1}$	39.0	1.2	5.06	9.13	37.8	0
Water Yield $l\ ha^{-1}\ s^{-1}$	7.20	0.22	0.94	1.69	6.98	0
COM/IND						
Discharge $l\ s^{-1}$	37.0	0.4	5.95	8.98	36.6	0
Water Yield $l\ ha^{-1}\ s^{-1}$	3.70	0.04	0.59	0.90	3.66	0
RURAL						
Discharge $l\ s^{-1}$	11.0	1.7	5.05	2.71	9.3	2
Water Yield $l\ ha^{-1}\ s^{-1}$	0.85	0.13	0.39	0.21	0.72	2
FORESTED						
Discharge $l\ s^{-1}$	78.5	27.0	53.47	20.30	51.5	2.5
Water Yield $l\ ha^{-1}\ s^{-1}$	0.65	0.23	0.45	0.17	0.42	2.5

The urban sub-catchments show very strong similarities. Correlations of water yield rates between the parking, residential and commercial/industrial sub-catchments are highly significant (Table 6). They exhibited rapid response to rainfall with time of measured peak flow corresponding to peak rainfall. High peak flows and rapid drops to low flow after cessation of rainfall were measured at all three urban sites. Mean, range and standard deviation of yield rate for the three urban sub-catchments were higher than for the basin outlet.

The parking lot had the highest peak, 9.09 l $ha^{-1}s^{-1}$ or nearly ten times the outlet, the highest range and standard deviation of water yield rate of all the sample sites. The residential sub-catchment had the highest mean yield rate.

The rural and forested non-urban basins were similar in response, with a highly significant correlation between them in water yield rate (Table 6). There was no significant correlation between the urban and non-urban sub-catchments in water yield rate. Low peak flow, with slow response, correspondingly slow recession and lags of more than two hours between peak rain and runoff peak were measured at the rural and forested sample sites. Mean, maximum and minimum water yield rates were lower from the non-urban sub-catchments than from the basin as a whole and very low in comparison with urban values. Standard deviation (0.21) and range (0.72) of water yield rate were higher for the rural sub-catchment than the basin outlet (0.15 and 0.55 respectively) and lower (with values of 0.17 and 0.42 respectively) for the forested sub-catchment

TABLE 6

Water yield rate; between site correlation

	PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
OUTLET	(-0.158) NS[x]	(-0.106) NS	(0.095) NS	0.727[y] 0.1%[z]	0.911 0.1%
PARKING		0.994 0.1%	0.942 0.1%	(0.174) NS	(-0.212) NS
RESIDENTIAL			0.938 0.1%	(0.205) NS	(-0.151) NS
COMM/IND				(0.416) NS	(-0.032) NS
RURAL					0.178 1%
FOREST					

[x]NS - not significant

y - correlation coefficient

z - significance level

than the outlet. The forested sub-catchment had lower peak flow, standard deviation and range and higher minimum and mean water yield rate than the rural sub-catchment.

The resultant water yield rate at the outlet (plotted at the largest scale in Figure 20, p. 67) was most similar to the non-urban sub-catchments, and highly significantly correlated to both rural and forest sites (Table 6, p. 71). There was no significant correlation between the outlet and the urban sub-catchments. In peak, mean and lag from rain peak of water yield rate the outlet fell between urban and non-urban values. The outlet water yield rate fell between rural and forest in standard deviation and range. The measured outlet minimum water yield rate was highest for all sites.

5.12 Water temperature

Temperature measurements are reported to half a degree Celsius for all samples in Appendix C, and plotted in Figures 15 to 19, pp. 62-66. Temperature was not measured at the outlet.

Residential runoff showed a very significant negative correlation of temperature with water yield rate (Table 7). No significant correlations between temperature and water yield rate appeared at the other sub-catchments.

With the exception of the correlation between the residential and the two non-urban sub-catchments, all correlations between sites of water temperature were highly significant (Table 8). The water temperature correlation between the residential and the rural and forested sub-catchments was very significant.

TABLE 7 Correlation between water yield rate and quality variables

	TEMPERATURE	CONDUCTIVITY	pH	PHOSPHATE	NITRATES	TURBIBITY	RAINFALL
OUTLET	not measured	-.933 0.1%	(0.330) NS	(-0.362) NS	(0.361) NS	.642 1%	(-0.158) NS
PARKING	(-0.440) NS	(-0.505) NS	(-0.004) NS	(-0.177) NS	(-0.311) NS	(0.000) NS	.982 0.1%
RESIDENTIAL	-.680 1%	-.818 0.1%	(-0.056) NS	(-0.054) NS	-.805 0.1%	.994 0.1%	.967 0.1%
COMM/IND	(-0.457) NS	-.579 5%	-.512 5%	(-0.056) NS	(-0.156) NS	.622 1%	.915 0.1%
RURAL	(0.083) NS	(0.163) NS	(0.089) NS	(0.181) NS	(0.010) NS	.711 1%	.715 1%
FORESTED	(0.485) 1%	-.692 NS	(0.552) NS	(-0.257) NS	.552 5%	.749 0.1%	(-0.270) NS

TABLE 8

Temperature; between site correlation

	PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
PARKING		0.862 0.1%	0.894 0.1%	0.895 0.1%	0.875 0.1%
RESIDENTIAL			0.809 0.1%	0.614 1%	0.685 1%
COMM/IND				0.903 0.1%	0.912 0.1%
RURAL					0.965 0.1%
FOREST					

The urban sub-catchments had higher maximum, minimum, mean, standard deviation and range of temperatures than the non-urban sub-catchments (Table 9). Also the urban site water temperatures had minima corresponding to flow peak, but the non-urban sub-catchments had minimum temperatures several hours before flow peak.

5.13 pH

The complete pH results are plotted for each of the six sample sites in Figures 15 to 20, pp. 62-67, and presented in Appendix C. Most samples taken were slightly acid. Exceptionally the parking lot showed a drop to an acidity of 4 near the beginning of the rainstorm and 3 hours prior to runoff peak. Also exceptionally there was a slightly alkaline reading of 7.1 at the commercial/industrial site for the first sample collected.

All sites had the minimum pH reading before the runoff peak (Table 10), but with the exception of the parking lot variation of pH was small. The parking lot had a standard deviation of 0.71 and range of 2.76 in pH. The next highest variation was the residential site with range of 0.47 pH units. The least variation was shown by the outlet samples with a range of only 0.18 pH units.

Parking lot runoff pH was very significantly correlated with that from the residential site and significantly correlated with that from the rural sub-catchment (Table 11). Also there was very significant correlation between residential and rural pH values, while the forested

Table 9

Temperature (^{o}C) summary; all-basin sampling

	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM Q PEAK (hours)
PARKING	12.0	6.0	8.5	1.94	6.0	0 min.
RESIDENTIAL	13.0	7.0	10.8	1.59	6.0	0 min.
COMMERCIAL/ INDUSTRIAL	13.0	6.5	8.9	1.87	6.5	0 min.
RURAL	10.0	5.0	7.0	1.32	5.0	-6 min.
FOREST	9.5	5.5	6.6	1.20	4.0	-3.5 min.

TABLE 10

pH summary; all-basin sampling

	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM Q PEAK (hours)
OUTLET	6.50	6.32	6.39	0.051	0.18	-6 min.
PARKING	6.76	4.00	6.20	0.711	2.76	-3 min.
RESIDENTIAL	6.72	6.25	6.42	0.128	0.47	-3 min.
COMMERCIAL/ INDUSTRIAL	7.10	6.60	6.9	0.132	0.50	-1 min.
RURAL	6.36	6.00	6.18	0.105	0.36	-2 min.
FOREST	6.33	6.10	6.25	0.063	0.23	-1.5 min.

TABLE 11

pH; between site correlation

	PARKING	RESIDENTIAL	COM/IND	RURAL	FOREST
OUTLET	(0.275) NS	0.508 5%	(−0.038) NS	(0.034) NS	(0.432) NS
PARKING		0.662 1%	(0.24) NS	0.517 5%	(0.419) NS
RESIDENTIAL			(0.186) NS	0.716 1%	(0.457) NS
COM/IND				(0.245) NS	(0.386) NS
RURAL					0.668 1%

site pH values were only very significantly correlated with rural values. Outlet pH was correlated significantly only with residential runoff. Commercial/industrial pH was not significantly correlated with any other sites.

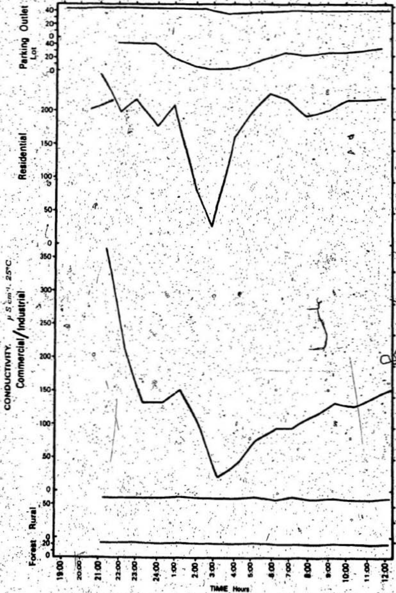
The only site which had significant correlation between pH and water yield rate was the commercial/industrial sub-catchment ($r = 0.512$). That site also had a very significant correlation between pH and conductivity of 0.635, the only correlation between pH and conductivity of significance.

There was little correlation of pH to conductivity. The only site with significant correlation of 0.635 (at the 1% level) between pH and conductivity was the commercial/industrial sub-catchment. The highest non-significant correlation coefficient between pH and conductivity (-0.417) was found for the forest runoff.

5.14 Conductivity

Conductivity as µS cm^{-1} at 25°C is plotted for each sample site in Figures 15 to 20, pp. 62-67, and for all sites in Figure 22. Specific values are also recorded in Appendix C.

Urban residential and commercial/industrial mean runoff conductivities were 4.5 and 3.1 times higher than the outlet runoff conductivity (Table 12). These urban sites had the highest peak conductivities, most notably to 770 µS cm^{-1} in the commerical/industrial runoff. The maximum



Conductivity of basin and sub-catchment runoff; all-basin sampling
Figure 22

conductivity values occurred at the start of the sampling period. Minimum conductivity values corresponded to discharge maximum at all three urban sample sites. Also, all three urban sites had much higher standard deviations and range of values than the outlet, although the parking lot runoff was lower in maximum, minimum, and mean than the outlet samples.

The urban sub-catchments were the only sites with significant conductivity correlations between sites (Table 13). Conductivity of commercial/industrial runoff was highly significantly correlated with parking lot runoff, residential and parking lot runoff conductivities were very significantly correlated and residential and commercial/industrial runoff conductivity was significantly correlated.

Runoff conductivity from the non-urban sample sites was much less variable than the urban and outlet samples (Table 12) with standard deviations of 3.4 and 2.1 for the rural and forested samples respectively.

The rural samples had no distinct minimum, with four samples of the value 120 μS cm^{-1}; however, the mean value was 1.4 times higher than that at the outlet. The forest runoff samples were lowest of all sites in mean, standard deviation and range of conductivity; however, the lowest measured forest runoff conductivity value occurred two and a half hours before runoff peak. That value was higher than residential and parking lot, and the same as commercial/industrial minima.

TABLE 12

Conductivity summary; all-basin sampling
(μS cm^{-1} · 25°C)

	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM PEAK Q (hours)
OUTLET	94	74	87.7	4.9	20	0 min.
PARKING	89	6	51.2	28.7	83	0 min.
RESIDENTIAL	540	57	398	125	483	0 min.
COMM/IND	770	43	274	163	727	0 min.
RURAL	130	120	124	3.4	10	–
FOREST	49	42	45.4	2.1	7	2.5 min.

TABLE 13

Conductivity; between site correlation

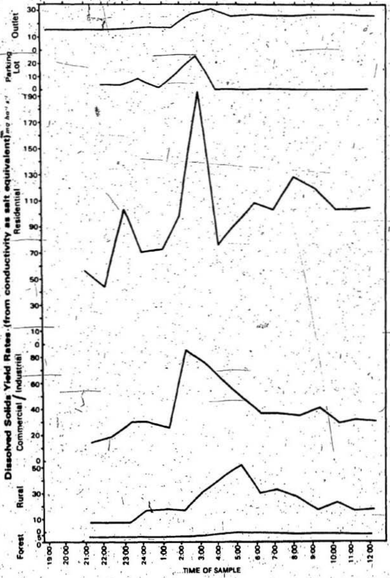
	PARKING	RESIDEN-TIAL	COM/IND	RURAL	FOREST
OUTLET	(0.469) NS	(-0.140) NS	(0.431) NS	(0.024) NS	(0.436) NS
PARKING		0.696 1%	0.835 0.1%	(-0.198) NS	(0.032) NS
RESIDENTIAL			0.611 5%	(-0.112) NS	(-0.059) NS
COM/IND				(-0.031) NS	(0.326) NS
RURAL					(0.461) NS

Outlet sample conductivities were not significantly correlated with samples from any other site and the minimum value occurred an hour after peak discharge. Values of maximum, minimum and mean were between those of the rural and forest site, but standard deviation and range of values were between those of the rural and parking lot sites.

In significant correlation between conductivity and discharge, the outlet and residential samples were highly significant and negatively correlated, the forest runoff samples were very significant and negatively correlated, and the commercial/industrial samples were significantly negatively correlated (Table 7, p. 73). Although the conductivity values plotted for the parking lot samples show a long shallow trough corresponding to the peak discharge values, this did not appear as a significant negative correlation. Because of its small variability, the rural runoff conductivity was not significantly correlated with discharge.

5.15 Dissolved solids yield rate

Dissolved solids yield rate was calculated as NaCl equivalent from conductivity values in $\mu S\ cm^{-1}$ at $25^{o}C$ multiplied by a factor of 0.475. These dissolved solids values were multiplied by water yield rate, and these values for all six sites are plotted in Figure 23, and specific values presented in Appendix C.



Dissolved solids yield rates of basin and sub-catchments (from conductivity as salt equivalent); all-basin sampling

Figure 23

The relationships between sites in dissolved solids yield rates (Table 14) changed very little from those of conductivity values (Table 12, p. 82). The maximum dissolved solids yield rate value at the residential site was greater than the commerical/industrial value and the minimum dissolved solids yield rate value at the outlet was higher than that at the rural site. In mean the outlet dissolved solids yield rate was slightly higher than the rural. Standard deviation of the residential samples was higher in dissolved solids yield rate than from the commercial/industrial site and the range of rural dissolved solids yield rate values was greater than the range at the outlet.

In correlation between sites of dissolved solids yield rates (Table 15), the pattern was similar to discharge correlations (Table 6, p. 71). Urban sites were all significantly correlated. Parking lot dissolved solids yield rate was very significantly correlated with that from the commercial/industrial site. Significant correlation was found between dissolved solids yield rates at the commercial/industrial and rural sites and at the residential and parking lot sites. Of the urban sub-catchments only the residential dissolved solids yield rate was significantly correlated with that of the outlet.

The rural and forest sites were highly significantly correlated in dissolved solids yield rate, and these non-urban sites were very significantly and highly significantly correlated in dissolved solids yield rates with the outlet respectively (Table 15).

TABLE 14

Dissolved solids yield rate summary;
all-basin sampling (mg ha^{-1} s^{-1} as NaCl equivalent)

	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM PEAK Q (hours)
OUTLET	31.4	15.5	23.06	4.92	15.9	7 max.
PARKING	25.7	0.6	4.20	6.91	25.1	0 max.
RESIDENTIAL	194.0	44.1	99.59	35.21	149.9	0 max.
COMM/IND	86.0	14.5	39.49	19.47	71.5	-1 max.
RURAL	51.8	7.7	22.90	12.58	44.1	0 max.
FOREST	14.5	5.1	9.45	3.41	9.4	-1/2 max.

TABLE 15

Dissolved solids yield rate; between site correlation

	PARKING	RESIDEN-TIAL	COM/IND	RURAL	FOREST
OUTLET	(-0.193) NS	0.540 5%	(0.292) NS	0.695 1%	0.867 0.1%
PARKING		0.567 %5	0.655 1%	(-0.027) NS	(-0.492) NS
RESIDENTIAL			0.547 5%	(0.431) NS	(0.353) NS
COM/IND				(0.468) NS	(0.123) NS
RURAL					0.737 0.1%

TABLE 16

Correlation between water yield rate and quality variable yield rates

	DISSOLVED SOLIDS YIELD RATE	PHOSPHATE YIELD RATE	NITRATES YIELD RATE	TURBIDITY YIELD RATE
OUTLET	0.986 0.1%	(0.175) NS	0.768 0.1%	0.823 0.1%
PARKING	0.930 0.1%	0.916 0.1%	(0.357) NS	0.994 0.1%
RESIDENTIAL	0.776 0.1%	0.994 0.1%	(0.194) NS	0.995 0.1%
COMM/IND	0.742 0.1%	0.713 1%	(-0.110) NS	0.996 0.1%
RURAL	0.998 0.1%	0.715 1%	0.983 0.1%	0.978 0.1%
FORESTED	0.995 0.1%	(0.279) NS	0.550 5%	0.980 0.1%

5.16 Phosphates

Phosphate values measured for each site are plotted in Figures 15 to 20, pp. 62-67, and values listed in Appendix C.

Urban runoff from the residential and the commercial/industrial areas was very similar to the outlet in phosphate content (Table 17). The parking lot runoff phosphate had the highest maximum value of 0.2 mg/l of any site, but also some phosphate values too low to be detected, thus giving that site the largest range and standard deviation of values.

Maximum non-urban runoff phosphate values were lower than those of urban runoff and the outlet discharge. The mean rural phosphate value of 0.02 mg l^{-1} was the same as from the commercial/industrial area, but the rural area had lower standard deviation and range of phosphate values. The forest site had the lowest range, standard deviation and mean phosphate values of any site.

There was little consistency in parallels of the occurrence in time of maximum and minimum values between sample sites. The parking lot values were similar to the outlet with maximums at three and five hours prior to discharge peak respectively. Low phosphate values occurred around flow peak at the parking lot and a minimum value occurred seven hours after flow peak. The outlet had minimum concentrations coincident with flow peak and five and a half hours after that.

The residential site had high phosphate values coincident with high discharge but the maximum phosphate values measured for five hours

TABLE 17

Phosphate summary; all-basin sampling (mg l^{-1})

SAMPLE SITE	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM PEAK Q (hours)
OUTLET	0.06	0.01	0.03	0.015	0.05	6 min.
PARKING	0.20	0.00	0.04	0.054	0.20	7 min.
RESIDENTIAL	0.06	0.01	0.04	0.014	0.05	6 min.
COMMERCIAL/ INDUSTRIAL	0.05	0.00	0.02	0.015	0.05	-2 min.
RURAL	0.04	0.01	0.02	0.010	0.03	-2 min.
FORESTED	0.04	0.0	0.003	0.006	0.02	3½ min.

before and seven hours after measured flow peak. The minimum value recorded was six hours after flow peak.

Phosphate values at the commercial/industrial sample site were at a maximum six hours after peak flow, and minimums occurred two hours before peak flow and at the end of the sample period.

The rural site phosphate values were at a maximum one hour after flow peak. Minimum values occurred two hours before and four and a half and six and a half hours after flow peak.

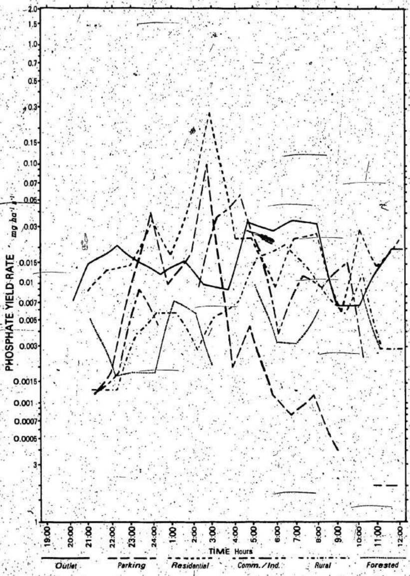
The forested site phosphate values were at a maximum four and a half hours after peak flow. However, the samples collected before and after that maximum were the minima in phosphate concentrations for the sub-catchment.

There were no significant correlations between sites in phosphate concentrations (Table 18). Neither were there significant correlations of phosphate values with discharge for any sample site.

5.17 Phosphate yield rate

Phosphate yield rate of runoff of all six sample sites is plotted in Figure 24. These values are the product of phosphate concentration in mg/l and discharge. All values are tabulated in Appendix C.

Of the sub-catchments and the outlet samples, the residential runoff had the highest phosphate yield rate in all respects (Table 19). The other urban sub-catchments, residential and commercial/industrial



Phosphate yield rates of basin and sub-catchments; all-basin sampling

Figure 24

TABLE 18

Phosphates; between site correlation

	PARKING	RESIDENTIAL	COM/IND	RURAL	FOREST
OUTLET	(0.343) NS	(0.053) NS	(-0.028) NS	(0.336) NS	(0.106) NS
PARKING		(0.060) NS	(0.001) NS	(0.0195) NS	(0.160) NS
RESIDENTIAL			(-0.287) NS	(-0.275) NS	(0.370) NS
COMMERCIAL/ INDUSTRIAL				(0.092) NS	(-0.280) NS
RURAL					(0.062) NS

had mean phosphate yield rates below that of the basin outlet, but the urban sites had higher standard deviation, range and maximum values. The minimums at these two urban sites were lower than at the outlet.

The parking lot and residential area had no lag of phosphate yield rate maximum from flow peak but the commercial/industrial runoff had a one hour lag. The minimum phosphate yield rates were seven, six, and nine hours after flow peak for the parking lot, residential and commercial/industrial sub-catchments respectively. The latter also had a minimum value two hours prior to flow peak.

The non-urban sub-catchments were similar to each other in phosphate yield rate for which values were lower than those of the outlet and the urban sub-catchments in maximum values, mean, range and standard deviation. The forest mean phosphate yield rate (0.002 mg $l^{-1}ha^{-1}$) was much the lowest, and that of the rural sub-catchment (0.008 mg $l^{-1}ha^{-1}$) was approaching that of the commercial/industrial and parking lot values. As for the commercial/industrial site, the rural site had a one hour lag between flow peak and peak phosphate yield rate, and peak values occurred seven and eight hours after flow peak at the end of the sample period.

The outlet phosphate yield rate in range and standard deviation was closer to the non-urban than the urban values; but the mean of 0.016 mg $ha^{-1}s^{-1}$ phosphate was higher than, but close to the 0.012 mg $ha^{-1}s^{-1}$ mean of the commercial/industrial and parking runoff. Extreme values were a maximum two hours after flow peak and the minimum 15 hours after flow peak.

Between parking lot and residential phosphate yield rate, there was highly significant correlation (Table 20) and there was significant correlation between outlet and rural phosphate yield rate. There were no other between site correlations.

The parking lot and residential phosphate yield rates were also highly significantly correlated with discharge, and the commercial/ industrial and rural phosphate yield rates were very significantly correlated with discharge. The outlet and forest phosphate correlations with discharge were not significant (Table 15, p. 86).

5.18 Nitrates

Nitrate values as NO_3 mg l^{-1} are plotted individually for each sub-catchment and the basin outlet in Figures 15 to 20, pp. 62-67. The values plotted are also tabulated in Appendix C.

The urban residential sub-catchment had a substantially higher mean (2.10 mg l^{-1} NO_3) than any other site, and the maximum nitrate concentration was high (Table 21). The minimum value of 0.17 mg l^{-1} was coincident with peak discharge. In standard deviation and range, the residential nitrates were close to those of the commercial/ industrial runoff, but the latter site had a much lower mean concentration of 0.29 mg l^{-1} NO_3 and a minimum value of zero detectable nitrates coincident with discharge peak. The maximum commercial/industrial nitrate value was an anomalously high value of 2.89 mg l^{-1} five hours after flood peak.

TABLE 19

Phosphate yield rate summary; all-basin sampling
(mg ha^{-1} s^{-1})

SAMPLE SITE	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG
OUTLET	0.035	0.006	0.016	0.009	0.029	2 max.
PARKING	0.091	0.0001	0.012	0.024	0.091	0 max.
RESIDENTIAL	0.288	0.006	0.039	0.068	0.282	0 max.
COMM/IND	0.056	0.001	0.012	0.015	0.055	1 max.
RURAL	0.022	0.001	0.008	0.006	0.021	1 max.
FORESTED	0.020	0.0	0.002	0.004	0.013	-½ max.

TABLE 20

Phosphate yield rate; between site correlation

	PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
OUTLET	(0.275) NS	(-0.198) NS	(-0.145) NS	0.583 5%	(0.363) NS
PARKING		0.927 0.1%	(0.349) NS	(-0.212) NS	(-0.160) NS
RESIDENTIAL			(0.457) NS	(-0.106) NS	(-0.084) NS
COMM/IND				(0.081) NS	(-0.219) NS
RURAL					(0.499) NS

The parking lot runoff had lower mean, standard deviation and range of nitrate concentrations than the other urban sub-catchments, but the mean of 0.14 mg l^{-1} was close to that of the outlet. Also, the standard deviation of 0.14 mg l^{-1} was closer to that of the outlet than to the other urban sample sites. A minimum of zero detectable nitrates occurred at the time of peak flow from the parking lot.

Of the two non-urban sub-catchments, the rural nitrate concentrations were higher. Also in mean, minimum and maximum values, the rural nitrates were higher than at the outlet. The rural nitrate standard deviation and range of values were next to lowest at 0.03 and 0.13 mg l^{-1} NO_3 respectively. The minimum value occurred one hour before measured peak discharge and the maximum value measured of 0.43 mg l^{-1} NO_3 was six hours before peak discharge.

The forest runoff contained very low nitrates concentrations. Except for the three samples centred around the time of discharge peak, nitrates were undetectable in all samples.

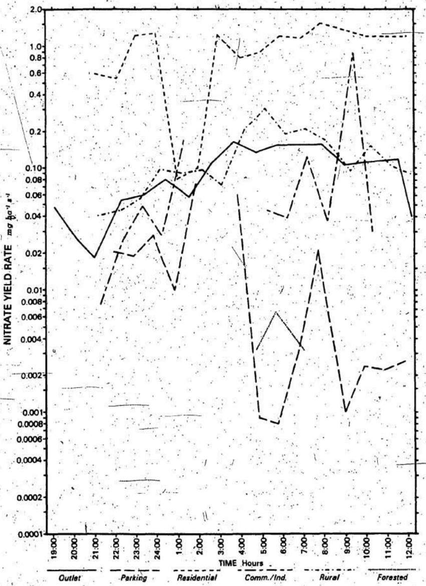
The outlet nitrate concentrations were at the minimum six hours before peak discharge and the maximum value was measured four hours after the main peak, but coincident with the start of a secondary discharge peak. The remainder of that peak had relatively low nitrate concentrations. The mean outlet nitrate concentration was closest to that of the parking lot, but the outlet nitrates standard deviation and range were most similar to the rural site.

There was no significant correlation between any sites in nitrate concentrations (Table 22). In correlation between nitrate concentrations and discharge rate the outlet, parking lot, commercial/industrial and rural sites did not have significant values. The residential nitrate concentrations were highly significantly and negatively correlated with runoff and the forest nitrate concentrations were significantly correlated with runoff (Table 7).

5.19 Nitrate yield rate

Nitrate yield rates presented are the product of nitrate concentrations and discharge yield rates, as mg $ha^{-1}s^{-1}$. These nitrate yield rates are plotted on a logarithmic scale for all six sample sites in Figure 25 and tabulated in Appendix C. One value from the parking lot, three from the commercial/industrial site and 13 from the forest site are not plotted as these samples had undetectable levels of nitrates.

The relationships between sites in nitrate yield rates (Table 23) remain similar to those of nitrate concentrations with some exceptions. For the urban sites conversion of concentration to yield rates made residential values much higher than those of the commercial/industrial site. With respect to maximum, standard deviation and range, residential values exceeded commercial/industrial values. Parking lot nitrate values calculated as yield rates fell below those of the outlet in maximum mean, standard deviation and range.



Nitrate yield rates of basin and sub-catchments; all-basin sampling
Figure 25

TABLE 21

Nitrate summary; all-basin sampling

SAMPLE SITE	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM PEAK Q (hours)
OUTLET	0.24	0.05	0.15	0.05	0.19	-6 min.
PARKING	0.53	0.00	0.14	0.14	0.53	0 min.
RESIDENTIAL	2.69	0.17	2.10	0.70	2.52	0 min.
COMM/IND	2.89	0.00	0.29	0.70	2.89	0 min.
RURAL	0.43	0.30	0.35	0.03	0.13	-1 min.
FORESTED	0.02	0.00	0.003	0.006	0.02	+½ min.

TABLE 22

Nitrate; between site correlation

	PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
OUTLET	(0.010) NS	(-.234) NS	(0.060) NS	(0.308) NS	(0.403) NS
PARKING		(0.280) NS	(-0.154) NS	(0.048) NS	(-0.372) NS
RESIDENTIAL			(0.149) NS	(0.321) NS	(0.168) NS
COMM/IND				(-0.067) NS	(-0.097) NS
RURAL					(0.325) NS

Rural standard deviation and range of values of nitrate yield rates were higher than the outlet values. As yield rates, the mean nitrate value of 0.088 mg $ha^{-1}s^{-1}$ for the outlet was closer to the commercial/industrial mean of 0.085 mg $ha^{-1}s^{-1}$ than to the parking lot value of 0.019 mg $ha^{-1}s^{-1}$. The standard deviation and range of outlet nitrate yield rates fell between those values for the parking lot and rural runoff.

Maximum nitrate yield rates occurred at different times than for nitrates as concentrations. The two non-urban sub-catchments had maximum nitrate yield rates concurrent with discharge peak. The outlet maximum nitrate yield rate was one hour after peak flow and that value for the residential and commercial/industrial areas was five and six hours respectively. For the parking lot maximum nitrate yield rate occurred one hour before flowpeak.

Only the rural and outlet values of nitrate yield rate were significantly correlated. This was at a highly significant level (Table 24).

The correlation between nitrate yield rate and discharge was highly significant for the rural and outlet samples and significant for the forested samples. There was no significant correlation between nitrate yield rate and discharge for the parking lot, residential and commercial/industrial samples (Table 16, p. 87).

TABLE 23

Nitrate yield rate summary; all basin sampling
(mg ha^{-1} s^{-1})

SAMPLE SITE	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM PEAK Q (hours)
OUTLET	0.162	0.018	0.088	0.042	0.144	1 max.
PARKING	0.073	0.001	0.018	0.023	0.072	-1 max.
RESIDENTIAL	1.534	0.541	1.079	0.276	0.993	5 max.
COMM/IND	0.895	0.001	0.085	0.217	0.894	6 max.
RURAL	0.315	0.040	0.134	0.075	0.275	0 max.
FOREST	0.013	0.000	0.002	0.004	0.013	0 max.

TABLE 24

Nitrate yield rate; between site correlation

SAMPLE SITE	PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
OUTLET	(-0.147) NS	(0.458) NS	(0.106) NS	0.810 0.1%	(0.455) NS
PARKING		(-0.278) NS	(-0.275) NS	(-0.088) NS	(-0.369) NS
RESIDENTIAL			(0.287) NS	(0.203) NS	(0.083) NS
COMM/IND				(-0.089) NS	(-0.050) NS
RURAL					0.579 5%

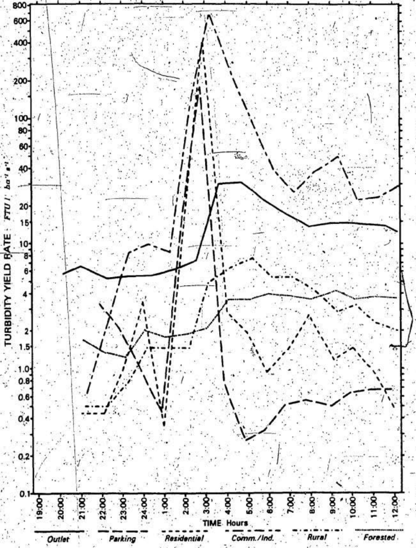
5.110 Turbidity

Turbidity values for each site are plotted in Figures 15-20, pp. 62-67, and as turbidity yield rates are plotted on one diagram in Figure 26. Measured values of turbidity are tabulated in Appendix C.

Urban runoff had the highest and lowest mean values. The commercial/industrial sample site had the highest mean value of 39.5 FTU as well as the highest values of minimum, maximum, range and standard deviation of turbidity (Table 25). There was no lag between turbidity and peak flow at the commercial/industrial site, and the minimum turbidity occurred at the start of the storm.

Residential runoff turbidity was relatively low. That site had the lowest mean of all sites of 6.8 FTU. However, the range of turbidity was high, next only to the commercial/industrial sites. The maximum turbidity measured at the residential site was concurrent with peak discharge and the lowest values were measured two hours before peak flow and at the end of the sample period.

Turbidity of the parking lot runoff had a mean value which fell between those of the commercial/industrial site and the outlet. The parking lot turbidity had the least range of values and lowest maximum of the three urban sub-catchments. The maximum turbidity value occurred five hours before peak flow with the first storm sample and a secondary lower peak turbidity value was coincident with peak flow. The minimum turbidity value was two hours after peak flow.



Suspended solids yield rates of basin and sub-catchments; all-basin sampling

Figure 26

TABLE 25

Turbidity summary; all-basin sampling

SAMPLE SITE	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG FROM PEAK Q (hours)
OUTLET	46	14	20.6	4.9	32	1 max.
PARKING	36	3	17.7	12.2	32	-5 max.
RESIDENTIAL	57	1	6.8	13.7	56	0 max.
COMM/IND	190	16	39.5	19.5	174	0 max.
RURAL	10	4	7.4	2.3	6	1 max.
FORESTED	14	7	11.1	1.8	7	3½ max.

TABLE 26

Turbidity; between site correlation

SAMPLE SITE	PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
OUTLET	(-0.382) NS	(-0.203) NS	(0.359) NS	0.595 5%	(0.388) NS
PARKING		(-0.034) NS	(-0.054) NS	(-0.076) NS	(0.039) NS
RESIDENTIAL			(0.490) NS	(0.160) NS	(-0.166) NS
COMM/IND				0.659 1%	0.546 5%
RURAL					0.652 1%

The two non-urban basins had low mean turbidity values, lower than the other sub-catchments, except the residential one. The rural mean turbidity (7.4 FTU) was lower than the forested (11.1 FTU). The range of turbidity values was similar for the two non-urban sub-catchments, and lower than other sample sites. The maximum turbidity values occurred after peak flow, one, two and four hours and three and a half hours after peak for rural and forest sub-catchments respectively. Non-urban minimum turbidity values occured early in the storm period.

At the outlet, mean turbidity values were measured which were between parking lot and commercial/industrial values. This mean (20.6 FTU) is more than double those of the non-urban samples. The outlet minimum turbidity level was only exceeded by that of the commercial/industrial runoff and the maximum was in between measured parking lot and residential turbidity values. The outlet values of turbidity standard deviation and range fell between the urban and non-urban values. Maximum turbidity was measured one hour after peak discharge at the outlet.

Between site correlation of turbidity was limited (Table 26). The outlet turbidity was significantly correlated only with that of the rural sub-catchment. The commercial/industrial runoff turbidity was highly significantly correlated with rural turbidity and significantly with the forest turbidity. There was also very significant correlation between rural and forest runoff turbidity.

Except for parking lot runoff, there was significant correlation between turbidity and discharge at all sites (Table 7, p. 73). The residential and forest discharge was highly significantly correlated with turbidity. Very significant correlation between turbidity and discharge occurred at the outlet, and commercial/industrial and rural sample sites.

5.111 Turbidity yield rate

Turbidity yield rates for all sites are plotted logarithmically in Figure 26, p. 103. The measure turbidity yield rate is the product of turbidity as FTU and water yield rate as $l\ ha^{-1}\ s^{-1}$ and calculated values are tabulated in Appendix C.

There were not many changes in the relative values of simple statistics in the transformation of turbidity to turbidity yield rates. Except those listed below statements about turbidity made in section 5.20 also apply to turbidity yield rates (Table 27).

Of the urban sample sites the parking lot had the highest minimum value, rather than the commercial/industrial site. The residential site, which had the lowest mean and minimum turbidity values, was not as low as the commercial/industrial and parking lot sites in turbidity yield rate mean and minimum respectively. Transformation to turbidity yield rate gave a maximum value from the parking lot coincident with peak discharge rather than a turbidity peak five hours before flow peak.

The non-urban sub-catchments had the lowest mean values of turbidity yield rate. The maximum turbidity yield rate at those sites occurred not after peak flow but coincident with it.

At the outlet, mean turbidity as a yield rate was between that of the parking lot and forest sub-catchments. The outlet also had the highest minimum turbidity calculated as a yield rate and the maximum value measured was between that of the urban and non-urban sample sites. The maximum outlet turbidity value shifted from one to two hours after peak discharge when calculated as a yield rate.

The three urban sites were each highly significant in correlation of turbidity yield rate with the other urban sites, but not with the non-urban or outlet sites (Table 28). The rural and forest sites were very significant in correlation of turbidity yield rate and those two sites were highly significant in correlation with the outlet.

All sites showed a highly significant correlation between turbidity yield rate and discharge.

5.112 Precipitation

Precipitation totals for the November 13-14 rainfall measured with six gauges within the study basin and two in the vicinity are presented in Table 29. The two gauges outside the basin were at the agricultural research station at a distance of 7.3 km and an azimuth of

TABLE 27

Turbidity yield rate summary; all-basin sampling

(FTU 1 $ha^{-1}s^{-1}$)

SAMPLE SITE	MAX.	MIN.	MEAN	STD. DEV.	RANGE	LAG
OUTLET	32.3	5.3	12.2	7.5	27.0	2 max.
PARKING	181.8	0.3	14.0	46.6	181.5	0 max.
RESIDENTIAL	410.4	0.4	27.8	102.1	410.0	0 max.
COMM/IND	703	0.64	87.7	174.1	702.4	0 max.
RURAL	7.7	0.5	3.2	2.3	7.2	0 max.
FORESTED	7.9	1.8	5.2	2.4	6.1	3½ max.

TABLE 28

Turbidity; between site correlation

SAMPLE SITE	PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
OUTLET	(-0.235) NS	(-0.189) NS	(0.037) NS	0.876 0.1%	0.758 0.1%
PARKING		0.998 0.1%	0.949 0.1%	(0.155) NS	(-0.254) NS
RESIDENTIAL			0.947 0.1%	(0.194) NS	(-0.191) NS
COMM/IND				(0.366) NS	(-0.078) NS
RURAL					0.712 1%

TABLE 29

Precipitation, November 13-14, 1979; all-basin sampling

GAUGE	type of gauge	total rainfall (mm)	distance from outlet of Leary's Brook (km)	azimuth bearing from outlet	altitude metres above sea level
OUTLET	weighing bucket recorder	10.5	-	-	55
1 Oxen Pond	wedge	10.7	1.5	258°	148
2 Thorburn Rd.	wedge	10.2	5.0	258°	184
3 Kenmount	wedge	9.1	6.7	231°	206
4 Pitcher's Path	wedge	9.7	2.7	277°	173
5 Kelsey's	wedge	9.9	3.8	228°	138
Torbay	tipping bucket recording	9.5	5.0	355°	141
Agricultural Station	tipping bucket recording	10.4	7.3	207°	114

207° from the Leary's Brook outlet, and the Torbay station at a distance of 5.0 km and azimuth of 355°.

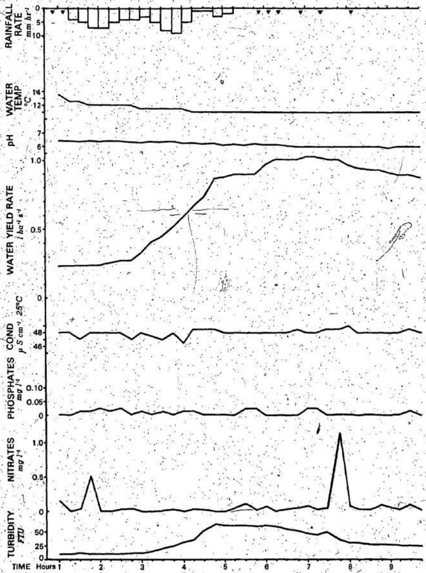
The outlet recording gauge, and gauges 1, 2, 4 and 5 of the wedge gauges are most representative of the areas of the Leary's Brook basin which were sampled November 13-14. Their positions are shown in Figure 4, p. 34. The range of total catch of these gauges was from 9.7 mm at gauge 4 to 10.7 mm at gauge 1, a difference of 10.4%. The low value of 9.1 mm at the Kenmount gauge, number 3, may be due to the placement of the gauge too close to trees or to an elevational effect.

The distribution of rainfall during the November 13-14 storm is reported for the outlet gauge in half hourly increments as an hourly rate in Figures 15-20, pp. 62-67, with runoff data. These were not plotted identically for each sample site because the half hourly rates are based on fifteen minute rainfall increments which were aggregated dependant on the timing of the sampling at each sample site.

5.2 Individual sub-catchment sampling

5.21 Forested sub-catchment sampling

The results of sampling the storm runoff of the Pitcher's Path forested sub-catchment for the storm of October 2, 1979, are presented in Figure 27. Samples were collected every fifteen minutes for nine hours during and after precipitation. With the exception of two anomalously high nitrate concentrations, there was great stability



Discharge characteristics of the forested area; individual sampling
Figure 27

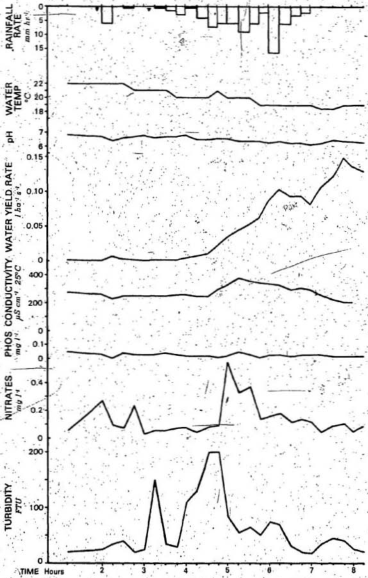
of response in all variables measured and response of discharge was very slow. The greatest change in water yield rate over fifteen minutes was 0.13 l ha^{-1} s^{-1}, an 18% increase, although the greatest 15 minute increase after the start of the storm in precipitation rate was 60%. There was a lag of three hours between rainfall and runoff peaks.

Both pH and temperature were stable, with an over all drop during the sampling period. Conductivity was variable within a narrow range of values from 46.5 to 49 µS cm^{-1}. The largest 15 minute conductivity change was an increase of 2 µS cm^{-1}. Phosphates concentrations varied over a narrow range from reading of 0 to 0.025 mg l^{-1}. Nitrate concentrations, except for two samples mentioned above, were mostly less than 0.2 mg l^{-1}. Also one sample was found to have a nitrate concentration of 1.1 mg l^{-1}, while the adjacent samples were 0.03 mg l^{-1}.

Turbidity was the one variable with a readily visible correlation with discharge, although discharge peak was lagged behind turbidity peak by about two and a half hours. The greatest turbidity change measured in 15 minutes was an increase of 16 FTU or 43%.

5.22 Rural sub-catchment sampling

Response of the rural Groves Road area to rainfall of August 5, 1979, was generally less stable than of the forested sub-catchment, although the rainfall rate of August 5 was also more variable (Fig. 28). A distinct though small discharge response was apparent from a short

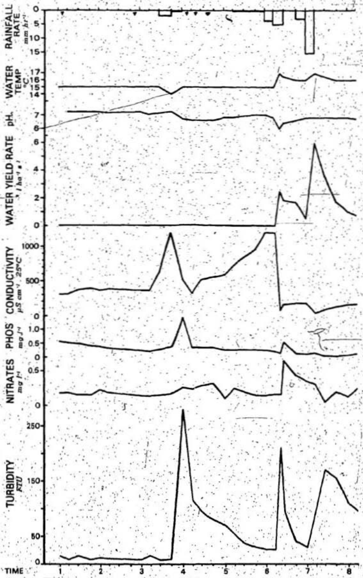


Discharge characteristics of the rural area; individual sampling
Figure 28

shower of 1.5 mm in fifteen minutes which also produced pH conductivity, phosphate, nitrate, and turbidity response. Only turbidity of these variables increased with discharge. As for the forested sampling of October 1, temperature and pH dropped slowly over the sampling period without any great short term changes. Discharge was stable, showing a good response to precipitation, but peak lagged by 1 1/2 hours. A 30% increase in water yield rate of 0.025 l ha^{-1} s^{-1} occurred over fifteen minutes in response to a 700% fifteen minute rainfall rate change. Conductivity values were stable, but of varying response. There was a dissolved solids dilution response to an initial shower, later followed by a flushing of solutes and a subsequent dilution as discharge increased further. Maximum fifteen minute conductivity change was an increase of 30 µS cm^{-1} or 15%. Phosphate variation was more stable for the rural short term sampling than for the forested. The variation of phosphates, though much less, was similar in direction to that of conductivity. Nitrates varied over a narrower range in the rural than in the forested individual site sampling. Response direction and timing of nitrates from the rural sub-catchment were similar to the conductivity variation, but more extreme. A 400% fifteen minute increase of 0.37 mg l^{-1} nitrates occurred. Turbidity also showed rapid variation, as well as flushing and depletion. A 400% increase in 15 minutes of 100 FTU occurred.

5.23 Commercial/industrial sub-catchment sampling

Fifteen minute sampling was carried out over most of a period of seven hours, as indicated in Figure 29, at the O'Leary Avenue commercial/industrial sub-catchment outfall on July 5, 1979. A very strong response to two periods of rainfall occurred. Although change of runoff in response to the first short rainfall was almost unmeasurable, there were effects in temperature, pH, phosphate and nitrate, and extreme response in conductivity and turbidity. A flushing and subsequent dilution effect occurred in conductivity, phosphates, nitrates and turbidity. In water yield rate, the maximum increase in fifteen minutes was tenfold or 5 l ha^{-1} s^{-1}! This increase arrived at the outfall as a distinct flood wave in response to a shower of 3.8 mm in fifteen minutes, or a fivefold rainfall increase in that time interval. The greatest change in conductivity occurred at that time also, with a drop of 1100 µS cm^{-1} or 93% dilution. Also, the greatest phosphate concentration change was a dilution of 1.0 mg l^{-1} in 15 minutes, a 75% decrease. Nitrate concentrations increased a maximum in fifteen minutes by 0.49 mg l^{-1} or 300%, but the most extreme change was a turbidity increase of 273 FTU or a thirty-nine times increase in fifteen minutes.



Discharge characteristics of the commercial/industrial area; individual sampling
Figure 29

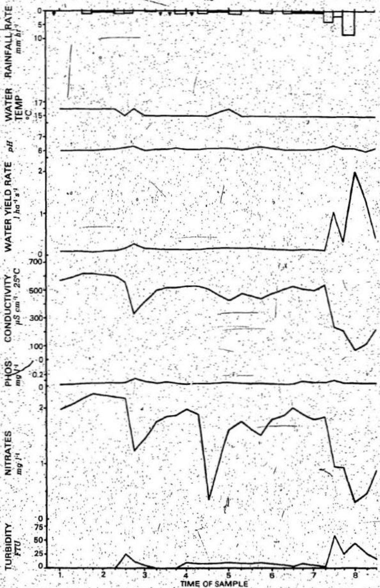
5.24 Residential individual sub-catchment sampling

The Ayreshire Place residential sub-catchment was sampled on August 13, 1979, on a fifteen minute sampling schedule over a rainfall period of seven and a half hours (Fig. 30). Response to changes in rainfall rate, as for the commercial/industrial sub-catchment, were rapid and extreme in water yield rate, conductivity, nitrate and turbidity. Fluctuations in pH, temperature and phosphate concentrations were small. The maximum 15 minute phosphate concentration change was an increase of 0.06 mg l^{-1} or 145% and the maximum change between samples of pH was 0.3 units.

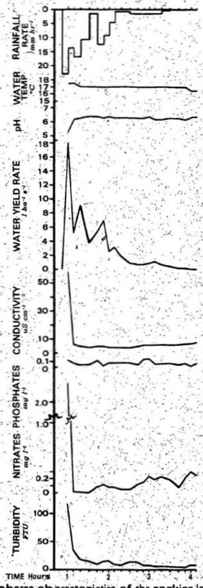
Water yield rate increased a maximum of 410% or 1.6 l ha^{-1} s^{-1} in 15 minutes for a 350% increase in rainfall rate between samples. Conductivity and nitrate concentrations followed a very similar pattern of dilution with runoff increases, except for a large anomalous drop in nitrate concentrations at hour 4:30. Conductivity had a maximum 15 minute change of -56% or 300 µS cm^{-1} and nitrate concentrations changes a maximum of -33% between samples, a drop of 0.6 mg l^{-1}. Turbidity had an extreme increase between samples of 2300% from 2.5 to 60 FTU.

5.25 Parking lot sub-catchment sampling

The hospital parking lot was sampled at a ten minute interval over a period of 3:15 hours during a rain storm and until cessation of flow on June 15, 1979 (Fig. 31). A sudden intense downpour of 5.5 mm of rainfall in less than ten minutes brought runoff to 18 l ha^{-1} s^{-1} from



Discharge characteristics of the residential area; individual sampling
Figure 30



Discharge characteristics of the parking lot; individual sampling

Figure 31

no flow. Although rainfall continued at a high rate of 2.2 mm per 10 minutes, water yield rate dropped dramatically by the second sample time and all other measured variables also changed, except water temperatures. Turbidity, nitrates, phosphates and conductivity all showed a strong first flush and subsequent dilution of which nitrates were the most extreme, dropping from 2.3 mg l^{-1} to 0.02 mg l^{-1} in ten minutes, a change of -99%. Turbidity dropped 110 FTU or -85%, conductivity dropped 53 μS cm^{-1} or 91%, phosphates dropped .04 mg l^{-1} or 33%, pH increased from 5.3 to 6.2, while water yield rate dropped 13 l ha^{-1} s^{-1} or 71% during the same 10 minute period.

During subsequent sampling much smaller fluctuations in measured variables occurred and water yield rate had the greatest variability, and a maximum ten minute change of 5.3 l ha^{-1} s^{-1} or -58%. Maximum change in ten minutes for other variables after the initial twenty minutes of runoff were conductivity 1 μS cm^{-1} or +25% phosphates 0.08 mg l^{-1} or +133%, nitrates 0.14 mg l^{-1} or +156%, and turbidity 6 FTU or +75%.

5.26 Short term changes in runoff and runoff quality undetected by one hour sampling

For each sub-catchment sampled for individual storms, there were several variables with maximum change over a fifteen or ten minute period of a magnitude greater than the overall change in the hour surrounding that period. These undetected short term changes are tabulated in Table 30 and presented with the ranges and standard deviations of values determined for the single storm all-basin sampling of November 13-14. Turbidity and phosphate values for most sub-catchments were found to have short term concentration changes larger than the range of values for the November 13-14 storm runoff. Undetected short term nitrate concentrations change during individual sampling of the two non-urban sub-catchments was also higher than the sampling period range of November 13-14. The parking lot and the commercial/industrial individual sub-catchment sampling also demonstrated very high short term discharge changes, larger than the November 13-14 water yield rate ranges for those sites.

5.3 Dry weather sampling

The 35 dry weather samples were collected to determine whether the sites selected for sampling during the all-basin sampling were reliably representative of their designated land use types. Also detection of anomalous sources of suspended solids or solutes was attempted.

The results of dry weather sampling are presented in Table 31 and the sites of samples are designated by sample numbers on Figure 4, p. 34. All of the samples were collected between 9:45 and 16:45 on the same day, July 17, 1980.

TABLE 30

Short term runoff variable change undetected by one hour sampling schedule compared with all-basin sampling

		PARKING	RESIDENTIAL	COMM/IND	RURAL	FOREST
TEMPERATURE	R[1]	6.0	6.0	6.5	5.0	4.0
(^{o}C)	sd[2]	2.0	1.6	1.9	1.3	1.2
	uc[3]	*	*	1	1	*
pH	R	2.8	0.5	0.5	0.4	0.2
	sd	0.7	0.1	0.1	0.1	0.1
	uc	*	0.3	0.5	0.1	0.1
WATER YIELD	R	9.1	7.0	3.7	0.7	0.4
RATE	sd	2.3	1.7	0.9	0.2	0.2
($l\ ha^{-1}s^{-1}$)	uc	14.	1.1	5.5	*	*
CONDUCTIVITY	R	83	483	727	10	7
($\mu S\ cm^{-1}$)	sd	29	125	163	3.4	2.1
(25°C)	uc	53	*	640	*	2
PHOSPHATE	R	0.2	0.05	0.05	0.03	0.02
($mg\ l^{-1}$)	sd	0.05	0.01	0.02	0.01	0.01
	uc	0.08	0.06	0.95	0.04	0.03
NITRATE	R	0.05	2.5	2.8	0.13	0.02
($mg\ l^{-1}$)	sd	0.01	0.07	0.7	0.03	0.01
	uc	0.01	0.04	0.3	0.17	1.1
TURBIDITY	R	33	56	72	6	7
(FTU)	sd	12.2	13v7	19.5	2.3	1.8
	uc	*	23	183	115	*

[1]range of all-basin sampling values

[2]standard deviations of all-basin sampling values

[3]undetected change - maximum 15 or 10 minute change less one hour change across same time period

*hourly change greater than maximum short time change

TABLE 31

Dry weather single-day sampling water quality

LAND USE	SAMPLE NO.	TIME	WATER TEMP (°C)	pH	CONDUCTIVITY (μS cm^{-1} .25°C)	TURBIDITY FTU
Outlet	1	9:45	16.0	6.8	145	–
Residential	3	10:15	14.0	6.3	680	4
residential	4	10:15	13.2	6.5	520	19
residential	5	10:30	14.0	6.7	350	4
residential	6	10:30	13.5	6.7	390	4
mean res.				6.6	490	8
Comm./Ind.	18	15:00	18.9	7.4	780	250
comm./ind.	19	15:10	18.0	9.5	360	30
mean c./i.				8.5	570	140
Rural	8	10:45	16.0	6.3	195	11
rural	7	10:45	17.0	6.7	60	6
rural	13	11:25	13.9	6.0	200	17
rural	11	11:30	16.0	6.5	80	7
rural	15	12:10	21.2	6.4	140	145
rural	16	13.15	19.0	6.3	54	28
rural	17	13:15	21.0	6.7	62	20
rural	31	16:50	16.5	6.3	73	4
rural	32	17:00	18.5	6.3	275	3
mean rural				6.4	127	27
Forest	9	11:00	15.5	6.6	48	12
forest	10	11:05	11.0	6.4	38	3
forest	34	12:15	18.0	6.2	39	13
forest	35	12:15	–	6.5	35	13
forest	37	12:15	17.2	6.3	34	10
forest	38	13:00	22.0	6.4	34	16
forest	39	13:00	23.0	6.2	38	–
forest	40	14:15	20.0	6.3	41	23

TABLE 31 (cont'd)

LAND USE	SAMPLE NO.	TIME	WATER TEMP (°C)	pH	CONDUCTIVITY (µS cm^{-1} .25°C)	TURBIDITY FTU
forest	33	-	16.0	6.2	84	13
forest	23	15:30	-	6.1	63	18
forest	25	15:50	19.3	6.0	32	18
forest	24	16:00	24.8	5.9	88	13
mean forest				6.3	48	14
re./ru[2]	2	9:52	16.4	6.3	680	4
ru./fo.	14	11:40	18.0	6.7	72	16
ru./fo./c.i.	20	15:15	21.7	7.0	120	17
fo./c.i.	22	15:30	18.5	6.8	71	17
c.i./fo.	29	16:30	21.6	6.9	88	18
fo./ru.	27	16:30	22.3	6.4	84	15
c.i./fo.	30	16:45	12.2	6.4	73	4

[1] underlined sites are those sampled in detailed study

[2] areas of mixed land use are designated with the order of areal predominance

Temperatures show a steady rise from morning to late afternoon, which prevents direct temperature comparison between all samples. However, the comparison of temperatures between samples collected consecutively from different land uses points out some strong differences. Notably the temperature of the open channel flow of the outlet was at least 2°C more than any of the residential runoff samples draining through pipes.

Average values of conductivity, turbidity and pH were calculated and are presented in Table 31, also with the water quality values measured at four all-basin sampling representative sub-catchments. The forested areas were very similar in water quality to the Pitcher's Path sub-catchment, although the pH of the Pitcher's Path sample was the highest measured. Turbidity was slightly lower than average at Pitcher's Path, but the conductivity at Pitcher's Path of 48 μS cm^{-1} was nearly equal to the mean forest value.

The rural all-basin sub-catchment - Groves Road - was of higher dissolved solids concentration but lower suspended solids concentrations than the rural sample mean. The pH of the Groves Road sub-catchment and the rural mean were very close - 6.3 and 6.4 respectively.

Of the small number of residential storm drain outfall samples, that from the Ayreshire Place all-basin sampling site had the highest conductivity and lowest pH. The turbidity was the same from Ayreshire Place (4 FTU) as from two of the three other residential outfalls sampled.

Samples from the two commercial/industrial sub-catchments were very different in all three quality measures. The O'Leary Avenue sub-catchment had a high pH of 7.4 but the other site had a much higher pH value of 9.4. Turbidity was nearly an order of magnitude higher at 250 FTU from O'Leary Avenue than from the other site (30 FTU); and conductivity of the O'Leary Avenue sample was more than double the conductivity of the other commercial/industrial sample - 780 and 360 μS cm^{-1} respectively.

There were four samples with particularly anomalous values. The residential sample number 4 was very turbid with 19 FTU while the other three sites sampled were all 4 FTU. As mentioned above, the commercial/industrial sample 19 was very different than the other sample of similar land-use, number 18. The pH of 9.5 of sample 19 was extremely high. The rural sample 15 had a very high turbidity of 145 FTU relative to other rural samples. The only other site which higher turbidity of all dry weather samples was from the O'Leary Avenue sub-catchment.

The mixed land-use sub-catchments are listed at the end of Table 31. In most cases, the measured water quality of the samples was most like that of the predominant land-use of that sub-catchment. Exceptionally, the two mixed commercial/industrial and forested sub-catchments (numbers 29 and 30) fell mostly into the same range of water quality values as forested samples, although the pH of sample 29 fell between the ranges of the two land-uses.

6.0 INTERPRETATION AND DISCUSSION

The discussion of results presented below is in an order and from a point of view different than that used in the report of results. Primarily the response of the Leary's Brook basin as a whole is discussed in terms of the hydrograph, the chemograph and the graph of suspended sediment variation, as measured by turbidity. The basin response is then explained where possible in terms of the spatial variation of sources of the response components, and at the same time the effects of variation in land use within the basin on the hydrological response of the basin are determined. Also, the related effects of lag and hysteresis of sediment and solute response are explained in terms of source areas and routing. Initially, however, some comparison is made between the study catchment and other areas, both natural and urbanized. The adequacy of one hour sequential rotational sampling for the description of runoff quantity and quality of the basin and its sub-catchments is discussed.

6.1 Comparison of Leary's Brook with Northeast Pond River

The response of Leary's Brook and its Pitcher's Path forested sub-catchment are here compared with the response of Northeast Pond River, a natural stream 10.5 km from the Leary's Brook outlet, in order to determine whether the forested sub-catchment response was similar to a natural stream, and to determine how much Leary's Brook runoff may be different than its natural state because of land use changes.

The mean daily discharge rate of Northeast Pond River for November 13-14, 1979, was 0.5 l ha^{-1} s^{-1} (Environment Canada, 1979). This is mid-way between mean values determined for the storm runoff of that period from the forested sub-catchment and Leary's Brook of 0.45 and 0.56 l ha^{-1} s^{-1} respectively. Augmentation of the Leary's Brook water yield rate was derived from the high yield rate urban areas.

Comparable water quality data for Northeast Pond River and Leary's Brook are presented in Table 32. The Northeast Pond River mean values are long term and include all seasons, while the Leary's Brook means are very short term autumn values; however, some inter-basin similarities and dissimilarities are highlighted. The Leary's Brook outlet and forested runoff pH values were very similar, and higher than that of the median pH of Northeast Pond River. The pH of 6.3 was the 90th percentile value for Northeast Pond River.

In conductivity the forested sub-catchment runoff was more like the mean of Northeast Pond River and Leary's Brook outlet showed a near doubling of conductivity resulting from land use changes. Comparison of conductivity between sub-catchments and Leary's Brook outlet (Table 12, p. 82) shows that the urban commercial/industrial and residential areas were major contributors to the outlet conductivity. However, the rural area also contributed at a higher rate than the forested, and the parking lot was little different in mean conductivity than the forested area.

TABLE 32

Mean water quality of Leary's Brook and Northeast Pond River*

	pH	CONDUCTIVITY ($\mu S\ cm^{-1} \cdot 25^{o}C$)	PHOSPHORUS ($mg\ l^{-1}$)	NITROGEN ($mg\ l^{-1}$)
Northeast Pond River (median 50% ile)	5.7	52	0.07 (total)	0.004 (NO_3+NO_2 dissolved)
Leary's Brook outlet	6.4	88	0.010 (reactive)	0.030 (NO_3)
Forested sub-catchment	6.3	45	0.001 (reactive)	0.001 (NO_3)

*Northeast Pond River data, NAQUADAT, 1980

In nutrient concentrations, the effect of land use is quite dramatic. The forest storm runoff concentrations of phosphorus and nitrate nitrogen appear to be well below the Northeast Pond River median values, which are very close to the Leary's Brook outlet mean concentrations. However, the Leary's Brook outlet nutrient values do not include non-reactive phosphorus, which may be held on particles of the considerable suspended sediment yield, nor are there nitrite values included. Thus, the Leary's Brook storm flow nutrient concentrations were undoubtedly higher than the Northeast Pond River median values. The mean outlet nutrient values were an order of magnitude higher than the forested values while the phosphate (Table 17, p. 89) and nitrate (Table 21, p. 99) mean concentrations for the other sub-catchments were all higher than the forested values, indicating that urban and rural land use has contributed to the augmentation of outlet nutrient levels.

The sampling showed that the November 13-14 storm runoff from Leary's Brook was augmented in water yield rate, dissolved load and nutrient concentrations relative to the runoff from the forest portions of the basin. The forested sub-catchment storm runoff was lower in nutrient concentrations than the long term median values for a comparable basin, but similar in dissolved solids yield. Thus, it is reasonable to consider the Leary's Brook forested sub-catchment to be in a natural condition for the purpose of comparison of land-use effects on the Leary's Brook runoff.

6.2 Comparison of Leary's Brook with other areas

While Grizzard et al. (1978) found that phosphorus and nitrogen as annual yield rates from urban areas were double those of non-urban, the storm runoff nitrate and phosphate mean yield rates of Leary's Brook differed more widely between the forested area and the outlet. Phosphate yield rates were nearly an order of magnitude greater for the whole basin than for the forested area, and half an order of magnitude greater from the parking and commercial/industrial areas than from the forested. However, the residential mean phosphorus (as reactive phosphate) yield rate of 0.013 mg ha^{-1} s^{-1} was the only value approaching that reported by Grizzard et al. (1978) of 0.06 mg ha^{-1} s^{-1} total phosphorus. All the mean phosphate yield rates measured for the various Leary's Brook sites fall below the range of mean phosphate yield rates for various urban land uses reported by Uttormark et al. (1974, cited in Whipple, 1978) as 0.139 to 0.72 mg ha^{-1} s^{-1}.

With respect to nitrate levels, Leary's Brook outlet had a measured storm runoff mean yield rate nearly one and a half orders of magnitude greater than from the forested contributing area, but the outlet value was well below Grizzard et al.'s (1978) reported value. The residential storm runoff mean nitrogen (nitrate) yield rate of 0.25 mg ha^{-1} s^{-1} approached Grizzard's reported total nitrogen value of 1.1 mg ha^{-1} s^{-1}.

Cherkauer (1975b) found two orders of magnitude increase between rural and suburban residential single storm suspended sediment yield rates (Table 1, p. 13). From Leary's Brook the suspended sediment yield rate (FTU 1 ha^{-1} s^{-1}) was five times higher from commercial/ industrial and residential storm runoff than from forest storm runoff. These urban sources produced a doubling of suspended sediment yield rate over forested rates at the outlet. Leary's Brook rural suspended sediment yield rate mean was notably half that from the forested area.

An order of magnitude difference between single storm total dissolved solids yield rates for rural and suburban residential areas of Milwaukee was reported by Cherkauer (1975b). There was also an order of magnitude difference between total dissolved solids yield rates (as measured by mean conductivity per hectare-second) from Leary's Brook forested and residential areas, but Leary's Brook outlet total dissolved solids yield rate was double the forest value, as was the rural value. Commercial/industrial dissolved solids yield was four times the forested, but the parking lot produced half the forested dissolved solids yield.

In comparison with other areas Leary's Brook had a much greater increase of nutrient yield rate from urban areas compared with a natural forested area, but these actual urban nutrient yield rates were still relatively low compared with other urban areas. Similarly, there was a strong difference between the natural runoff and the urban in suspended and dissolved solids yield rates, although the sampling of the parking lot area showed that urban yield rates as means can be as low or lower than forested runoff.

6.3 Utility of one hour sampling schedule

Each representative sub-catchment was sampled individually for a separate storm on a fifteen or ten minute sampling schedule to determine the adequacy of one hour sampling to detect variations in runoff quantity and quality. On the basis of the more frequent sampling, it is apparent that considerable variation of discharge and qualitative measures can occur which would not be detected with hourly sampling. The high variability of urban runoff and very rapid urban response produces a greater likelihood of runoff changes which might not be detected by hourly sample collection. The steady slow response of forested and rural runoff makes hourly sampling of these sites more reliable.

The short term changes in variables which were undetectable by hourly samples, as reported in Table 30, p. 122, were the extreme short term changes measured for the individual storms. These errors tended to be related to rapid changes of discharge, the extreme example of which is the result of the sudden start of intense rainfall when the parking lot was sampled individually. During the rotational sampling of all sub-catchments on November 13-14, there was one period of intense rainfall beginning near 02:00 hours. This followed a period of lower intensity, rather than a period of no rainfall. All urban sub-catchments, where fast response was most likely to be expected, showed very strong response to the high intensity rainfall in the sample of the hour following that. Although the values measured were probably not the extreme values of that period of runoff, the response was detected by the hourly sampling schedule. All variation of discharge and quality variables during the November 13-14 hourly sampling was obviously not detected, but the hourly sampling schedule did detect considerable variation, even from the most extreme response sub-catchment - the parking lot. Also, very strong differences in response between different land use sub-catchments have been shown by the hourly sampling; therefore, for the purposes of this study, the hourly sampling schedule has been considered sufficient, although interpretation has necessarily been made in light of possible error due to sampling frequency.

6.4 Dry weather sampling

Dry weather sampling of the Leary's Brook basin as a whole was carried out to determine the adequacy of the storm sampled sub-catchments to represent the land-uses for which they were selected. The variability of storm runoff would make single samples collected for comparison of 35 sites during storm runoff unreliable; however, dry weather sampling is of limited value in comparison of storm runoff characteristics. It was assumed that runoff quality would not vary significantly during dry weather over the ten hour sampling period.

That the residential and commercial/industrial sub-catchments had significant flow during dry weather indicates a probable connection of the sanitary sewage system to the storm sewage system. The extremely high conductivities and in the case of the two commercial/industrial sites, the high pH values measured may also be indicative of some point source runoff intrusion. For other sampling periods reported here, too, there was a "baseflow" from the residential and commercial/ industrial sub-catchments before and after the storm runoff period, although the commercial/industrial "baseflow" was very low ($0.3\ l\ s^{-1}$ for the individual sampling); whereas for all three sampling periods, the parking lot sub-catchment had no runoff except storm period runoff.

When single sample site values for dry weather runoff were compared between land-uses, there were few distinguishing differences and much overlap of values. The commercial/industrial samples were distinguishable by their very high pH and the residential sites had extremely high conductivity values, but these overlapped with the commercial/industrial conductivities. However, if dry weather sample quality is compared by land use average values, strong differences appear, and these are similar to the differences between the average values determined from the storm runoff sampling collected from the representative sub-catchments by rotational sampling (Table 33). A comparison of the rank of average values differentiates urban and non-urban sites for storm and dry-weather runoff with respect to pH and conductivity; but, for turbidity values, the residential runoff had the lowest average values of all sites and the commercial/industrial runoff the highest.

TABLE 33

Comparison of dry weather and storm water quality mean values

		pH	(rank)	CONDUCTIVITY ($\mu S\ cm^{-1} \cdot 25^{o}C$)	(rank)	TURBIDITY FTU	(rank)
Residential	storm	6.4	2	398	1	7.8	4
	dry	6.6	2	490	2	8	4
Comm./Ind.	storm	6.9	1	275	2	40	1
	dry	8.5	1	570	1	140	1
Forest	storm	6.3	3	45	4	11	2
	dry	6.3	4	48	4	14	3
Rural	storm	6.2	4	125	3	7.4	3
	dry	6.4	3	127	3	27	2

Thus, the representative site storm runoff values could not be used to predict specific storm values for runoff from similar land use areas of the Leary's Brook basin. Nevertheless, it remains reasonable to use the rotationally sampled sub-catchments for comparison between land use effects on water quality.

6.5 Precipitation during the November 13-14 storm

The rainfall received during the November 13-14, 1979, sampling period was from a frontal system and it may be assumed that the rainfall distribution was similar throughout the basin and throughout the storm period to that measured at the outlet. The total catch of eight gauges varied by a maximum of 17.6%. Much of that difference (7.2%) occurred at the Kenmount hill gauge and may have been the result of gauge placement too near some trees or the result of the unusual topographic position of the gauge at a high elevation relative to the other gauges. The variation of total rainfall on the Leary's Brook basin, and particularly on the sampling sub-catchments, appears to have been small enough to allow comparison between the sub-catchments and the assumption of the same precipitation input throughout the basin.

6.6 Variation of response to the November 13-14 storm in Leary's Brook basin

6.1 Correlation of response between basin and sub-catchments

A summary of the similarities between the outlet runoff and the monitored sub-catchments is presented as significant correlations for each variable in Table 34. Outlet runoff was significantly correlated with rural response as water yield rate, dissolved solids yield rate, phosphate yield rate, nitrate yield rate, turbidity and turbidity yield rate. Although it could not be construed from these correlations that the rural runoff was controlling the outlet response, it does indicate some similarities between the rural sub-catchment and the basin as a whole. Like the rural area, the Leary's Brook basin is still dominated by natural vegetation and drainage, but the human use of the land has had an effect. The outlet runoff showed less correlation to forested response than to the rural, although there was still highly significant forest-outlet correlation in water yield rate, conductivity as dissolved solids yield rate and turbidity yield rate. However, of the urban sub-catchments, only the residential runoff was significantly correlated to the basin runoff, and only with respect to dissolved solids yield rates. This indicates that in spite of strong differences between urban and non-urban runoff as indicated in Table 33, p. 136, the outlet runoff remains much like the non-urban runoff in discharge and quality variation.

TABLE 34

Correlation of response between Leary's Brook basin and sampled sub-catchments

	PARKING	RESID.	COMM./IND.	RURAL	FOREST
WATER YIELD RATE	-	-	-	0.727 0.1%	0.911 0.1%
pH	-	0.508 5%	-	- 1%	- 0.1%
CONDUCTIVITY	-	-	-	-	-
CONDUCTIVITY YIELD RATE	-	0.540 5%	- -	0.695 1%	0.867 0.1%
PHOSPHATES	-	-	-	-	-
PHOSPHATE YIELD RATE	-	-	-	0.583 5%	-
NITRATES	-	-	-	-	-
NITRATE YIELD RATE	-	-	-	0.810 0.1%	0
TURBIDITY	-	-	-	0.595 5%	-
TURBIDITY YIELD RATE	-	-	-	0.876 0.1%	0.758 0.1%

6.62 Hydrographic response

The Leary's Brook hydrograph of the November 13-14 storm showed rapid response to rainfall and peaked at a value of 0.9 l ha^{-1} s^{-1} within two hours following peak rainfall. There was a response also to the second of two low rainfall peaks prior to the main storm. Following the main peak there was a rapid recession, almost as steep as the rising limb. A low, broad secondary peak to 0.68 l ha^{-1} s^{-1} also appeared, centred five hours after the main peak. This was followed by a slow recession, on which about 10 hours after the cessation of all precipitation the water yield rate was still more than 0.2 l ha^{-1} s^{-1} above the pre-storm level of 0.35 l ha^{-1} s^{-1}.

The rapid response, both in rise and fall of the hydrograph, can be attributed to the runoff of the proximal urban residential and commercial/industrial areas of the basin. During the main storm period there was little increase in contribution from the more distant rural and forested areas, which did not respond strongly to rainfall until after 03:00 hours at the sub-catchment sample sites.

The distal slow response non-urban portions of the basin were the main contributors to the secondary peak, which had the characteristics of the hydrographs measured on the rural and forested sub-catchments of slow rise, broad peak and a slow recession. The contributions from the urban areas were much reduced for the secondary peak. Although some increase in urban runoff may have reached the outlet near 08:30 hours in response to the shower centred at about

06:30 hours, this would not have been large. The rapid drop of all three urban hydrographs indicates that little of the runoff at the outlet after 05:00 hours was contributed from urban areas.

When the level of response as water yield rate is considered, the effect of the non-urban majority of the basin remains the most prominent influence. Discharge levels at the outlet were most like those measured at the non-urban sub-catchments. In water yield rate, there was no significant correlation between the basin as a whole and the three urban areas monitored, but there was highly significant correlation of water yield rate between the basin and the rural and forested sites with r values over 0.7 and 0.9 respectively.

Although the urban areas contributed visible and measurable amounts to the basin runoff, out of proportion to their area, the hydrograph of the basin was dominated by the non-urbanized areas. The urban runoff caused a short sharp peak superimposed on the long low hydrographic response of the remainder of the basin.

6.63 Chemographic response

In the order of two-thirds of the runoff peak flow of Leary's Brook at the time of 03:40 hours was urban derived. Given the rapid drop in the urban contribution, from about 06:00 hours a larger portion than two-thirds of the runoff would have been from non-urban sources. It can therefore be expected that the outlet water quality would reflect these proportions.

6.631 pH

The Leary's Brook runoff pH was quite steady over the measurement period, although there was an overall slight rise during that time. The mean pH for the basin was between the values measured for the urban and non-urban sites, but the outlet had the least pH variation of all sites and all sites had minimum pH values before the runoff peak. The only correlation of significance with the outlet pH was the residential runoff pH. This may have been due to similar dilution timing for the two chemographs. The probable residential sanitary sewage overflow was diluted by storm runoff in a similar manner to the dilution of flow by urban runoff at the outlet causing similar pH fluctuations; however, the only other significant correlation between the residential and the outlet samples was in dissolved solids yield rate.

Conductivity does not appear to have been a function of pH change. Except for a small number of samples there was little pH variation at any sample site and pH was mostly near neutral. The single site with a significant correlation between pH and conductivity was the commercial/industrial area, but this was a positive correlation, with the most acidic samples having the lowest conductivities, the reverse of that expected if conductivity were pH controlled.

6.632 Conductivity

The basin conductivity was very stable with a mean value of 88 S cm^{-1}. There was a drop of 20 S cm^{-1} corresponding with peak flow, followed by a four hour rise to pre-peak levels. as for the discharge peak, the response of the urban areas produced the conductivity minimum at the outlet, although the extreme dilution and depression of the conductivity at the urban sites did not appear at the outlet, probably due to the continued base flow of non-urban areas and the varied routing of the conductivity troughs from urban areas. The rural and forested sub-catchments held steady conductivity values through the monitoring period without minimums at flow peak.

The aggregation of urban and non-urban runoff at the outlet produced no significant correlation with any of the sub-catchment conductivity values. However, the outlet showed a conductivity drop characteristic of the urban areas, though to a lesser degree. The mean conductivity of the basin outlet remained intermediate between rural and forested values. Thus, with respect to conductivity, as for discharge, the basin runoff was dominated by the non-urban contribution. The 20% drop from pre-storm levels in conductivity to the minimum outlet value was caused by dilution with urban runoff, and is an effect out of proportion to the urban area contributing diluant which was 11% of the basin.

6.633 Dissolved solids yield rate

Translation of conductivity to dissolved solids yield rate produced a low peak corresponding to the discharge peak value. In the following recessional period, dissolved solids yield rate remained high. Four sub-catchment sample sites showed much higher yield rates than the outlet and more variability, the exception being the forest site, which maintained low dissolved solids yield rates. Large amounts of dilute forest runoff and the channel mixing of the various higher dissolved solids sources produce the resultant steady single-peaked outlet curve for dissolved solids yield rate.

6.634 Phosphates

Variation of phosphate concentrations of basin runoff appeared to be of a somewhat random nature. There was neither a significant correlation between phosphate concentration and water yield rate for the basin as a whole, nor was there significant correlation of the same variables for any of the monitored sub-catchments. However, comparison of the plotted curves of phosphates and discharge for the outlet (Figure 20, p. 67) does show a small drop in phosphate concentrations corresponding to both the urban and non-urban peaks in the outlet hydrograph, centred at 03:39 hours and 09:30 hours respectively. However, three depressions in phosphate concentrations at 20:10, 13:16 and 16:29 hours corresponded to low or decreasing water yield rates. Thus, an inverse relationship between phosphate concentrations and water yield rates was not established resulting from dilution of phosphates with increasing discharge. Nevertheless, the two troughs in phosphate concentrations at the outlet which correspond to the two discharge peaks are most likely the result of dilution of urban and non-urban phosphates with peak flow.

Unlike the other urban sub-catchments, the residential site maintained discharge rates and phosphate concentrations at pre-storm levels after 10:00 hours. Again this indicates a probable ground-water or direct sanitary sewage transfer of phosphate rich water to the residential runoff.

6.635 Nitrates

Nitrate concentrations at the outlet of Leary's Brook fell in a narrow range from 0.05 to 0.24 mg l^{-1}. Although there was a long low rise in concentrations during the time of peak runoff from 02:30 to 11:30 hours, there was no significant correlation between nitrate concentrations and discharge, and no significant correlation of these concentrations at the outlet with any of the sampled sub-catchments. However, when calculated as nitrate yield rates, there was a strong positive correlation between the outlet and the rural sub-catchment.

As for other variables, the outlet values appear to be intermediate between urban and forested values. But unlike most other variables, there was a strong difference between the different urban sub-catchments sampled, and also between the two non-urban sub-catchments. The consistently low forest runoff nitrate values were not reflected in the rural sub-catchment samples. This latter site had higher mean nitrate concentrations than either the commercial/industrial or the parking lot sites. The residential nitrate concentrations averaged very high, 2.10 mg l^{-1}, and these values were only matched in one other anomalous sample, at the commercial/industrial site. These high residential nitrate values again point to a source of nitrates such as spillover from sanitary sewage. The high mean nitrate yield rate at the outlet of 0.09 mg ha^{-1} s^{-1} may also indicate other high nitrate sources within the basin. This was a considerable value since the forested majority was contributing about two orders of magnitude less nitrate yield rate ($\bar{m}$ = .002 mg ha^{-1} s^{-1}). Also in support of a sanitary sewage source of nitrates at the residential site, there was a highly significant negative correlation between nitrates and discharge at the site, which was not apparent at other sites. This effect was probably the dilution effect of storm water runoff on a continuous supply of sanitary sewage spillover. The drop in phosphate yield rate in residential runoff for two samples corresponding to discharge peak may be the result of the suppression of sanitary sewage intrusion as the storm drain filled with street drainage (see Figure 25, p. 98).

6.64 Suspended sediment response

6.641 Turbidity

Turbidity of discharge at the basin outlet rose with the increase in discharge, but peaked one hour later. Also, with the first recession of the hydrograph turbidity fell to a low, lagged one hour after the discharge trough, before increasing again over a five hour period. Finally, there was a small short peak of turbidity two hours after a similar peak on the hydrograph. This produced a correlation coefficient of only 0.6 (significant at the 1% level), which would be better correlated if the peaks of turbidity and discharge were aligned.

The likely source of the high turbidity is the urban area. In particular, the commercial/industrial sub-catchment provided large quantities of suspended material, while little contribution in suspended matter was made by the non-urban sub-catchments. This runoff became an effective diluent of urban suspended matter in the latter part of the storm runoff.

The lag of peak turbidity after flood peak may be a dilution effect of low turbidity urban runoff coincident with flood peak. A channel routing lag effect is not possible in such a small basin, as established by Glover and Johnson (1974). The turbidity yield rate plotted in Figure 26, p. 103, shows major peaks corresponding to flood peak, as occurred at the sub-catchments. It appears that some source of suspended material, not in immediate proximity to the outlet, provided large suspended sediment amounts, which arrived at the outlet after the peak of runoff. The urban areas continued to supply suspended sediment for the rest of the sampling period, which maintained turbidity for the basin above that of the forested and rural areas.

6.642 Turbidity yield rate

Turbidity yield rate produced at the outlet a curve most like the discharge curve, although the suspended sediment lag flattened the first peak and slowed recession (Figure 26, p. 103). All three urban sub-catchments produced peak values an order of magnitude higher than the outlet peak, while the rural turbidity yield rate was less than one third the outlet value and that of the forest was nearly an order of magnitude lower than at the outlet. Without the dilution of urban runoff by the non-urban pre-storm baseflow, suspended solids concentrations at the outlet would have been higher at peak flow. The very low post-storm turbidity yield rate of the parking lot runoff, however, indicates that a paved area once flushed of available solids can produce extremely clean runoff.

The outlet turbidity yield rate response pattern was very similar to the rural and forest pattern, but the high peak and high average turbidity yield was derived from the urban areas. Correlation was highly significant between the outlet and both the rural and forest turbidity yield rates, but not significant between the outlet and the urban basins. However, the urban areas contributed substantially to the outlet turbidity peak yield rate. The high yield rate of commercial/industrial turbidity even after runoff had dropped considerably may explain the high values maintained at the outlet.

6.7 Spatial control of solute and sediment dynamics

6.71 Spatial control of suspended sediment dynamics

Both turbidity and turbidity yield rate of Leary's Brook plotted against water yield rate (Figures 32 and 33) show a very distinct hysteresis and lag of suspended sediment peak behind discharge. Although the commercial/industrial and the rural turbidity rating curves show similar anti-clockwise hysteresis, and the forested turbidity rating is lagged, these effects in the sub-catchments are not sufficient to explain the lag and hysteresis at the outlet. Rather, it seems more likely that a spatial control of turbidity variation at the outlet acts through rating of high turbidity with peak runoff from a distal urban source area.

The rating of turbidity yield rate on water yield rate strongly emphasizes the binary nature of the outlet suspended sediment dynamics. The hysteretic loop, largely a result of urban response, has the steep climb and drop of the urban sub-catchments; but the start and end of the outlet hydrograph follow a pattern and slope very similar to the non-urban sub-catchments, which control those portions of the basin runoff.

Although the parking lot runoff had a clockwise hysteresis of turbidity yield rate, probably as the result of flushing and depletion of available material, this did not occur at the other urban sub-catchments. In the case of the residential sub-catchment a short term hysteresis and flush might have occurred but was undetected by the

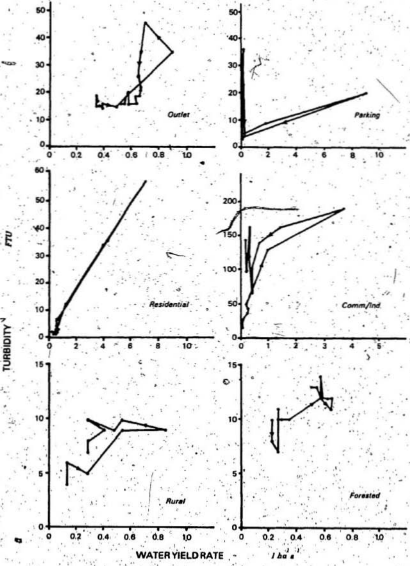


Figure 32 Rating of turbidity against water yield rate; all-basin sampling

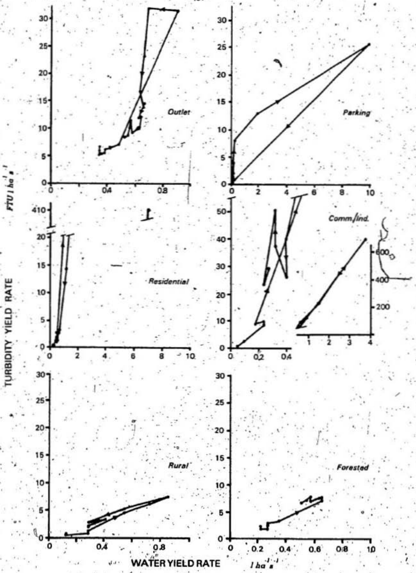


Figure 33 Rating of turbidity yield rate against water yield rate; all-basin sampling

hourly sampling. Just the reverse appeared at the commercial/industrial site. Turbidity was maintained at high levels after flood peak producing anti-clockwise hysteresis. An explanation may be made in terms of variable source area, by which runoff peak was derived from fast response, high water yield paved and roofed areas. As runoff from those areas receded, contribution increased from slower response low water yield areas in the central part of the basin, which were unpaved and unvegetated and provided high turbidity to the tail of the storm runoff.

6.72 Spatial control of solute dynamics

The hybrid nature of the Leary's Brook response to the November 13-14 rainfall is again emphasized by the rating of conductivity and dissolved solids yield rate against water yield rate (Figures 34 and 35). The outlet solute response showed a hysteretic dilution with storm runoff from urban areas and a lesser dilution from the non-urban areas. From the urban sub-catchment solute rating curves, it can be seen that the early response to rainfall was both a rapid dilution and fast increase in solutes yield rate. However, during the period of heavy rainfall, the slope of the rating curve of dissolved solids yield rate was much less. For the commercial/industrial sub-catchment, the decreasing rate of supply of solutes produced a very distinct clockwise hysteretic loop, sloped like the non-urban curves on the rising limb. The non-urban solute ratings showed little dilution on the rising limb, but on the recession limb dilution or depletion reduced conductivity

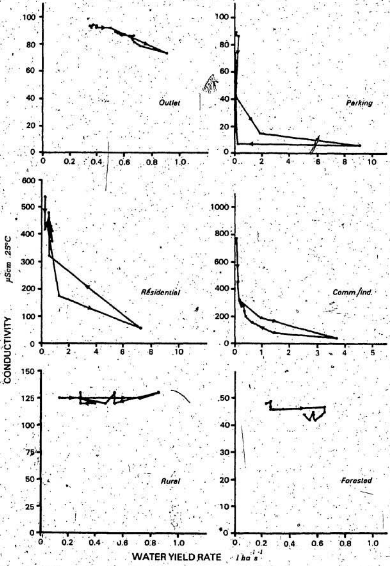


Figure 34
Rating of conductivity against water yield rate; all-basin sampling

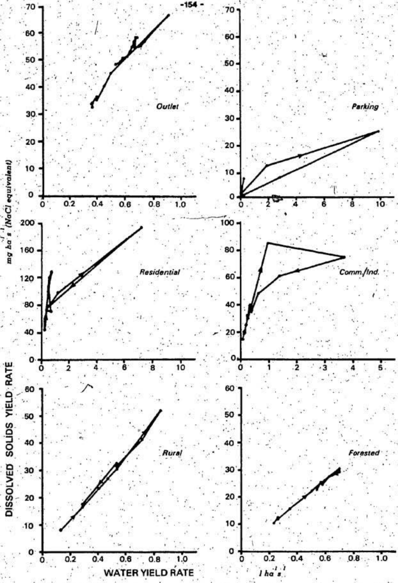


Figure 35
Rating of dissolved solids yield rate against water yield rate; all-basin sampling

of the forest runoff, and the rural runoff recession appeared to vary between dilution and augmentation of solutes. The lack of dilution on the rising limb of the non-urban solute ratings indicates the continued dominance of throughflow during the runoff event. The later dilution was probably also derived from short residence time throughflow, since the dilution began long after any surface flow derived from peak rainfall would have arrived at the sample point.

The resultant outlet solute ratings showed dilution as conductivity, which was intermediate between the extremes of urban and non-urban response. The rating of dissolved solids yield rate at the outlet plotted as a pronged curve with the longer tine urban derived and the shorter from the later effect of the non-urban runoff.

7.0 CONCLUSIONS

7.1 Summary of Leary's Brook water quality variation

During the sampling of a single storm runoff event, in which several land-use types were sampled separately, strong differences in both quantity and quality between urban and non-urban runoff were determined. With reference to the two extremes of the five sub-catchments sampled, these differences were largely the result of differences of surface materials and surface shape as they affect flow rates and solute and sediment availability.

From the forested area runoff was delayed by interception and throughflow, and by routing through a rough natural channel. In contrast, the artificial/urban surface of the parking lot was built to react quickly, with a smooth impermeable surface and grading of surface and channel to minimize detention. As a result, not only was the parking lot discharge response rapid, but any available solutes or sediments were readily and rapidly removed. In general, urban areas, and particularly those of the Leary's Brook basin, unpaved surfaces are smoothed and compacted, which minimizes infiltration and detention.

The resultant effect on runoff of the forest characteristics noted above was a high base flow from the prior storms, a slow throughflow response to rainfall and a low peak runoff. At the same time an equivalently low and steady solute and suspended sediment loss from the forested sub-catchment was recorded. In strong contrast, the urban parking lot had no baseflow, but an immediate and high peak of runoff response to rainfall, and high sediment and solute yield rates.

The aggregate response of these two extremes, and the other land-use types of residential, commercial/industrial and rural sub-catchments, showed at the basin outlet an early sharp peak rising from a high base flow, followed by a low secondary peak. These peaks were from urban and non-urban areas respectively, and these sources were reflected in the qualitative measures. The runoff quantity and quality variation at the outlet was demonstrated to be a response to non-uniform storm runoff generation controlled by land use. However, the overall basin response was still most controlled by the majority of the basin - the non-urban areas; although even between rural and forested areas, there were considerable differences in water, chemical and suspended solids responses.

The parking lot runoff also showed that urban land use by itself does not determine poor quality runoff, but construction and management practices do, as can be the case with forested and rural areas.

7.2 Utility of the sampling method

With the sampling procedure used in this research, most of the response at the outlet was explainable in terms of the sub-catchments sampled. The rotational sampling method provided optimal comparability of the several sample sites, in that both antecedent moisture input and precipitation during the sampling period were coincident and effectively identical. Although the rotational sampling strategy limited the sampling frequency for five sites to one hour, and some detail was therefore lost, the very strong differences between the sub-catchments were readily apparent. The method was not sufficient for prediction of solute or suspended solid yield rates. Nevertheless, the order of magnitude of change with urbanization was apparent.

7.3 Suggestions for further study

The success of the method with sampling carried out largely by hand by one individual indicates a potential for further research of value if more outlay in labour and capital were possible. Several individuals could provide more frequent sampling with near simultaneous sampling and timing, and since the length of the sample period was limited by the stamina of the individual sampler, more individuals sampling could extend the sample period considerably.

Alternatively additional instrumentation might be used to automate the procedure. Simultaneous and continuous determinations of water quality and quantity from several sites could provide more precise and valuable information on the sources of these variables in the basin and on how the aggregate is derived.

The variables measured in this research were necessarily of a limited number due to time and financial constraints; however, wider analysis could provide more information on basin runoff processes. In particular, determination of more specific ions in the dissolved load as well as the chemistry of the suspended sediment load could be used to separate the hydrograph more precisely for the determination of the contributions of various land-uses.

7.4 Significance of the results for basin development

The Leary's Brook basin is likely to be affected by continued rapid urban expansion. At the same time, the natural drainage system may continue to be ignored or at best controlled only for simple rainfall and other disposals. Since Leary's Brook drains through a park, the quality of the basin's runoff will be likely to be more important in future for its recreational and aesthetic value, while at the same time there will be greater potential for chemical deterioration and coincident siltation of Long Pond and Rennie's River, as well as increased potential for flood damage.

Amelioration of these problems may be provided in the construction stages as well as retroactively. The restriction of channelization, the prevention of connection to the storm sewers of impervious areas where possible, especially those most likely to receive spillages of contaminants such as oil, the construction of detention basins, the maintenance of vegetation cover and the careful isolation of storm sewers from the sanitary sewage system are some of the many possible control methods.

With ongoing development the Leary's Brook basin provides a valuable catchment for research into the effects of urbanization. It is hoped that this research will not merely be a record of urban runoff deterioration.

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APPENDIX A

TWENTY-FOUR HOUR AUTOMATIC SAMPLER: DESIGN AND USE

A.1 Sampler design

An automatic sampler was designed which could be built with available expertise and relatively inexpensive and readily available materials. Rather than using a rotating distribution system, such as the design by Walling and Teed (1971), the operating principle of the sampler was sequential rotation of a set of sample bottles to a position under a single fixed spout. This pipe was connected to a submersible pump in the stream.

One litre sample bottles were fitted on a two tiered plywood turntable (Figure. A1). The upper tier was of diameter 60.9 cm, so that 24 bottles fitted tightly around the perimeter and could be held at even spacing against the turntable by a rubber cord. The turntable rolled on furniture casters.

Drive for the turntable was given by a twelve volt automotive (Toyota) windshield wiper motor, which ran at appoximately 30 rpm. This speed was geared down to one revolution per day, delivered to a spindle fixed through the centre of the turntable.

A switching system was incorporated so that the sampling pump was turned on for approximately ten minutes every hour (Figure A.2). The switch was controlled by a small lever, which was pushed to an on position by wooden cams. Twenty-four one cm wide cams were spaced

Figure A.1 Twenty-four hour automatic sampler

This view shows the motor and gear box in centre foreground, the pump switch lever against a cam to the right foreground, the spout in the right background and the levelling legs in the lower foreground.

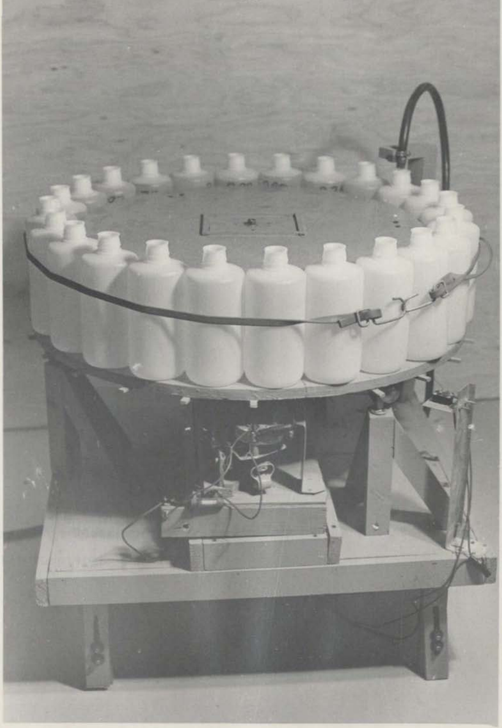
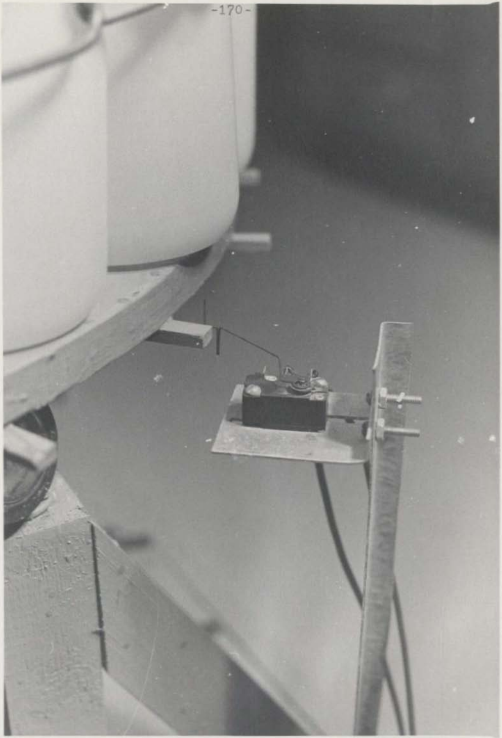


Figure A.2 Close-up of pump switch against a cam of sampler turntable



evenly around the perimeter of the lower tier of the turntable. The length of switch closure was controllable by adjustment of the distance of the switch from the turntable.

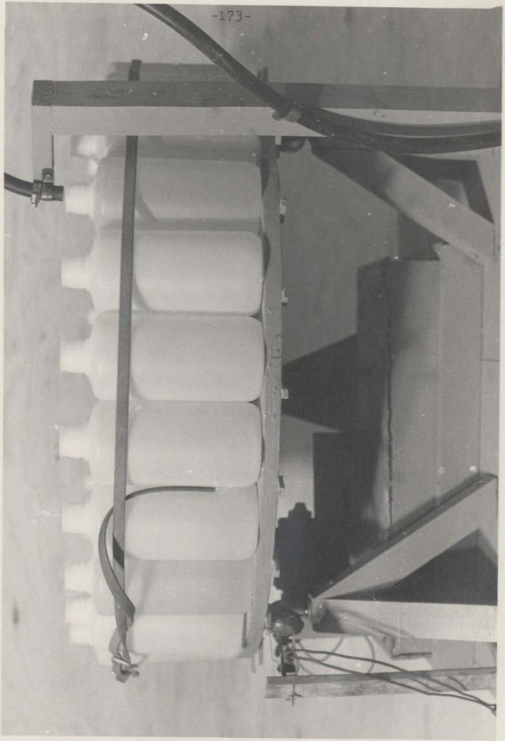
A.2 Sampler adjustment and installation

Before field installation, the sampler was tested for speed and adjusted for sample timing in the laboratory. Motor speed was adjusted with a rheostat control. Pump timing was adjusted to ten minutes by movement of the on-off switch. Then the bottles were rotated on the turntable relative to the cams, to the position shown in Figure A.3, so that the pump was turned on before a bottle came under the spout. Relative position of the switch and the bottles is shown in Figure A.3. This adjustment was somewhat insensitive, but each position was tested so that the pump would run at least five minutes before the water flowing from the spout started filling any sample bottle.

In the field the sampler was installed within a chain-link fence enclosure adjacent to the flow measurement section of the Leary's Brook outlet. A 30 m buried plastic pipe (2 cm) was connected from the sampler to a twelve volt submersible marine bilge pump in the stream. The pump was altered so that intake was through a 15 cm length of plastic pipe held vertically in the channel. The pump was fixed to a molded concrete weight for anchorage and the intake was then positioned at a distance of 25 cm from the stream bed. This

Figure A.3 Side view of sampler

The spout is on the right and the pump switch to the left foreground.



height was to inhibit the collection of non-suspended solid load in the sample.

The period of pump operation before sample collection was provided to prevent contamination between adjacent samples. All but three metres of the sampling pipe emptied by gravity between samples. The five minute pre-sample pump run was thought sufficient to empty out the slug of water in the pipe from the previous sample and to rinse out the full length of the pipe.

The twelve volt pump and motor were used so that the sampler might be operated by car batteries, but this proved unreliable. The voltage drop as the battery drained caused a gradual slowing of the turntable motor, which was extreme in colder weather. Power was obtained by connecting a battery charger on 110 v current through two twelve volt batteries to the sampler. The batteries provided a short-term power back-up in case the 110 v power supply were accidentally interrupted.

Timing of the samples as reported in Figure 20, p. 67, was determined by even interpolation between the time of the first sample, 19:06 November 13 and the last at 19:45 November 14. One sample was collected by hand operation of the pump switch at 11:35 November 14, as a loose cam did not operate the switch in that hour. The sampler was protected in the field by a shelter. White painted plywood covered the top, and sides were plastic covered to keep out rain. The shelter was well ventilated at corners and underneath to keep samples as cool as possible.

A.3 Sampler calibration

A series of hourly stream samples were collected with the sampler during a test run and a set of corresponding hand-samples was collected. Eight pairs of samples were collected and analyzed for conductivity, pH, turbidity, phosphate and nitrate by the same analysis methods as used for other storm sampling. Values determined are presented in Table A.1.

The collection methods and analysis timing for the two sample sites were similar to those of the November 13-14 storm runoff sampling. The eight calibration hand-collected sample were manually depth integrated from the channel centre just downsteam of the sampler intake. Conductivity of these samples was determined immediately and samples were then refrigerated until laboratory analysis was carried out at the end of the eight hour sample period. On the other hand, the eight samples collected automatically were left in the sampler until 24 hours after the first collection and then analyses were carried out in the laboratory.

The collection mechanism and timing of the automatically collected samples was somewhat different than for the hand samples. The automatic sampler drew water from a single depth. Also the movement of the bottle under the spout produced an increasing rate of flow into the bottle as it filled, so that the samples collected were five minute time integrated and skewed to the end of the five minutes. These differences in

TABLE A.1

Comparison of automatically collected (A)
and hand collected samples (H)

	CONDUCTIVITY ($\mu S \cdot cm^{-1} \cdot 25^oC$)		pH		TURBIDITY FTU		PHOSPHATES ($mg\ l^{-1}$)		NITRATES ($mg\ l^{-1}$)	
	H	A	H	A	H	A	H	A	H	A
1	123	130	6.6	6.5	13	15	0.03	0.03	0.25	0.27
2	145	130	6.7	6.5	13	8	.03	.02	.30	.27
3	130	118	6.8	6.5	25	25	.01	.05	.24	.25
4	115	105	6.4	6.5	28	25	.04	.06	.21	.15
5	120	105	6.5	6.4	38	25	.04	.05	.25	.22
6	130	115	6.5	7.1	25	22	.01	.04	.28	.25
7	130	118	6.5	6.4	33	18	.02	.02	.25	.27
8	130	118	6.7	6.6	20	15	<.01	.03	.22	.25
mean H-A	+14		+0.2		+7		-0.02		+0.01	

timing and method of sample collection might have been expected to produce differences between the two sample sets in the measured water quality variables. The differences in values between hand and automatically collected samples might be expected to be both positive and negative This did occur for each variable, although conductivity and turbidity differences were in the same direction or nil for seven of the eight samples. This probably indicates a time drift of conductivity and possibly turbidity. Other variables showed less consistancy of difference direction. Also within samples the variation of difference direction was inconsistent, except for sample two.

Water quality variable values for the Leary's Brook outlet are reported as measured from automatically collected samples from the November 13-14 storm runoff sampling period. It is clear that these values would have been different if runoff had been sampled by hand. However, it was not felt that the calibration sampling was adequate for prediction of hand sampling values, nor was it thought to be essential that hand sampled values be determined. Since no total storm load determination was desired but the pattern of quality variation was essential, the automatically collected samples were considered useful and sufficient for the study purposes.

APPENDIX B

H FLUME, CONSTRUCTION AND USE

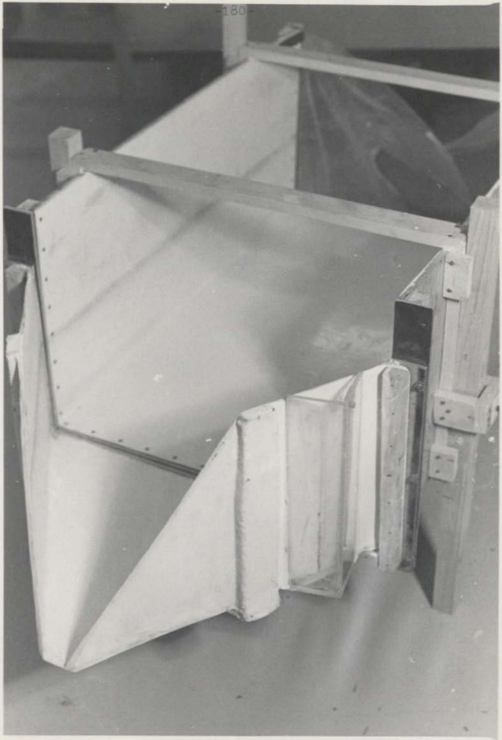
B.1 Design and manufacture

A 0.3 m H-flume (1 foot), to be used where four of the sub-catchments drained through culverts, was constructed for discharge measurement. The dimensional construction followed design specifications for a flat floored H flume given by Holtan, Minshall and Howard (1968), however construction materials were changed. The flume section was constructed of glass fibre and resin molded over plywood having the required exterior dimensions. The inside and outside of the flume were covered in an opaque coating resin. The flume throat section is illustrated in Figure B.1.

A stilling well constructed of acrylic plastic was installed on the side of the flume. The well contained a clear plastic ruler adjusted vertically with the zero point level with the flume bed, so that stage could be read directly.

A drop box of length 0.93 m and height 0.42 m was built of plywood and lined with resin. This length was less than the 1.5 m required by the design criteria, but allowed for easier portability. The remaining length of approach was provided by a plastic apron attached to the upstream end of the drop box. The box was attached to the flume and apron by sealed flanges. On the exterior of the approach box four brackets were built by which 5 x 5 cm section wooden legs could be

Figure B.1 H flume throat section
The flume section was constructed of fibreglass and the stilling well of transparent acrylic plastic.



installed and adjusted for raising the flume to the desired height and for levelling on uneven installation sites. The assembled flume, approach box and apron are shown in Figure B.2.

B.2 H flume calibration

The flume was calibrated in the laboratory up to a discharge of 2.2 l s^{-1}. These calibration values and the rated values of Holton, Minshall and Howard (1968) are plotted in Figure B.3. The rating curve used for discharge determinations as indicated, is the extrapolation of laboratory calibration to meet the design specification rating curve. The wide spread between the two ratings at lower discharge was thought to be the result of a flare of the flume lip at its lower end and to the very low hydraulic roughness of the resin coating. The flare was the result of the inability to fold the fiberglass wrapping to 90° to conform to the mold. Away from the lip a sharper corner was formed in the flume with resin infilling.

B.3 H flume installation

The H flume assembly was transported to each sampling site on a car roof and installed by one individual. The assembly was placed longitudinally in front of the culvert mouth being gauged with a gap of 60 to 70 cm and levelled with the adjustable legs so that the approach box floor was approximately six centimetres below the level of the culvert lower lip.

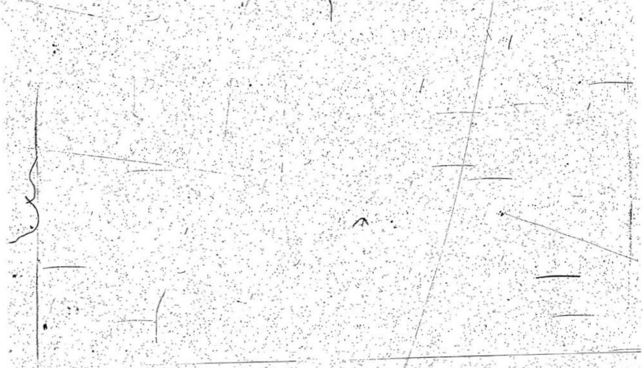
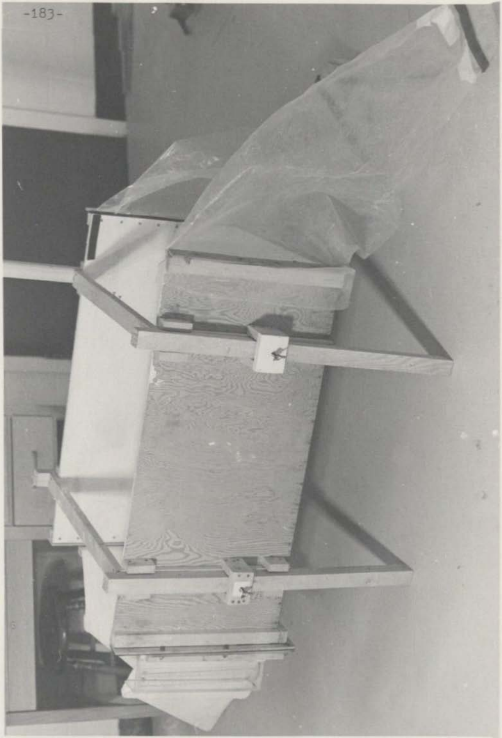


Figure B.2 H flume assembly

Flume section to the left shows the position of the stage scale in the stilling well. The central approach box is elevated on the adjustable legs and the flexible plastic connecting apron is on the right.



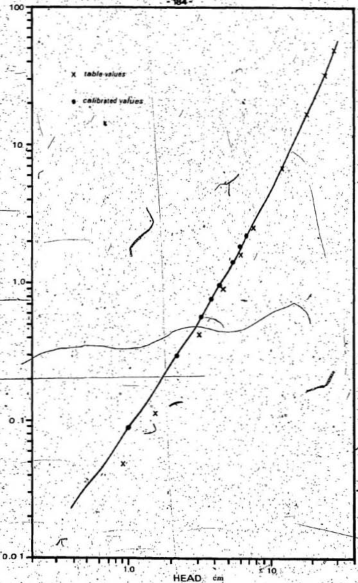


Figure B.3 H flume rating curve

Connection to the pipe was made with a heavy polyethylene plastic apron. On the upstream lip of the apron a rope was bound into the edge with a heat seal and a length of one centimeter thick neoprene strip was glued on the underside just behind that. This lip provided a gasket and flange which was wedged into the pipe mouth. The wedging was done with a flexible strip of galvanized sheet metal held in place by a wedged in wooden cross member. For example, for the 0.91 m inside diameter O'Leary Avenue pipe a strip of sheet metal 1.7 m long was fitted behind the apron gasket lip. The wooden wedge to hold this in place was 0.90 m long. This was sufficient to hold the apron in position during sudden increases in flow, and up to a peakflow near the top of the flume. There was very little loss of water around the apron gasket. The flexibility and length of the apron and the distance between culvert mouth and approach box allowed the apron to fill out and down. This provided a small head pool above the approach box, which would have provided greater velocity reduction than the equivalent length of approach box.

The H flume design generally has the advantage of accurate discharge measurement over a wide range of values, due to the backward slope of the throat section. This sloping throat section creates a large curvature of water surface, so that the effective crest width increases and the high point of curvature retreats from the throat with increasing discharge (Ackers et al., 1978). Also, where bedload and suspended load of debris is high, as can be carried by urban runoff the flat floor of the H flume is swept clean. The further advantage of the design is its adaptability. The design as presented here has the adavantages of portability, and can be adapted to installation at the mouth of various sized culverts, and on uneven ground.

APPENDIX C

SAMPLE DATA

All-basin sampling

Leary's Brook Outlet

No.	Time h	Discharge $1\ s^{-1}$	pH	Conductivity μScm^{-1} 25°C	Reactive Phosphate mg 1^{-1}	Nitrates mg 1^{-1}	Turbidity FTU
1	19:06	715	6.3	92	0.05	0.13	17
2	20:10	715	6.3	92	0.02	0.07	16
3	21:50	710	6.3	94	0.04	0.05	19
4	22:18	704	6.3	94	0.06	0.15	15
5	23:22	730	6.3	94	0.04	0.16	15
6	0:26	79[illegible]	6.4	93	0.03	0.20	14
7	1:31	780	6.5	92	0.04	0.13	16
8	2:35	983	6.4	92	0.02	0.22	15
9	3:39	1802	6.4	74	0.01	0.18	35
10	4:43	1405	6.4	79	0.05	0.19	46
11	5:47	1335	6.4	82	0.04	0.22	35
12	6:51	1294	6.5	85	0.05	0.23	26
13	7:56	1335	6.4	87	0.05	0.24	21
14	9:00	1347	6.3	86	0.01	0.16	22
15	10:04	1347	6.4	87	0.01	0.17	22
16	11:35	13[illegible]	6.5	86	0.03	0.18	21
17	12:12	1312	6.3	86	0.03	0.06	19
18	13:16	1261	6.4	86	0.01	0.11	19
19	14:21	1229	6.4	86	0.03	0.14	16
20	15:25	1180	6.4	87	0.03	0.13	16
21	16:29	1168	6.4	87	0.01	0.12	20
22	17:33	1138	6.4	87	0.02	0.12	18
23	18:39	1113	6.4	88	0.03	0.17	16
24	19:45	1064	6.4	89	0.02	0.15	16

Numbers 2 to 17 inclusive used in correlation analysis with other sites.

All-basin sampling

Leary's Brook Outlet; yield rates of

No.	Water $l\ ha^{-1}\ s^{-1}$	Dissolved Solids $mg\ ha^{-1}\ s^{-1}$	Phosphates $mg\ ha^{-1}\ s^{-1}$	Nitrates $mg\ ha^{-1}\ s^{-1}$	Suspended Solids FTU $l\ ha^{-1}\ s^{-1}$
1	0.358	32.94	0.018	0.047	6.09
2	0.358	32.94	0.007	0.025	5.73
3	0.355	33.4	0.014	0.018	6.75
4	0.352	33.19	0.021	0.053	5.28
5	0.365	34.3	0.015	0.058	5.48
6	0.397	36.9	0.012	0.079	5.56
7	0.390	35.9	0.016	0.051	6.24
8	0.492	45.3	0.010	0.11	7.38
9	0.901	66.7	0.009	0.16	31.5
10	0.703	55.5	0.035	0.13	32.3
11	0.668	54.8	0.027	0.15	23.4
12	0.647	55.0	0.033	0.15	23.4
13	0.668	58.1	0.033	0.160	14.0
14	0.674	58.0	0.007	0.11	14.8
15	0.674	58.6	0.007	0.12	14.8
16	0.663	57.0	0.020	0.12	13.9
17	0.656	56.4	0.020	0.039	12.5
18	0.630	54.2	0.006	0.069	12.0
19	0.642	55.2	0.019	0.090	10.3
20	0.590	55.3	0.018	0.077	9.[illegible]
21	0.584	50.8	0.006	0.070	11.7
22	0.569	49.5	0.011	0.068	10.2
23	0.557	49.0	0.017	0.095	8.91
24	0.532	47.4	0.011	0.080	8.51

[1] as NaCl equivalent

All-basin sampling

Hospital parking lot sub-catchment

NO.	TIME h	TEMP. ^{o}C	DISCHARGE $l\ s^{-1}$	pH	CONDUCTIVITY $\mu S\ cm^{-1}$ 25°C	REACTIVE PHOSPHATE $mg\ l^{-1}$	NITRATES $mg\ l^{-1}$	TURBIDITY FTU
1	20:53	–	0.0	–	–	–	–	–
2	21:55	8.0	0.09	6.4	89	0.02	0.24	36
3	22:53	7.0	0.09	5.6	87	0.09	0.21	23
4	23:51	6.0	0.20	4.0	86	0.20	0.14	5
5	0:51	7.0	0.09	5.6	43	0.11	0.11	5
6	1:52	6.0	1.8	6.0	15	0.01	0.04	9
7	2:47	6.0	9.1	6.3	6	0.01	0.00	20
8	3:50	8.5	0.20	6.3	7	0.01	0.30	4
9	4:50	7.5	0.09	6.5	18	0.05	0.01	3
10	5:46	9.0	0.04	6.6	42	0.03	0.02	8
11	6:47	9.5	0.04	6.6	61	0.02	0.08	13
12	7:45	9.0	0.04	6.6	52	0.03	0.53	14
13	9:00	10.5	0.02	6.6	60	0.02	0.05	25
14	9:56	10.5	0.02	6.6	61	0.00	0.12	32
15	10:52	11.0	0.02	6.8	67	0.01	0.11	34
16	11:52	12.0	0.02	6.8	74	0.01	0.13	34

Hospital parking lot, yield rates of

No.	Water l ha^{-1} s^{-1}	Dissolved Solids mg ha^{-1} s^{-1}	Phosphates mg ha^{-1} s^{-1}	Nitrates mg ha^{-1} s^{-1}	Suspended Solids FTU l ha^{-1} s^{-1}
1	0.0	–	–	–	–
2	0.09	3.80	0.0018	0.022	3.24
3	0.09	3.70	0.0081	0.019	2.07
4	0.20	8.10	0.040	0.028	1.00
5	0.09	1.8	0.0099	0.009[illegible]	0.45
6	1.83	13.0	0.018	0.073	16.5
7	9.09	25.07	0.091	0.036	182
8	0.20	0.66	0.0020	0.060	0.80
9	0.09	0.77	0.0045	0.0009	0.27
10	0.04	0.79	0.0012	0.0008	0.32
11	0.04	1.15	0.0006	0.0032	0.52
12	0.04	0.98	0.0012	0.021	0.56
13	0.02	0.57	0.004	0.0010	0.50
14	0.02	0.58	0.0001	0.0024	0.64
15	0.02	0.63	0.0002	0.0022	0.68
16	0.02	0.70	0.0002	0.0026	0.68

All-basin sampling

Ayreshire Place residential sub-catchment

NO.	TIME h	TEMP. ^{o}C	DISCHARGE $l\ s^{-1}$	pH	CONDUCTIVITY $\mu S\ cm^{-1}$ .25^{o}C	REACTIVE PHOSPHATE $mg\ l^{-1}$	NITRATES $mg\ l^{-1}$	TURBIDITY FTU
1	20:59	11.5	1.2	6.4	540	0.04	2.69	2
2	22:05	10.5	1.2	6.3	420	0.06	2.46	2
3	23:00	11.0	2.6	6.3	460	0.03	2.54	2
4	23:58	10.0	3.6	6.3	375	0.05	1.88	5
5	0:58	10.5	1.9	6.3	440	0.05	2.28	1
6	1:58	8.0	6.5	6.3	175	0.05	0.82	12
7	2:54	7.0	39	6.4	57	0.04	0.17	57
8	4:00	10.0	2.6	6.4	340	0.05	1.70	6
9	4:58	10.0	2.6	6.5		0.05	1.91	4
10	5:53	11.0	2.6	6.5	480	0.02	2.52	2
11	6:55	11.5	2.6	6.6	460	0.05	2.46	3
12	7:55	11.5	3.6	6.4	410	0.04	2.29	4
13	9:08	12.0	3.2	6.4	430	0.01	2.27	2
14	10:04	12.5	2.6	6.4	460	0.06	2.54	3
15	11:00	13.0	2.6	6.7	460	0.03	2.54	2
16	12:00	12.5	2.6	6.8	465	0.05	2.53	1

All-basin sampling

Ayreshire Place sub-catchment, yield rates of:

NO.	WATER $l\ ha^{-1}\ s^{-1}$	DISSOLVED SOLIDS $mg\ ha^{-1}\ s^{-1}$	PHOSPHATES $mg\ ha^{-1}\ s^{-1}$	NITRATES $mg\ ha^{-1}\ s^{-1}$	SUSPENDED SOLIDS FTU $l\ ha^{-1}\ s^{-1}$
1	0.22	56.7	0.009	0.592	0.44
2	0.22	44.1	0.013	0.541	0.44
3	0.48	104	0.014	1.22	0.96
4	0.67	70.7	0.034	1.26	3.4
5	0.35	73.1	0.018	0.798	0.35
6	1.20	99.2	0.060	0.984	14
7	7.20	194.0	0.288	1.22	410
8	0.48	77.0	0.024	0.816	2.9
9	0.48	-	0.024	0.916	1.9
10	0.48	109	0.010	1.21	0.96
11	0.48	104	0.024	1.18	1.4
12	0.67	129	0.027	1.53	2.7
13	0.59	120	0.006	1.34	1.2
14	0.48	104	0.029	1.22	1.4
15	0.48	104	0.014	1.22	0.96
16	0.48	105	0.024	1.21	0.48

All-basin sampling

O'Leary Avenue commercial/industrial sub-catchment

NO.	TIME	TEMP. °C	DISCHARGE $l\ s^{-1}$	ph	CONDUCTIVITY $\mu S\ cm^{-1} \cdot 25^{o}C$	REACTIVE PHOSPHORUS $mg\ l^{-1}$	NITRATES $mg\ l^{-1}$	TURBIDITY FTU
1	21:17	8.5	0.40	7.1	770	0.03	0.19	16
2	22:22	8.0	0.88	6.9	450	0.02	0.28	28
3	23:20	7.0	2.3	6.8	280	0.03	0.21	37
4	0:16	8.0	2.3	6.8	280	0.02	0.12	43
5	1:17	8.0	1.7	6.8	320	0.00	0.10	50
6	2:1[illegible]	7.5	9.6	6.6	190	0.01	0.00	130
7	3:13	6.5	37	6.7	43	0.01	0.00	190
8	4:[illegible]	7.0	14	6.1	93	0.04	0.00	162
9	5:16	8.0	6.4	6.9	160	0.03	0.07	140
10	6:15	8.5	3.9	6.9	200	0.01	0.10	102
11	7:13	9.0	3.9	6.9	200	0.03	0.32	66
12	8:13	9.5	3.1	6.7	240	0.03	0.12	120
13	9:24	10.5	3.1	7.0	280	0.05	2.89	163
14	10:20	11.0	2.3	6.9	270	0.01	0.00	99
15	11:18	13.0	2.3	7.0	295	0.00	0.00	103
16	12:17	12.0	2.0	6.9	325	0.00	0.18	146

All-basin sampling

O'Leary Avenue commercial/industrial sub-catchment

yield rates of:

NO.	WATER $l\ ha^{-1}\ S^{-1}$	DISSOLVED SOLIDS $mg\ ha^{-1}\ S^{-1}$	PHOSPHATES $mg\ ha^{-1}\ S^{-1}$	NITRATES $mg\ ha^{-1}\ S^{-1}$	SUSPENDED SOLIDS FTU $l\ ha^{-1}\ s^{-1}$
1	0.04	14.5	0.0012	0.0076	9.64
2	0.09	18.7	0.0018	0.025	2.5
3	0.23	30.4	0.0090	0.048	8.5
4	0.23	30.4	0.0046	0.028	9.9
5	0.17	25.7	0.0009	0.017	8.5
6	0.96	86.0	0.0096	0.0038	125
7	3.70	75.1	0.037	0.015	703
8	1.40	61.5	0.0560	0.0056	227
9	0.64	48.3	0.019	0.045	90
10	0.39	36.8	0.0039	0.039	40
11	0.39	36.8	0.012	0.13	26
12	0.31	35.0	0.0093	0.037	37
13	0.31	40.9	0.0016	0.89	51
14	0.23	29.2	0.0023	0.030	23
15	0.23	32.0	0.0012	0.0009	24
16	0.20	30.6	0.0010	0.036	29

All-basin sampling

Groves Road rural sub-catchment

NO.	TIME h	TEMP. ^{o}C	DISCHARGE $l\ s^{-1}$	pH	CONDUCTIVITY $\mu S\ cm^{-1} \cdot 25^{o}C$	PHOSPHORUS $mg\ l^{-1}$	NITRATES $mg\ l^{-1}$	TURBIDITY FTU
1	21:11	6	1.7	6.1	125	0.01	0.31	4
2	22:16	6	1.7	6.1	125	0.01	0.34	4
3	23:14	5	1.7	6.2	125	0.03	0.43	6
4	0:11	6	3.8	6.1	125	0.02	0.34	5
5	1:11	6	3.8	6.1	130	0.02	0.31	5
6	2:12	6	3.8	6.1	125	0.01	0.33	5
7	3:06	6.5	7.0	6.1	125	0.01	0.32	9
8	4:12	6.5	9.4	6.0	125	0.01	0.30	9
9	5:11	6.5	11	130	130	0.02	0.37	9
10	6:10	7.0	7.0	6.3	120	0.04	0.36	10
11	7:08	7.0	7.0	6.3	130	0.03	0.39	10
12	8:07	7.5	6.2	6.1	120	0.02	0.36	9
13	9:19	8.0	3.8	6.3	125	0.02	0.33	10
14	10:15	8.5	5.3	6.3	120	0.03	0.37	9
15	11:12	9.0	3.8	6.4	120	0.01	0.36	8
16	12:14	10	3.8	6.2	125	0.01	0.31	7

All-basin sampling

Groves Road rural sub-catchment, yield rates of:

NO.	WATER $l\ ha^{-1}\ s^{-1}$	DISSOLVED SOLIDS $mg\ ha^{-1}\ s^{-1}$	PHOSPHATES $mg\ ha^{-1}\ s^{-1}$	NITRATES $mg\ ha^{-1}\ s^{-1}$	SUSPENDED SOLIDS FTU $l\ ha^{-1}\ s^{-1}$
1	0.13	7.7	0.0013	0.040	0.52
2	0.13	7.7	0.0013	0.044	0.52
3	0.13	7.7	0.0039	0.056	0.78
4	0.29	17	0.0051	0.099	1.5
5	0.29	18	0.0058	0.090	1.5
6	0.29	17	0.0029	0.096	1.5
7	0.54	32	0.0054	0.17	4.9
8	0.72	43	0.0072	0.22	6.5
9	0.85	52	0.017	0.37	7.7
10	0.54	31	0.022	0.19	5.4
11	0.54	33	0.016	0.21	5.4
12	0.48	27	0.0096	0.17	4.3
13	0.29	17	0.0058	0.096	2.9
14	0.41	23	0.012	0.15	3.7
15	0.29	17	0.0029	0.10	2.3
16	0.29	17	0.0029	0.090	2.0

All-basin sampling

Pitcher's Path forested sub-catchment

NO.	TIME h	TEMP °C	DISCHARGE $l\ s^{-1}$	pH	CONDUCTIVITY $\mu Scm^{-1} \cdot 25°C$	REACTIVE PHOSPHORUS $mg\ l^{-1}$	NITRATES $mg\ l^{-1}$	TURBIDITY FTU
1	21:07	6.0	27	6.2	48	0.03	0	10
2	22:11	5.5	27	6.3	48	0.01	0	8
3	23:08	5.5	32	6.2	49	0.01	0	7
4	0:05	6.0	32	6.2	46	0.01	0	11
5	1:06	6.0	32	6.2	47	0.04	0	10
6	2:06	5.5	34	6.3	46	0.03	0	10
7	3:01	6.0	42	6.2	46	0.01	0	10
8	4:07	6.0	68	6.1	45	0.00	0	12
9	5:05	6.0	78	6.3	47	0.03	0.01	11
10	6:00	6.5	78	6.3	45	0.01	0.02	12
11	7:03	6.5	75	6.3	44	0.01	0.01	12
12	8:02	7.0	69	6.3	42	0.02	0	12
13	9:14	7.0	68	6.3	44	0.00	0	14
14	10:10	8.5	68	6.3	44	0.03	0	12
15	11:08	8.5	65	6.3	42	0.01	0	13
16	12:06	9.5	60	6.3	44	0.00	0	13

All-basin sampling

Pitcher's Path forest sub-catchment, yield rates of:

NO.	WATER $1\ ha^{-1}\ s^{-1}$	DISSOLVED SOLIDS $mg\ ha^{-1}\ s^{-1}$	PHOSPHATES $mg\ ha^{-1}\ s^{-1}$	NITRATES $mg\ ha^{-1}\ s^{-1}$	SUSPENDED SOLIDS $FTU/1\ ha^{-1}\ s^{-1}$
1	0.23	10.8	0.0068	0	2.3
2	0.23	10.8	0.0023	0	1.8
3	0.26	12.9	0.0026	0	1.8
4	0.26	12.1	0.0026	0	2.9
5	0.26	12.4	0.011	0	2.6
6	0.28	13.0	0.0085	0	2.8
7	0.35	15.9	0.0035	0	3.5
8	0.57	25.5	0.0000	0	6.8
9	0.65	30.7	0.020	0.0065	7.8
10	0.65	29.4	0.0065	0.013	7.8
11	0.63	27.7	0.0063	0.0063	7.5
12	0.58	24.3	0.012	0	6.9
13	0.57	24.9	0.0000	0	7.9
14	0.57	24.9	0.017	0	6.8
15	0.54	22.7	0.0054	0	7.0
16	0.50	22.2	0.000	0	66

Individual sampling

Pitcher's Path forested sub-catchment (cont'd)

TIME hr	PRECIP. mm hr^{-1}	DISCHARGE l s^{-1}	TEMP ^oC	CONDUCTIVITY $\mu Scm^{-1} \cdot 25^oC$	pH	TURBIDITY FTU	REACTIVE PHOSPHATES mg l^{-1}	NITRATES mg l^{-1}
18:45	0	108	11.0	48	6.1	62	0.025	0.115
19:00	0	108	11.0	48	6.3	60	0.025	0.021
19:15	0.1	116	11.0	48	6.2	62	0	0.068
19:30	0.1	121	11.0	48	6.2	60	0	0
19:45	0.3	121	11.0	48	6.1	55	0	0.038
20:00	0	121	11.0	49	6.0	52	0	0.051
20:15	0.1	124	11.0	48	6.0	47	0.025	0.081
20:30	0	124	11.0	48	6.0	54	0.025	0.030
20:45	0.1	121	11.0	49	6.0	50	0	0.051
21:00	0	121	11.0	49	6.0	35	0	1.14
21.15	0	117	11.0	49	6.0	30	0	0.072
21:30	0.1	114	11.0	48	6.0	30	0	0.034
21:45	0	112	11.0	48	6.0	27	0	0.026
22:00	0	112	11.0	48	6.0	27	0	0.089
22:15	0	110	11.0	48	5.9	27	0	0.064
22:30	0	108	11.0	48	6.0	25	0	0.027
22:45	0	108	11.0	49	6.0	25	0.015	0.089
23:00	0	105	11.0	48	6.0	25	0	0.012

Individual sampling

Hospital parking lot sub-catchment

TIME hr	PRECIP. mm hr^{-1}	DISCHARGE l s^{-1}	TEMP ^oC	CONDUCTIVITY $\mu S\ cm^{-1}\ 25^oC$	pH	TURBIDITY FTU	REACTIVE PHOSPHATES mg l^{-1}	NITRATES mg l^{-1}
23:50		0						
24:00	22.9	18	17.5	58	5.3	118	0.12	2.27
0:10	13.7	5.2	17.5	6	6.2	35	0.08	0.021
0:20	16.8	9.1	17.0	4.5	6.3	18	0.05	0.017
0:30	10.7	3.8	17.0	4.0	6.4	15	0.06	0
0:40	1.5	1.8	17.0	5.0	6.4	10	0.02	0.093
0:50	12.2	7.0	17.0	5.0	6.3	15	0.05	0.12
1:00	9.1	2.6	17.0	4.0	6.4	16	0.08	0.085
1:10	4.6	3.2	17.0	4.0	6.3	10	0.08	0.081
1:20	0.76	1.8	17.0	4.0	6.3	8	0.08	0.055
1:30	0.76	0.91	17.0	4.0	6.3	14	0.08	0.059
1:40	1.5	0.70	17.0	5.0	6.3	14	0.06	0.13
1:50	1.5	0.70	17.0	6.0	6.3	8	0.14	0.16
2:00	1.5	0.91	17.0	6.0	6.3	8	0.15	0.24
2:10	1.5	1.1	17.0	6.0	6.4	7	0.07	0.20
2:20	1.5	0.70	17.0	6.0	6.2	6	0.07	0.24
2:30	0.46	0.42	17.0	6.0	6.2	6	0.08	0.20
2:40	0	0.20	17.0	6.5	6.3	6	0.06	0.09
2:50	0	0.19	17.0	7.0	6.2	5	0.08	0.23
3:00	0	0.015	16.5	7.0	6.4	8	0.04	0.31
3:10	0	0.013	16.5	8.0	6.4	8	0.08	0.26

Individual sampling

Ayreshire Place residential sub-catchment

TIME hr	PRECIP $mm\ hr^{-1}$	DISCHARGE $l\ s^{-1}$	TEMP ^{o}C	CONDUCTIVITY $\mu Scm^{-1}\ 25^{o}C$	pH	TURBIDITY FTU	REACTIVE PHOSPHATES $mg\ l^{-1}$	NITRATES $mg\ l^{-1}$
14:20	trace	0.74	17	540	6.1	8	0.25	3.04
16:00	trace	0.54	16	570	6.0	tr	0.03	1.98
16:30	0	0.52	16	620	6.0	tr	0.05	2.18
16:45	0.25	0.48	16	620	6.1	0	0.06	2.26
17:15	0.25	0.57	15	600	6.2	0	0.06	2.20
17:30	0.25	0.90	16	560	6.3	0	0.07	2.18
17:45	0.17	1.5	16	330	6.0	25	0.14	1.24
18:00	0	0.90	15	420	6.1	12	0.09	1.45
18:15	0.05	0.85	15	500	6.1	5	0.06	1.77
18:30	0.03	0.80	15	520	6.2	tr	0.09	1.86
18:45	0.03	0.80	15	520	6.1	tr	0.06	1.88
19:00	0.03	0.08	15	530	6.1	0	0.05	1.99
19:15	0.03	0.08	15	530	6.2	0	0.06	1.90
19:30	0.20	0.94	16	510	6.2	0	0.06	0.36
20:00	0.10	0.98	15	430	6.1	10	0.07	1.62
20:15	0.25	0.90	15	480	6.2	8	0.06	1.77
20:30	0.05	1.1	15	460	6.3	8	0.05	1.62
20:45	0.08	0.93	15	440	6.2	10	0.05	1.52
21:00	0.17	0.85	15	480	6.1	8	0.05	1.81
21:15	0.05	0.80	15	510	6.1	5	0.04	1.87
21:30	0.20	0.77	15	530	6.1	4	0.05	2.02
21:45	0.17	0.80	15	510	6.1	8	0.10	1.91
22:00	0.17	0.80	15	500	6.2	5	0.07	1.80
22:15	0.17	0.74	15	540	6.4	2	0.07	1.85
22:30	0.89	5.7	15	240	6.2	60	0.11	0.95
22:45	0.46	1.9	15	210	6.2	25	0.06	0.94
23:00	2.08	11	15	71	6.2	45	0.06	0.31
23:15	0	6.0	15	120	6.0	25	0.06	0.48
23:30	0	2.5	15	220	6.2	15	0.06	0.89

Individual sampling

O'Leary Avenue commercial/industrial sub-catchment

TIME hr	PRECIP mm hr^{-1}	DISCHARGE $l\ s^{-1}$	TEMP ^{o}C	CONDUCTIVITY μScm^{-1} $25^{o}C$	pH	TURBIDITY FTU	REACTIVE PHOSPHATES mg l^{-1}	NITRATES mg l^{-1}
17:40	0	0.32	15	325	–	15	0.60	0.23
17:55	tr	0.32	15	325	7.2	8	0.52	0.23
18:10	0	0.32	15	370	7.2	15	0.50	0.19
18:25	0	0132	15	390	7.2	8	0.42	0.18
18:40	0	0.32	15	370	7.2	12	0.40	0.29
18:55	0	0.32	15	380	7.1	11	0.34	0.23
19:40	tr	0.32	15	365	7.2	8	0.25	0.17
19:45	0	0.32	15	360	7.0	15	0.23	0.17
20:10	0	0.32	15	620	7.1	7	0.28	0.19
20:25	2.0	0.09	14	1200	7.2	8	0.40	0.21
20:40	0.51	0.70	15	520	6.7	280	1.5	0.33
20:55	0.10	0.73	15	320	6.6	115	0.47	0.29
21:10	0.10	0.52	15	520	6.6	95	0.46	0.35
21:25	0.10	0.43	15	560	6.6	80	0.46	0.39
21:40	0	0.26	15	590	6.8	70	0.37	0.12
21:55	0	0.20	15	720	6.8	–	–	0.31
22:10	0.20	0.15	15	840	6.9	38	0.29	0.25
22:25	0.20	0.12	15	960	7.0	30	0.28	0.21
22:40	0.20	0.10	15	1200	7.0	27	0.27	0.18
22:55	3.7	0.12	15	1200	6.8	27	0.23	0.20
23:05	–	25	17	85	6.0	210	0.17	0.19
23:10	5.1	18	16.5	160	6.4	95	0.55	0.79
23:25	0	17	16	180	6.6	40	0.14	0.54
23:40	3.1	5.2	16	180	6.3	30	0.13	0.43
23:55	15	60	17	40	6.3	100	0.17	0.37
0:10	0	37	16.5	89	6.3	170	0.05	0.06
0:25	0	18	16	130	6.3	155	0.05	0.25
0:40	0	[illegible]	16	160	6.3	110	0.10	0.17
0:55	0	7.6	16	170	6.2	95	0.13	0.30

Individual Sampling

Groves Road rural sub-catchment

TIME hr	PRECIP. mm hr^{-1}	DISCHARGE l s^{-1}	TEMP ^oC	CONDUCTIVITY $\mu Scm^{-1} \cdot 25^oC$	pH	TURBIDITY FTU	REACTIVE PHOSPHATES mg l^{-1}	NITRATES mg l^{-1}
19:10	0	tr	22	275	6.8	20	0.05	0.053
20:00	tr	tr	22	260	6.7	25	0.03	0.27
20:15	6.1	0.09	22	230	6.4	35	0	0.092
20:30	0	0.04	22	245	6.6	40	0.04	0.073
20:45	0.5	0.03	21	250	6.7	20	0.03	0.24
21:00	tr	0.02	21	250	6.8	25	0.03	0.031
21:15	0.5	0.03	21	250	6.6	150	0.03	0.053
21:30	1.5	0.03	21	250	6.7	35	0.04	0.057
21:45	3.0	0.03	20	260	6.7	30	0.03	0.076
22:00	0.5	0.06	20	260	6.8	110	0.02	0.076
22:15	4.1	0.11	20	250	6.5	130	0.02	0.046
22:30	7.1	0.15	20	250	6.5	200	0.02	0.84
22:45	6.1	0.30	21	300	6.6	200	0.01	0.094
23:00	6.1	0.46	20	330	6.6	85	0.02	0.55
23:15	9.1	0.59	20	380	6.4	55	0.05	0.33
23:30	6.1	0.70	20	360	6.4	65	0.03	0.37
23:45	2.0	0.83	19	350	6.4	50	0.01	0.14
24:00	16	1.1	19	340	6.3	75	0.03	0.16
0:15	6.1	1.4	19	330	6.4	70	0.03	0.18
0:30	3.0	1.2	19	300	6.3	30	0.02	0.12
0:45	2.0	1.2	19	310	6.3	20	0.03	0.14
1:00	0	1.1	19	300	6.2	18	0.03	0.12
1:15	0	1.4	19	260	6.3	35	0.03	0.046
1:30	0	1.6	19	230	6.5	45	0.02	0.092
1:45	0	2.0	19	210	6.4	40	0.02	0.11
2:00	0	1.8	19	210	6.4	25	0.02	0.05
2:15	0	1.7	19	200	6.3	20	0.02	0.088

Individual sampling

Pitcher's Path forested sub-catchment

TIME hr	PRECIP. mm hr^{-1}	DISCHARGE 1 s^{-1}	TEMP ^oC	CONDUCTIVITY $\mu Scm^{-1} \cdot 25^oC$	pH	TURBIDITY FTU	REACTIVE PHOSPHATES mg l^{-1}	NITRATES mg l^{-1}
14:15	tr	28	13.5	48	6.4	10	0	0.16
14:30	tr	28	12.5	48	6.4	10	0	0
14:45	4.1	28	12.5	47	6.4	12	0.015	0.033
15:00	5.1	28	12.0	48	6.4	10	0.015	0.50
15:15	7.1	28	12.0	48	6.4	10	0.025	0
15:30	7.1	31	12.0	48	6.4	10	0.015	0
15:45	5.1	33	12.0	48	6.4	10	0.025	0.03
16:00	4.1	33	12.0	47	6.3	12	0	0.04
16:15	4.1	40	11.5	48	6.3	12	0.015	0
16:30	3.0	49	11.5	48	6.4	15	0	0
16:45	5.1	54	11.5	47	6.3	20	0.015	0.009
17:00	8.1	62	11.5	48	6.4	25	0	0.034
17:15	9.1	71	11.5	47	6.3	32	0.015	0
17:30	5.1	80	11.0	49	6.3	42	0.015	0.038
17:45	1.0	89	11.0	49	6.2	54	0	0.034
18:00	1.0	104	11.0	49	6.3	65	0	0
18:15	3.0	106	11.0	48	6.1	62	0	0
18:30	2.0	108	11.0	48	6.2	62	0	0.055